WATER-USE AND YIELD OF ROOIBOS TEA (ASPALATHUS LINEARIS) IN THE WINTER RAINFALL AREAS OF SOUTH AFRICA

Daleen Lötter, Sebinasi Dzikiti, Wasanga Mkhanzi, Sarel Haasbroek

WATER
RESEARCH
COMMISSION

TT 878/22

WATER-USE AND YIELD OF ROOIBOS TEA (*ASPALATHUS LINEARIS*) IN THE WINTER RAINFALL AREAS OF SOUTH AFRICA

Report to the
WATER RESEARCH COMMISSION

by

Daleen Lötter[1], Sebinasi Dzikiti[1,2,3], Wasanga Mkhanzi[2], Sarel Haasbroek[1]

[1] Council for Scientific and Industrial Research, Smart Places

[2] University of the Western Cape, Earth Sciences

[3] Stellenbosch University, Department of Horticultural Science

WRC Report No. TT 878/22
May 2022

Obtainable from
Water Research Commission
Private Bag X03
Gezina
PRETORIA, 0031

orders@wrc.org.za or download from www.wrc.org.za

The publication of this report emanates from a project entitled: ***Water use and physical as well as economic productivity of indigenous herbal teas in the winter rainfall region*** (WRC Project No. K5/2961//4)

ISBN 978-0-6392-0436-9

Printed in the Republic of South Africa

EXECUTIVE SUMMARY

BACKGROUND

The Water Research Commission commissioned the study on "*Water use and yield of rooibos tea (Aspalathus linearis) in the winter rainfall areas of South Africa (WRC K5/2961//4)*".

Several indigenous plants of South Africa are used to brew herbal infusions for making tea as well as for culinary and medicinal purposes. Rooibos tea is the most renowned and economically important of these herbal tea plants. It belongs to the genus *Aspalathus* which is part of the legume family (Fabacea) of South Africa's fynbos biome. *Aspalathus linearis* occurs naturally in the mountain ranges on the West Coast of South Africa, but it is also commercially cultivated across the area. Rooibos grows in acidic, nutrient poor sandstone soils of the fynbos region and is well adapted to the harsh Mediterranean climate of the region (Sprent et al., 2010). The plant develops a strong taproot descending to 2 m or more to survive summer droughts (Morton, 1983).

The rooibos tea industry is highly diversified, and apart from its primary market, which is focused on herbal teas, it also develops functional foodstuffs and beauty products (Cheney and Scholtz, 2015). According to the Rooibos Council more than 20 000 tons of rooibos are produced in the Cederberg region per year (Rooibos Council, 2020). About half is exported to more than 60 countries, meaning rooibos accounts for about 87% of South Africa's tea exports. At the local level the industry makes an important contribution to rural livelihoods, providing income and employment to approximately 8 000 farm laborers in South Africa. More jobs are created in other parts of the value chain such as processing, packaging, transport and retailing.

Despite the plant being able to tolerate harsh climatic conditions, extreme droughts and increasing temperatures in recent years have placed pressure on the productivity of the rooibos crop. Many farmers have reported more erratic rainfall patterns, such as a shift in the onset of the rainy season, poor rainfall distribution throughout the growing season and more intense heat waves.

The main objective of this study was to investigate how the water use and yield of rooibos tea vary under current growing conditions in the prime production areas in the winter rainfall areas of South Africa. The study also sought to provide insights on how the projected future climatic conditions will affect the water requirements of rooibos tea crops. The research outputs are intended to enable the formulation of policies and recommendations to facilitate the development of best management practices and appropriate climate change adaptation strategies for the sustainable production and growth of the rooibos tea industry.

RATIONALE

The rooibos growing area is semi-arid characterized by low and erratic rainfall, high evapotranspiration rates and nutrient poor soils. Rooibos is grown exclusively under rain-fed conditions. Therefore it is vulnerable to changes in the distribution and timing of rainfall events. Although rooibos is well adapted to low rainfall and large fluctuations in temperature, projected changes in climatic conditions in the major growing regions are likely to induce changes beyond the species' evolutionary adaptation potential.

Predictions are that rainfall may decrease by between 20% and 40% (relative to the average present day winter rainfall) over the rooibos production region (DEA, 2013; Engelbrecht et al., 2009). The projected negative rainfall anomalies may attain values that are well outside those associated with the present-day climatological regime. Coupled with the rainfall decline is a projected increase in maximum temperatures of between 2°C and 3°C (Engelbrecht et al., 2015) which may contribute to an increase in the length and intensity of extreme temperature events. Given that the Cederberg area (Fig. 1) is already water-limited, an annual average temperature increase of 2°C to 3°C, coupled with less rainfall, could significantly impact the hydrological and climate regime of the region.

Direct impacts of these changing climate conditions include an increase in evaporative demand, a decrease in soil moisture availability and increasing soil temperatures. As rooibos is a rain-fed plant, the projected climatic conditions will alter the water relations and water use of the plant with concomitant changes in crop suitability and yield. Managing and monitoring soil moisture in areas such as the semi-arid West Coast of South Africa will become critically important to ensure sustainable rooibos production.

There is currently no information on the water requirements of rooibos tea and how this crop may respond to more frequent dry periods and prolonged droughts projected by climate models. Previous studies regarding rooibos productivity and water use, were mainly based on either climate envelope modelling, experimental control of moisture conditions under glasshouse conditions or by inferring water use through indirect methods such as carbon isotope analysis. These did not account for field observations and measurements of actual water use by the plants over complete growing cycles. So there remains a question as to how actual water use relates to biomass accumulation and yield.

AIMS AND OBJECTIVES

This research primarily focused on developing a better understanding of the current levels of water use by commercially cultivated rooibos tea in relation to water availability. More specifically, this study addressed the following objectives:

1) To review the current state of knowledge regarding the ecology, productivity, environmental and water requirements of rooibos tea;
2) To derive accurate quantitative information on the water use of the indigenous rooibos tea crop under current climatic conditions;
3) To quantify relationships between yield and water use for the indigenous rooibos;
4) To derive information on the key drivers of water use and yield variability;
5) To establish detailed information on how tea crops respond to water stress imposed by soil water deficit (inadequate rain) or by extreme weather conditions;
6) To provide insights on potential implications of climate change on the water requirements and productivity of rooibos tea crops in the Western Cape.

METHODOLOGY

The study was conducted over three years (2019-2021) in prime rooibos growing areas in the Western Cape Province. The first (2019/20) and second (2020/21) years involved detailed data collection using a range of measurement techniques of the soil-plant-atmosphere interactions in rooibos fields in the Cederberg region. The third year focused on completing the analysis of data collected in Years 1 and 2, scenario modelling, and gap filling. Two study sites were identified based on their climatic attributes, enabling data collection from different geographical and agro-climatological regions (Fig. 1).

The first study site was located about four kilometres to the south of the town of Porterville (coordinates 33° 2'17.20"S, 18°58'13.18"E). The long-term average rainfall for the area is just over 400 mm/year, which is on the high side compared to the average for the surrounding areas. The second study site (coordinates 32° 9'52.86"S, 18°48'39.03"E) was located approximately 8 km to the west of the town of Clanwilliam (Fig. 1). This area was somewhat drier than the Porterville site with a long-term average rainfall less than 250 mm/year. The soils at Clanwilliam were sandier than those at Porterville and thus they had a lower water holding capacity.

Methods used to quantify the water use of rooibos tea included:

1. The eddy covariance technique for quantifying whole field evapotranspiration (ET) based on the turbulent exchange of energy and water vapor fluxes above the crop canopy. These data were collected at 30 minute intervals over the entire growth cycle from crop regeneration in spring (September) until harvest in summer (February).
2. Actual rooibos crop transpiration, measured using the stem heat balance sap flow gauges on individual plants scaled up to the whole field level, and;
3. Evapotranspiration based on the soil water balance approach.

Figure 1. Location of the rooibos fields studied

Ancillary data collected include the site microclimates, soil physical and chemical properties, soil moisture in the root zone, plant growth, and yield. These data were used to develop a simple water-use and yield model for rooibos. The evapotranspiration model was based on a simple combination Penman-Monteith big leaf approach in which the whole field was assumed to be a single uniform surface. The relationship between the measured cumulative evapotranspiration and biomass accumulation data through the season were used to develop the yield model. The water-use model was calibrated using data collected from the Porterville site and validated with that from the Clanwilliam site.

Lastly, the model was used to estimate changes in crop water requirements under the envisaged climate change scenarios for the key rooibos producing areas. We used climate change scenarios from the conformal-cubic atmospheric model (CCAM) developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) assuming the business as usual RCP 8.5 pathway. Simulations were done for the period spanning the historic and future climate (1960-2100).

RESULTS AND DISCUSSION

This study is the first of its kind to present continuous data on the actual evapotranspiration (ET) and energy balance of a rooibos crop from the beginning of the growing season until harvest. Seasonal changes in the water use and how this is related to crop growth and yield were quantified. Simultaneous measurements of ET and transpiration allowed the partitioning of water use between beneficial water use by rooibos (transpiration) and the non-beneficial water use (field floor evaporation and weed transpiration) to be determined. These data provide insights on the best management practices to conserve water in the rain fed production systems.

While rooibos can indeed grow under harsh conditions, this study showed that its transpiration can decrease substantially with increasing water deficit in the root zone. Numerous studies have demonstrated that there exists a positive correlation between crop yield and cumulative transpiration because plants open their stomata to transpire in exchange for CO_2 gain. Therefore, higher soil water deficits, often associated with droughts, can indeed lead to substantial reduction in rooibos yield as confirmed by the recent severe droughts from 2016 to 2018 in the Western Cape Province in South Africa.

The solar radiation and vapor pressure deficit of the air were very strong drivers of rooibos transpiration with an R^2 of 0.71 and 0.68, respectively. Soil water deficit in the root zone had a somewhat weak effect on the daily transpiration ($R^2 \sim 0.60$) likely indicating that the crop had access to water from the deeper soil layers. More importantly our data showed that more than 36% of the annual total ET (291 mm/yr.) was consumed during the first three months of the growing season (September to November). This was mostly evaporation of the residual soil moisture from the winter rains (May-August) and transpiration by weeds. Actual crop transpiration during the early months was negligible with up to 84% of ET emanating from the combined effect of soil evaporation and transpiration by weeds. Daily peak transpiration by the rooibos at maximum canopy cover rarely reached 1.0 mm confirming the observation that this crop uses very little water, when compared to other crops such as fruit trees. Being a sclerophylous shrub that is adapted to dry environments, this observation was not surprising.

While rooibos is not produced under irrigation, this study shows that significant quantities of water stored in the soil profile are depleted early in the growing season before the crop reaches peak growth rate. Therefore, careful management of weeds and cover crops early in the season is critical to preserve the soil water reserve for later use. But its growth and yield can be significantly impacted by prolonged dry spells. Therefore, appropriate adaptation strategies to curb the early season water losses should be developed to cope with the projected future dry conditions for the sustainability and growth of the rooibos industry.

All six the climate change models for the rooibos producing areas suggest significant increases in air temperature and decreases in rainfall. Projected increases in the reference evapotranspiration and the actual evapotranspiration were in the range 11 to 18% for the reference evapotranspiration and 7 to 13% for actual ET by 2099. The model suggests a slower increase in actual crop water use relative to the atmospheric demand because of the increase in the vapor pressure deficit which causes stomata to close beyond certain thresholds. Ecological studies on the suitability of different regions in the Cape Floral Region to grow rooibos under climate change suggest a substantial shrinkage in the area where rooibos will be able to grow in future as the growing conditions become unfavorable. Similar findings were reported for the fynbos biome in the Cape Floral Region which is in the same family as rooibos. The present study however, sheds light on the possible impacts of climate change on the water requirements and yield of rooibos.

CONCLUSIONS AND RECOMMENDATIONS

This study has, for the first time, presented actual evapotranspiration (ET) and energy balance data for the rooibos crop over a complete growing cycle. With this continuous dataset, it was possible to quantify seasonal changes in rooibos water use and how this is related to crop growth and yield and establish a baseline for assessing the consequences of climate change for cultivated rooibos tea.

There is consensus amongst a range of climate models for a significant increase not only in average temperatures, but also extreme temperatures and heat waves over the Greater Cederberg region. Moreover, future climate projections also point to changes in the temporal and spatial variation in rainfall with rainfall events that will become more sporadic appearing at more irregular intervals. This study has shown that these changing climate conditions will cause increased crop stress levels in rooibos plants with concomitant effects on yield.

This study has also indicated that the severity of impacts will not be spatially homogeneous. The rooibos production region varies in topography with rainfall from as little as 150 mm per annum on the West Coast and lowlands to over 1000 mm on the interior plateaus of the Cederberg mountain range. Cultivation in sub-optimal locations or marginal areas is likely to decrease rapidly under the influence of accelerated global climate change. These represent the most vulnerable areas and reflect the differences between the lowland areas and the mountain sites, and also between the north-western and southern range of the production area. In the lowlands along the west coast and the northern periphery of the production areas, the occurrence of optimum cultivation conditions will become erratic as the suitable areas tend to expand south-eastwards in the future.

This study also demonstrates that rooibos as a member of the fynbos family, uses very little water. The rooibos water-use rates are lower than those reported by previous authors on other fynbos species growing in wetter ecosystems. An important finding in this study is that peak water use is reached before the crop growth reaches its maximum growth phase leading to substantially higher non-beneficial water losses. Therefore, the rooibos industry should implement water demand management practices that reduce water loss from the field floor to conserve soil water which can sustain crops later in the growing season. Examples of water demand management practices include the use of green mulches between the plant rows and removing the weeds early in the growing season before rooibos transpiration levels rise to preserve the residual soil moisture from the winter rains. Contour ridges on sloping terrain can also trap substantial amounts of runoff which can later be utilized by the plants.

The study has also shown that the Penman-Monteith model could be applied to give reasonable estimates of ET on rooibos fields at the weekly time step. This model can be applied to not only predict future crop water requirements, but to also estimate the water use of the rooibos in other growing regions.

While this study has made significant progress in better understanding the seasonal changes in rooibos water use through the use of micro-meteorological techniques, future research could benefit from the use of *in-situ* plant water status and gas exchange measurements to refine and support analysis of the seasonal dynamics of water stress experienced by the tea crops and their responses to precipitation pulses.

ACKNOWLEDGEMENTS

We acknowledge support from the Water Research Commission for initiating and funding this study through WRC project K5/2961//4. We extend our gratitude to members of the project reference group for their guidance and contributions during the course of the study. We also gratefully acknowledge technical support from Mr Sarel Haasbroek and in-kind support from the Rooibos Council of South Africa. Lastly we thank Mr Hanro Knoetzen of Eikenhof farm in Porterville and Mr Willie Nel of Ysterfontein farm in Clanwilliam for allowing us to use their productive fields.

The authors would like to thank the following members of the reference group for the assistance and constructive discussions during the course of the project:

Dr Samkelisiwe Hlophe-Ginindza	Water Research Commission (Chairperson)
Prof. Sylvester Mpandeli	Water Research Commission
Dr Luxon Nhamo	Water Research Commission
Dr Theresa Volschenk	Agricultural Research Council Infruitec-Nietvoorbij
Prof. Tafadzwa Mabhaudhi	University of KwaZulu-Natal
Prof. Wim van Averbeke	Tshwane University of Technology
Mr Barney Kgope	Department of Forestry, Fisheries and the Environment

TABLE OF CONTENTS

LIST OF FIGURES

LIST OFTABLES

LIST OF ABBREVIATIONS AND SYMBOLS

Roman symbols

A	Branch leaf area	cm^2
A_{st}	Stem cross sectional area	cm^2
C_p	Specific heat at constant pressure	$J\ kg^{-1}\ K^{-1}$
d	Zero plane displacement height	m
e_a	Actual vapor pressure of the air	kPa
e_{sat}	Saturation vapor pressure of the air	kPa
E	Soil evaporation	mmd^{-1}
ET_o	Reference evapotranspiration	$mm\ d^{-1}$
ET	Actual evapotranspiration	$mm\ d^{-1}$
G	Soil heat flux	$W\ m^{-2}$
g_s	Surface conductance	$m\ s^{-1}$
g_m	Maximum surface conductance	$m\ s^{-1}$
H	Sensible heat flux	$W\ m^{-2}$
k_{d1}	Parameter for VPD stress factor	kPa^{-1}
k	Extinction coefficient	-
k_{st}	Stem thermal conductivity	$W\ m^{-1}K^{-1}$
K_{sh}	Radial sheath conductance	$W\ K^{-1}$
LAI	Leaf area index	-
Mw	Molar mass of water vapor	g
Ma	Molar mass of air	g
Pa	Atmospheric pressure	kPa
P_{in}	Input power	W
q_r	Radial heat loss across instrument	W
q_v	Axial heat conduction along stem	W
q_f	Heat carried by sap	W
r_a	Aerodynamic resistance	$s\ m^{-1}$
RH	Average relative humidity	%
RH_{max}	Maximum relative humidity	%
RH_{min}	Minimum relative humidity	%
R_n	Net all wave radiation	$W\ m^{-2}$
R_s	Shortwave radiation	$W\ m^{-2}$

R_{ns}	Net shortwave radiation	$W\ m^{-2}$
R_{nl}	Net longwave radiation	$W\ m^{-2}$
r_s	Stomatal resistance	$s\ m^{-1}$
R_{so}	Clear sky shortwave radiation	$W\ m^{-2}$
SF	Stem sap flow	$g\ h^{-1}$
SWC	Soil water content	$cm^3\ cm^{-3}$
SWC_{max}	Soil water content at saturation	$cm^3\ cm^{-3}$
SWC_{min}	Soil water content at the wilting point	$cm^3\ cm^{-3}$
T	Average air temperature	°C
T_b	Gauge temperature upstream of heater	°C
T_a	Gauge temperature downstream of heater	°C
T_c	Area averaged transpiration	$mm\ d^{-1}$
T_{max}	Maximum air temperature	°C
T_{min}	Minimum air temperature	°C
u_2	Wind speed at 2.0 m	$m\ s^{-1}$
VPD	Vapor pressure deficit of the air	kPa
$VPD_{\_open}$	Vapor pressure deficit for stomata to open	kPa
x	Thermocouple gauge spacing	cm
z_m	Height of measurement of wind speed	m
z_h	Height of measurement of relative humidity	m
z_{oh}	Roughness length for heat and humidity	m
z_{om}	Roughness length for momentum transfer	m

Greek symbols

α	surface albedo	-
Δ	slope of saturation vapor pressure vs temperature curve	$kPa\ K^{-1}$
ρ	density of air	$kg\ m^{-3}$
ε_a	emissivity of the air	-
ε_s	emissivity of the surface	-
γ	psychrometric constant	$kPa\ K^{-1}$
λ	latent heat of vaporization	$J\ kg^{-1}$

CHAPTER 1

1. INTRODUCTION

1.1. Background

The fynbos biome forms part of the Cape Floral Region (CFR) of South Africa and is known for its exceptional degree of biodiversity. The biome stretches from Clanwilliam on the West Coast to Port Elizabeth on the Southeast Coast (Bond and Goldblatt, 1984). Rooibos tea (*Aspalathus Linearis*), is one of over 7 000 plant species that occur in the Fynbos Biome and mainly found on the western mountainous parts of the Western Cape (Bond and Goldblatt, 1984). Not only does it grow wild in the mountains of the Cederberg, it is also cultivated widely in the greater Cederberg region and therefore it is also of significant economic importance.

Commercial producers cultivate the Nortier type which is an ecotype that was successively selected from wild types (Cheney & Scholtz, 2015). Rooibos is used to brew herbal tea as well as for culinary and medicinal purposes. It is the most renowned and economically important indigenous herbal tea plant in South Africa and is scientifically proven to have extensive health benefits. This caffeine-free tea contains rare nutrients like quercetin and bioflavonoids, powerful antioxidants such as aspalathin and has therefore important antioxidant and anti-inflammatory properties (Joubert & Schulz, 2006).

Rooibos is exported to more than 30 countries around the world and earns an estimated R 500 million per year. At present, about 12 000 metric tons of Rooibos are produced in South Africa per year. The country consumes 4 500 to 5 000 tons and the rest is exported (Rooibos Council, 2019). Conventional prices for rooibos fluctuate greatly depending on climatic conditions and the area planted (Rooibos Council, 2019). Rooibos production, processing and packaging is a labor-intensive process, and the industry is therefore one of the largest employers of people from the rural provinces of South Africa, providing both permanent and seasonal employment opportunities. According to the South African Rooibos Council, the industry directly employed about 8 000 people as of 2019 (Rooibos Council, 2019). Further employment is created in downstream activities such as processing, packaging and retailing of the crop. The sector is also attracting other producers such as grain farmers who want to diversify their crops and take advantage of the easier growing conditions for rooibos in their area.

There are approximately 300 commercial and 150 small scale farmers involved in rooibos tea cultivation across the production area of the Greater Cederberg. The small scale farmers are mostly located in the areas of Wupperthal and Nieuwoudtville on the Heiveld (Fig. 2). Both of these communities also harvest wild tea from near pristine areas and market it separately as a niche product. They are organized into cooperatives with Wupperthal cooperative that has 170 members and produces from 80 to 100 tons of rooibos while the Heiveld cooperative has 42 members producing about 45-55 tons of rooibos annually. Both cooperatives use production techniques where indigenous knowledge has been firmly embedded in the harvesting and processing of the tea. Rooibos has received geographic indicator status (GI) and protection in the European Union, due to the ecologically important environment within which the plant is cultivated, its limited geographical range, and strong link with local farmers' heritage. This gave rooibos tea manufacturers of South Africa full ownership of the rooibos name. GI status meant that only products produced in those areas that are approved by the industry, could be marketed under those names. Rooibos/Red Bush is the first African food to receive the status of a protected designation of origin in the EU register.

Being endemic to the West Coast of South Africa, and having unique soil and climatic requirements, rooibos cannot be cultivated anywhere else in the world (reference!). All demand is supplied from a single production area that is approximately 200 x 100 kilometres in extent (Fig. 2).

The production area is bounded by the Atlantic Ocean on its west side and the Cederberg mountain range in the east while Nieuwoudtville in the Northern Cape Province and the Berg River form its northern and southern boundaries. The west coast area experiences cold wet winters and hot dry summers with about 300-350 mm of rain per annum. As a hardy, dry land crop, rooibos is often subjected to drought conditions and is typically not affected as harshly as other more rain-dependent crops. The plant develops a strong taproot descending to 2 m or more in the field to survive the summer drought periods (Morton, 1983). Rooibos can also endure temperatures ranging from 0°C to over 45°C.

In recent years however, more extreme drought events and increasing temperatures have placed pressure on the productivity of the rooibos crop. The rooibos industry reported large scale losses during the 2003 and 2012 growing season to such an extent that the demand for the crop exceeded supply. Many farmers have reported more erratic rainfall patterns, such as a shift in the onset of the rainy season, poor rainfall distribution throughout the growing season and more intense heat waves.

Climate model analysis of parameters important for rooibos production (rainfall frequency and intensity, temperature extremes and wind speed) indicate that, in the coming decades, plants may experience a shorter period of water availability during winter, and prolonged exposure to summer conditions (high temperatures and water stress). These climatic changes could bring about conditions well outside the existing climate regime, and adaptive capacity of rooibos tea.

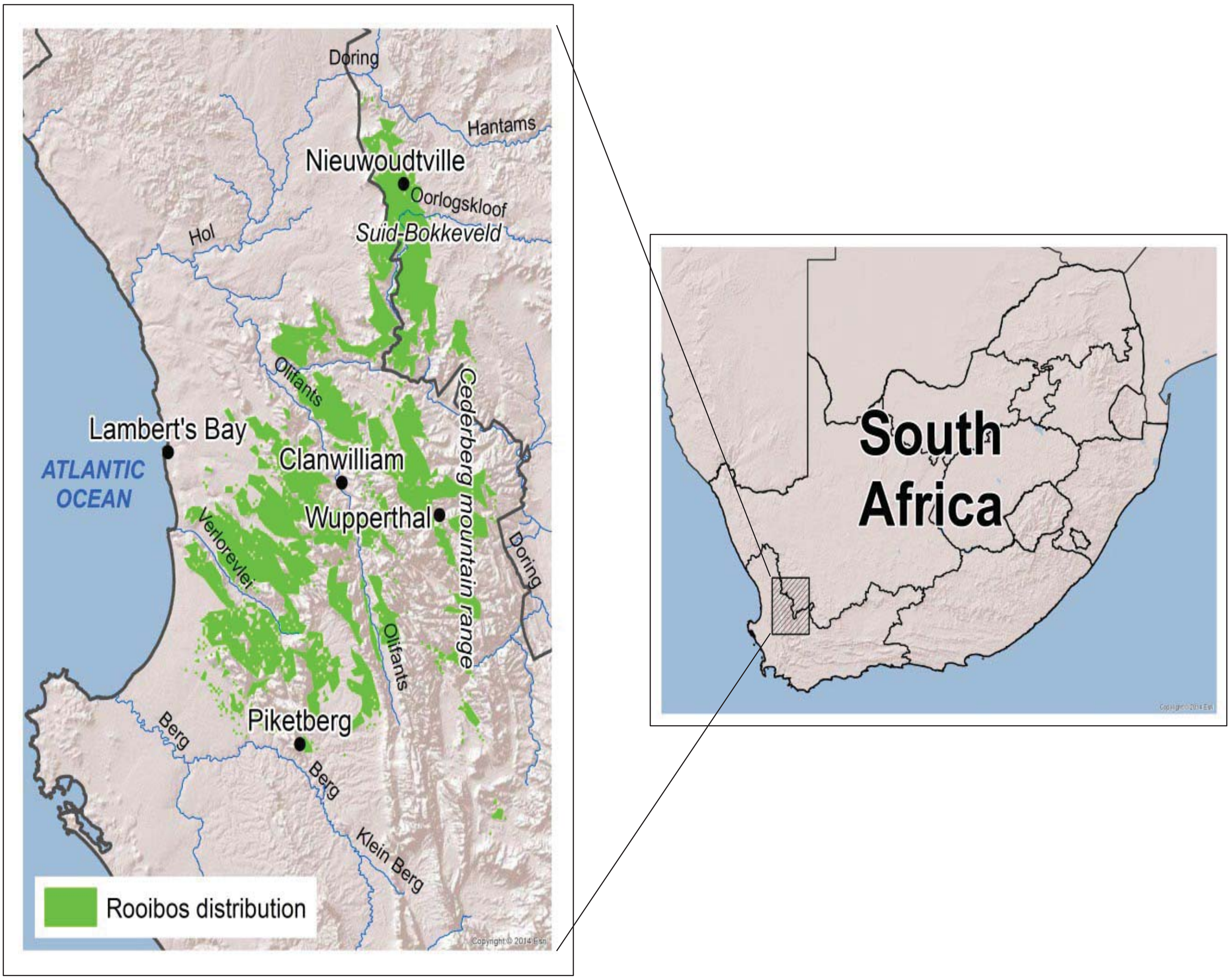

Figure 2. Map of the Cederberg region, showing the natural distribution of rooibos in the north-western part of the Western Cape province, South Africa

1.2. Rationale

Important research questions regarding the sustainability of the rooibos tea crop are linked to climate change given that the Western Cape is expected to get warmer and drier in future (Engelbrecht et al., 2013, 2009). Relatively few studies have addressed the impacts of variable water availability and water-use efficiency on rooibos yield dynamics (Archer et al., 2009) indicated that climate change would place significant additional pressure on rooibos production in an area where rainfall is already low and variable. Projections for the main production area are that temperatures will increase alongside a decline in rainfall during critical months. This means that that critical threshold in terms of water and heat stress may occur more often under future climate scenarios.

In follow up research regarding climate change and rooibos Lötter (2015) used leaf gas exchange measurements and carbon isotope ratios to monitor water-use efficiency in wild and cultivated plants. Both methods revealed better water-use efficiency as an adaptive strategy in wild plants under dry conditions. In a glasshouse experiment MacAlister et al. (2020a) found that plants grown under low moisture conditions produced 50% lower biomass compared to plants grown under adequate moisture conditions. In a separate study MacAlister et al. (2020b) assessed rooibos crop biomass along temperature gradients across the rooibos production area. They found that increasing temperatures had a negative impact on crop biomass although phenolic content as a measure of tea quality did not change.

Some studies have also considered the effect of fertilization, soil depth, and residue management on the soil water balance (SWB), biomass water-use efficiency (WUEB) and growth of rooibos (Nieuwoudt, 2017; Van Heerden, 2019; Van Schalkwyk, 2018). These studies have shown that soil fertility, soil physical and chemical properties play a significant role in the ability of the plant to tolerate drought.

Climate change projections for the rooibos production area depict similar trends in future as already observed by the farmers. Predictions are that rainfall may decrease by between 20% and 40% (relative to the average present day winter rainfall) over the rooibos production region (DEA, 2013a; Engelbrecht et al., 2009) by the year 2050. The projected negative rainfall anomalies may attain values that are well outside those associated with the present-day climatological regime. Coupled with the rainfall decline is a projected increase in maximum temperatures of 2°C to 3°C (Engelbrecht et al., 2015) which may contribute to an increase in the length and intensity of extreme temperature events. Given that the Cederberg area is already water-limited, an annual average temperature increase of 2 to 3°C, coupled with less rainfall, could significantly impact the hydrological and climate regime of the region.

Direct impacts of these changing climate conditions include an increase in evaporative demand, a decrease in soil moisture availability and increasing soil temperatures. As rooibos is a rain fed plant, these climate projections will alter the water relations and water-use patterns of the plant with concomitant changes in crop suitability and yield. Managing and monitoring soil moisture in areas such as the semi-arid West Coast of South Africa will become critically important to ensure sustainable rooibos production.

Previous studies regarding rooibos productivity and water use, were mainly based on either climate envelope modelling, experimental control of moisture conditions under glasshouse conditions or by inferring water use through indirect methods such as carbon isotope analysis. These did not account for field observations and measurements of actual water use by the plants over complete growing cycles and there remains a question as to how actual water use relates to biomass accumulation and yield.

There is currently very limited information regarding water use of rooibos under different field conditions and how the crop responds to prolonged droughts. The focus of this project was on closing these important information gaps for the sustainability and growth of the indigenous tea industry through detailed studies of the ecophysiology and water relations of rooibos under different microclimatic and soil conditions.

1.3. Aims and Objectives

1.3.1. General aim

This research primarily focused on developing a better understanding of the current levels of water use by commercially cultivated rooibos tea in relation to water availability. More specifically, the study determined how water use and crop yield varied with climatic conditions. This information was used to develop a simple evapotranspiration model which was applied to predict potential changes in the crop water requirements and yield under the projected future climatic conditions in the region. In future, this information can be used for developing yield models and for predicting how crop yield might change under changing climate conditions (decline in rainfall, increase in evapotranspiration).

The research outputs should enable formulation of policies, recommendations, and guidelines to facilitate the development of best management practices and appropriate climate change adaptation strategies for the rooibos sector.

1.3.2. Specific objectives

1. To review the current state of knowledge regarding the ecology, productivity, environmental and water requirements of herbal tea in the winter rainfall region;
2. To derive accurate quantitative information on the water use of the indigenous rooibos tea crop under current climatic conditions;
3. To quantify relationships between yield and water use for rooibos crops;
4. To derive information on the key drivers of water use and yield variability;
5. To establish detailed information on how tea crops respond to water stress imposed by soil water deficit (inadequate rain) or by extreme weather conditions;
6. To provide insights on potential implications of climate change on the water requirements and productivity of rooibos tea crops in the Western Cape.

CHAPTER 2

2. KNOWLEDGE REVIEW

2.1. Indigenous plant products of the Cape Floral Region

Botanically, the Cape Floral Region (CFR) of South Africa is the smallest and most species-rich of the world's six floral kingdoms. Fynbos covers only about 6.7% of South Africa (about 85 000 km^2) but has the largest number of plant species of any biome in the country (about 7500) (Rebelo et al., 2006). The region has both a high species density and diversity with over 9000 vascular plant species, of which 70% are endemic (Goldblatt and Manning, 2002) and therefore regarded as a global "hotspot" of biodiversity. The fynbos biome stretches from the Cederberg in the north-west, around the Western Cape coast and into the Eastern Cape up to the Nelson Mandela Metropole.

The remarkable species richness of the Cape Floral Kingdom is not only important in terms of biodiversity but also economic and medicinal value. In 2005 natural resource economists estimated the total economic value of the fynbos region's biodiversity as over R 10 billion per year. This is equivalent to over 10% of the Western Cape Province's Gross Domestic Product at the time (Turpie et al., 2003). More than 200 different products of the fynbos biome are marketed internationally from South Africa, of which more than 90% are harvested from or cultivated within their natural habitat. Some of the most famous products originating from the fynbos biome includes rooibos tea (*Aspalathus linearis*), honey bush tea (*Cyclopia spp*), aloe bitters (*Aloe ferox*), thatch reed (*Thamnochortus insignis, Thamnochortus erectus*), and the wild flower industry (Conradie and Knoesen, 2009). Both cut and dried flowers are harvested or cultivated with the main commercial types being Proteacea (*Protea, Leucospermum, Leucadendron*) while species such as *Brunia, Phylica* and *Erica* species are also used. Cape Flora SA statistics indicate that between 2016/2017 about 1.7 million stems of silver brunia (*Brunia laevis*) were exported, placing it as the second-most harvested species in the wild in South Africa in the mixed greens category. Recent estimates of the cut flower industry's economic value is not available but in 1997 (Higgins et al., 1997) estimated it to exceed US$10 000/km^2 in certain areas.

Other particular important uses of fynbos plants are for traditional medicine, commercial herbal teas and functional foods. Examples include rooibos tea (*Aspalathus linearis*), honey bush tea (*Cyclopia genistoides*), buchu (*Agathosma betulina* and *A. crenata*), hoodia or ghaap (*Hoodia gordonii*), sutherlandia or cancer bush (*Lessertia frutescens*) and sceletium or kougoed (*Mesembryanthemum tortuosum*) (Joubert et al., 2017; Van Heerden et al., 2003; Van Wyk and Gorelik, 2017; Viljoen, 2010).

2.2. Review and description of Cape plants used as herbal teas

Herbal teas are consumed for their taste and aroma. They are also used as traditional medicines while some species are mixed with other teas to improve the flavor of the tea. In a recent publication by (Van Wyk and Gorelik, 2017), a comprehensive list of Cape plants that are used (or have been used) as hot beverages are described. They present data on the historical and contemporary ethnobotanical uses of 52 species from 15 Cape genera (*Agathosma, Aspalathus, Catha, Cyclopia, Geranium, Helichrysum, Lessertia, Leysera, Mentha, Mesembryanthemum, Plecostachys, Rafnia, Stachys, Thesium* and *Viscum*). According to (van Wyk and Gorelik, 2017), the tea and coffee drinking tradition of early European settlers in the 17th century may have stimulated the use of numerous indigenous plants as tea and coffee substitutes.

In another survey on the use of indigenous plant resources of the Cape Floristic Region, (De Vynck et al., 2016) compiled a list of all known edible, medicinal and otherwise useful plant and animal species used by contemporary Khoe-San descendants of South Africa's Cape South Coast. From the identified 58 indigenous edible plant species it was found that *Salvia africana-lutea L. (Lamiaceae*), *Viscum capense L.f. (Viscaceae)*; *Cyclopia genistoides* (L.) R.Br. (*Fabaceae*); were used as herbal tea, while *Mentha longifolia* (L.) *Huds*. (*Lamiaceae*) was used to flavor tea. In the next section we give a description of the most important plants, found in the Western Cape that were or are harvested, processed and consumed as herbal teas (as described by Van Wyk and Gorelik, 2017).

2.2.1. Agathosma

Important species: *A. betulina, A. crenulata, A. serratifolia*

Vernacular name: Buchu, boegoe

Buchu is one of the earliest and best known medicinal plants and export products from South Africa. Although *Agathosma* species (buchu) is sometimes consumed as tea it is more commonly used as an ingredient of mixtures and as a source of essential oil used as flavourant and fragrance (Van Wyk and Gorelik, 2017). Historically buchu was used to treat a wide range of ailments such as chronic rheumatism and gout, as diuretic and diaphoretic to promote kidney and bladder health and as general tonic (Moolla and Viljoen, 2008; Viljoen, 2010). Although there are 150 Agathosma species that are indigenous to South Africa, the three most important species from a commercial perspective are *A. betulina*, *A. crenulata* and *A. serratifolia.* They occur naturally from Nieuwoudtville to Grootwinterhoek (*A. betulina*), and from Tulbagh to Worcester, southwards to the Hottentot's Holland Mountains (*A. crenulata*), whereas *A. serratifolila* is mostly found in the Swellendam area, (Van Wyk and Gorelik, 2017). These three species are used internationally and locally for a variety of medicinal purposes.

Agathosma Crenulata *Agathosma betulina* *Agathosma serratifolia*

source: (SANBI, 2020)

Figure 3. The three most important buchu species from a commercial perspective

2.2.2. Aspalathus

Important species: *Aspalathus linearis*

Vernacular names: Rooibos tea (English), rooibostee, rooitee, bossietee, rooibossie, stokkiestee, naaldetee (Afrikaans)

The *Aspalathus* (Fabaceae, Tribe Crotalarieae) consists of 279 species (Dahlgren, 1984) and is the largest member of the pea family endemic to South Africa. Although rooibos tea (*Aspalathus linearis*) is the most well-known species that belongs to this genus, there are several other species such as *Aspalathus alpestris, Aspalathus cordata, Aspalathus crenata* and *Aspalathus pendula* that were once consumed by local people as herbal teas for its health benefits. Local people referred to these tea types as “bossiestee, stekeltee or sweeptee”. Within the *Aspalathus linearis* species group there is also several wild types of rooibos tea, also known as ecotypes. These wild types display considerable morphological, ecological, genetic and chemical variation. Historically, professional producers of “tea” from *A. linearis* distinguished between the following five different types of rooibos (mainly based on the colour that the tea yield):

- Rooi (red) – Nortier type: This is the type that is currently cultivated by commercial producers and was successively selected from wild types;
- Cederberg type: obtained from the wild forms out of which the cultivated Nortier Type has been selected;
- Rooi-bruin (red-brown): obtained from wild plants growing in the northern production area around Clanwilliam to Vanrhynsdorp;
- Vaal (grey): obtained from wild plants growing in the Cederberg;
- Swart (black): obtained from wild plants growing in the rocky regions of the Cederberg Mountains.

In a more scientific approach to distinguish between the various sub-types of rooibos, Van Wyk and Gorelik (2017) classify the following eight main categories based on distinct morphological and chemical differences as well as fire survival strategy, vegetative and reproductive morphology, isozyme patterns and flavonoid composition:

- Southern sprouter (Cape Peninsula, Franschhoek Pass to Ceres and Tulbagh): A small plant with a prostrate growth form, somewhat hairy leaves and yellow flowers;

- Grey sprouter (Citrusdal area): This is the source of the vaal tea described above;
- Northern sprouter (Citrusdal to Cederberg and Bokkeveld): This is called rankiestee by (Malgas and Oettle, 2007) and the tea quality is comparable to that of the red tea type;
- Nieuwoudtville sprouter also known as heiveldtee;
- Red type (seeder) (Clanwilliam region to Nardouwsberg). This type is represented by the commercial form, also known as the Rocklands type or Nortier type;
- Black type (seeder) (Piketberg, Paleisheuwel and Citrusdal areas);
- Wupperthal type (seeder) (Cederberg region): Some local inhabitants of the Cederberg have called this "bloublommetjiestee"
- Tree type (seeder) (Citrusdal area): A sparse, tall plant of up to 3-4 m high and also called "langbeen tea".

Figure 4. Cultivated rooibos (Nortier type)

2.2.3. Cyclopia

Important species: *C. subternata, C. genistoides and Cyclopia intermedia*
Vernacular name: Honey bush tea/ Bushtea (English) Heuningtee, Bergtee, Boertee, Bossiestee (Afrikaans)

The *Cyclopia* genus also belongs to the legume or pea family and consists of 23 species. Being endemic to the fynbos biome the plants are well adapted to the acidic, mostly sandy, nutrient-poor soils of the coastal plains and mountainous regions of the winter and bimodal rainfall regions of the Eastern and Western Cape provinces. The species have very specific habitat preferences and are usually restricted to very small areas and very specific habitats, such as high mountain peaks, marshy areas, shale bands and wet slopes.

The leaves and stems are used to make the tea, which contains no caffeine but there is also potential use by the cosmetic and pharmaceutical industries due to the high levels of antioxidants. From a commercial perspective there are five species that are either wild harvested or cultivated. From these five species, *Cyclopia intermedia* is most popular but is almost exclusively harvested from the wild, and can sustainably be harvested only every second or third year, making it difficult and uneconomical to cultivate. The main cultivated species are *C. subternata* and *C. genistoides* and these are localised in the area from Overberg to Langkloof, with approximately 200 hectares under cultivation in total.

Different honey bush tea species prefer different temperatures and climate conditions. Generally, honey bush prefers the cooler, wetter, misty conditions on the southern slopes of the mountains. However, depending on the species they have specific habitat preferences and their distribution varies between mountain slopes, perennial streams, marshy areas and coastal bands (DAFF, 2016). Since honey bush is endemic to the fynbos biome, the plants are well adapted to the acidic, mostly sandy, nutrient-poor soils of the coastal plains and mountainous regions of the winter and bimodal rainfall regions of the Eastern and Western Cape provinces. Honey bush species therefore prefer well-drained, sandy to sandy loam-type soils with a low pH (below five), low phosphorus and low nematode (roundworm) counts. There is a significant rainfall gradient across the honey bush distribution area, ranging from 200-600 mm of average annual rainfall. In higher rainfall areas the plants grow more quickly to reach a potentially harvestable size in a shorter time (McGregor, 2017). There is also anecdotal evidence that the distribution of *C. intermedia* populations is strongly correlated with the occurrence of mist as only source of moisture during certain months of the year.

Sowing in seedling trays, via seeds or cuttings, takes place between summer and autumn, and the young seedlings are grown in a nursery before being planted out during the winter, preferably before the end of August. Harvesting time varies between the different species, but is usually done before they flower (July-October), as the flowers drain the energy reserves of the plants. Re-sprouters (*C. genistoides*) can be harvested about two to three years after planting. The seeders (*C. subternata*) can be harvested about one to two years after planting, depending on the soil and climate, but need to be cut back during harvesting to 30-50 cm above the ground in the early winter. Following the first harvest in plantations, the plants can be harvested annually. Honey bush needs to be planted in full sun. Seedlings should be watered for the first two weeks. After that the plants are only watered in excessively dry conditions.

The honey bush industry is relatively small compared to the rooibos industry. Most of the annual harvest comes from wild plants and mostly from the Langkloof area. Cultivated honey bush is produced by a few commercial growers as well as community-based growers. These previously disadvantaged communities in Haarlem, Ericaville and Groendal make up about 15% of the total area under cultivation (DAFF, 2016; Joubert et al., 2011; Morrison, 2008).

3. *C. intermedia*

2. *C. subternata*

1. *C. genistoides*

source: (SANBI, 2020)

Figure 5. The most important honey bush tea species

2.2.4. Geranium

Important species: *Geranium incanum*

Vernacular name: Carpet Geranium (English), Bergtee, vrouebossie (Afrikaans); ngope-sethsoha, tlako (Sotho).

The geranium family consists of several genera of plants commonly referred to as geraniums or cranesbills. In terms of herbal tea and medicinal plants, the *Geranium incanum* is the most important species. The species are endemic to the coastal regions of the Western and Eastern Cape. Locally known as “vrouebossie” or “bergtee”, the leaves of the plant are used to make a traditional tea which is used as an old remedy by people from the Cape to treat kidney and bladder ailments, stomach cramps, nausea, vomiting, diarrhoea and flatulence.

Figure 6. *Geranium incanum*

source: (SANBI, 2020)

2.2.5. Helichrysum

Important species: *Helichrysum patulum*

Vernacular name: honey everlasting (Eng.); kooigoed (Afr.); impepho (isiXhosa); phefo (Sesotho).

Several aromatic species of Helichrysum have been recorded as medicinal teas, but locally the most familiar species is *Helichrysum patulum* (also called Kooigoed). This plant grows on sandy flats and coastal dunes and inland on south-facing, lower mountain slopes of the southern Western Cape, from the Cape Peninsula and Stellenbosch, along the coast to Groot Brak River and Mossel Bay. They are tough plants; able to survive prolonged drought, and are wind resistant and frost tolerant. The fresh leaves are boiled in water and drunk as tea for colds and flu, menstrual pains and to cleanse kidneys and liver ("SANBI", 2019).

Figure 7. ***Helichrysum patulum***

source: (SANBI, 2020)

2.2.6. Lessertia

Important species: *Lessertia frutescens*

Vernacular name: sutherlandia, cancer bush, balloon pea (Eng.); umnwele (Xhosa & Zulu); kankerbos, blaasbossie, blaas-ertjie, eendjies, gansiekeurtjie, klappers, hoenderbelletjie (Afr.)

Lessertia frutescens, formerly known as *Sutherlandia frutescens* is one of the most acclaimed medicinal plants in Southern Africa because of its strong reputation as a cure for cancer. It is therefore also called "kankerbossie". However, there is no scientific evidence yet for the numerous claims and anecdotes that it can cure cancer. Research on other properties such as its potential as an immune booster in the treatment of HIV/AIDS is also in progress. It is also known to be used in the treatment of several other ailments such as colds, flu, asthma, TB, bronchitis, rheumatism, rheumatoid arthritis and osteo-arthritis, liver problems, etc. (SANBI, 2020). *Lessertia frutescens* is widely distributed throughout the dry parts of southern Africa. It is a drought resistant plant that occurs naturally in the fynbos biome as well as in parts of the Eastern, and Northern Cape provinces and some areas of KwaZulu-Natal and Mpumalanga. It shows remarkable variation within its distribution.

Figure 8. ***Lessertia frutescens***

source: (SANBI, 2020)

2.2.7. Leysera

Important species: *L. gnaphalodes* and *L. tenella*

Vernacular name: yellow daisy tea, dune tea bush (Eng.); geelblommetjietee, duinetee, hongertee, teebos, skilpadtee, teringtee (Afr.)

Leysera gnaphalodes, commonly known as dune tea bush or yellow daisy tea has historically been a very popular plant used to make tea in the Cedarberg region. The leaves of *leysera gnaphalodes* are used to create a pleasant infusion with a blend of aromatic flavours and a sweetish taste (SANBI, 2020). This species occurs in the winter rainfall parts of South Africa and thrives in dry sandy areas.

Figure 9. ***Leysera gnaphalodes***

source: (SANBI, 2020)

2.2.8. Mentha

Important species: *Mentha longifolia* subsp. *capensis*

Vernacular name: wild mint (Eng.); kruisement, balderjan (Afr.); Koena-ya-thaba (Southern Sotho); inixina, inzinziniba (isiXhosa); ufuthana lomhlanga (Zulu)

Mentha longifolia or wild mint is a fast-growing, perennial herb that has a strongly aromatic scent (Codd, 1983). It occurs from Calvinia down to the Cape Peninsula through the Eastern Cape, Lesotho, Orange Free State, KwaZulu-Natal to Gauteng and Limpopo the Northern Province. Wild mint is a popular traditional medicine. It is mainly used for respiratory ailments but many other uses have also been recorded. It is mostly the leaves that are used, usually to make a tea that is drunk for coughs, colds, stomach cramps, asthma, flatulence, indigestion and headaches (Goldblatt and Manning, 2002).

Figure 10. ***Mentha longifolia***

source: (SANBI, 2020)

2.2.9. Plecostachys

Important species: *Plecostachys serpyllifolia*

Vernacular name: cobwebbush (Eng.); vaaltee, kooigoed (Afr.)

Plecostachys serpyllifolia, is commonly known as vaaltee and kooigoed (Smith, 1966) .The species is closely related to Helichrysum and has historically been an important Cape herbal tea. It occurs on sandy coastal flat areas of the Western Cape and Eastern Cape as far as southern KwaZulu-Natal.

Figure 11. ***Plecostachys serpyllifolia***

source: (SANBI, 2020)

2.2.10. Rafnia

Important species: *Rafnia amplexicaulis and R. acuminata*

Vernacular names: Liquorice bush (English), soethoutbossie, veldtee (Afrikaans)

Rafnia amplexicaulis (L.) Thunb. is a woody shrub of the legume family (*Fabaceae*, subfamily Papilionoideae) endemic to the Cape fynbos region of South Africa (Kinfe et al., 2015). Vernacular names in Afrikaans include soethoutbossie ("liquorice bush" or literally "bush with sweet-tasting wood") and veldtee ("veld tea") (Smith, 1966). The leaves of *Rafnia amplexicauli* are used as a traditional medicinal tea in Cape (Khoi-San and Cape Dutch) Herbal Medicine. It is used for treating asthma, influenza, back problems and infertility, while roots are traditionally used as a substitute for liquorice (Van Wyk, 2008). Some studies (Van Wyk, 2011a, 2011b) suggest that *Rafnia amplexicaulis* and other species may have considerable potential for developing new commercial herbal teas.

Figure 12. *Rafnia amplexicaulis*

Source: (SANBI, 2020)

2.2.11. Stachys

Important species: *Stachys aethiopica, Stachys rugosa*

Vernacular names: *Stachys aethiopica* – African stachys, wild sage (Eng.); katbossie, katpisbossie Afr.); bokhatha, bolae-ba-litaola, likhobe-tsa-balisana (SSo.)

S*tachys rugosa* – grey tea stachys (Eng.); vaaltee, bojanntee, boesmantee, dassiekruie (Afr.); taraputsoe (SSo.)

Stachys aethiopica with the common name wild sage and S*tachys rugosa* (grey tea) are used as herbal teas to treat colds, fevers and influenza (Van Wyk and Gorelik, 2017). *Stachys aethiopica* has a wide distribution range that extends from the Western Cape through to the Eastern Cape, Free State, Mpumalanga and Limpopo. *Stachys rugosa* is found in habitats of rocky mountain slopes or plateau, usually with higher clay content.

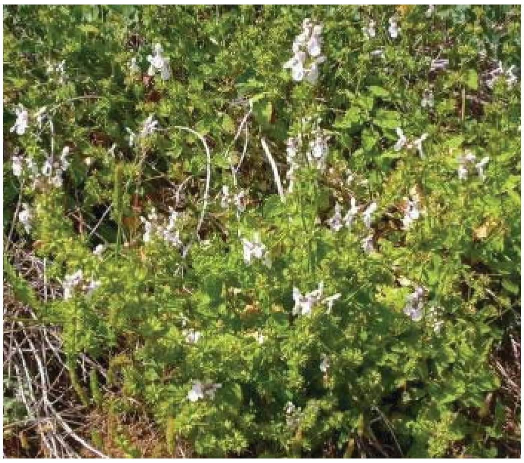

Figure 13. ***Stachys aethiopica***

Source: (SANBI, 2020)

2.2.12. Thesium

Important species: *Thesium macrostachyum*, *T. carinatum*

Vernacular names: Lidjiestee, jakkalstee

The *thesium macrostachyum* species occurs in the Wupperthal area in the Cederberg (Van Wyk and Gorelik, 2017). The inhabitants of the Cederberg refer to this species as lidjiestee and even consider it to be superior to rooibos tea in taste. Another species that is sometimes referred to as wild rooibos, is *T. carinatum* or locally called Jakkalstee. This tea is mixed with the commercial red type of rooibos tea to give the tea more substance or to improve flavour (Van Wyk and Gorelik, 2017).

Figure 14. ***Thesium macrostachyum***

Source: (SANBI, 2020)

2.2.13. Viscum

Important species: *Viscum capense*

Vernacular names: Cape Mistletoe, Voëlent, Litjiestee

Viscum capense is used in the Western Cape region as a herbal tea and most people refer to the species as "voëlent". The species distribution is widespread, from Namibia through the Northern Cape and Western Cape, eastwards to the Little Karoo (Goldblatt and Manning, 2002).

Figure 15. ***Viscum capense***

Source: (SANBI, 2020)

2.3. Ecology and distribution of rooibos tea

Rooibos (*Aspalathus linearis (Brum.f) Dahlg*.) is an endemic leguminous shrub and belongs to the genus *Aspalathu*s (Fabaceae, Tribe Crotalarieae) which consists of 279 species (Dahlgren, 1984). Leaves and twigs of the plant are used to produce a herbal beverage known as rooibos tea which is internationally renowned for its health-promoting properties being caffeine free and containing compounds which act as anti-oxidants.

The specie was first described circa 1768 but wild plants have been collected and utilized by local inhabitants of the Cederberg mountains for centuries. The economic value of rooibos was however not recognized until the 1930s when Dr P. Le Fras Nortier and associates commenced with intensive research on the cultivation of the tea which led to the development of the well-known rooibos tea industry as it is known today. This cultivated "Nortier" type, after Dr. Nortier, was thus selected from the wild plants based on qualities such as growth rate, seed production and especially taste (Hawkins et al., 2011). Both commercially grown rooibos and endemic wild types are harvested for local and international markets.

Several wild types, also known as ecotypes exist and have been distinguished in previous studies (Hawkins et al., 2011; Malgas et al., 2010). More specifically, (Heerden et al., 2006) differentiate seven rooibos tea ‘types’ based on distinct morphological and chemical differences. These ecotypes differ in especially growth form but also fire survival strategy, vegetative and reproductive morphology, isozyme patterns and flavonoid composition. Wild populations are differentiated by the local population mainly on its morphology leading to it being given vernacular names such as Bossie tea, Long-legged tea, Creeper tea, Tree tea, etc. Amongst the wild *A. Linearis* types found across the geographic range wild shrub type (Bossie tea) is the dominant ecotype in the Suid-Bokkeveld, whereas creeper and long-legged tea can be found in the Wuppertal region.

In light of climate change, an important difference between cultivated plants and certain wild types is also the mode in which it regenerates. *A. Linearis* regenerates either through re-growth from seed or re-sprouting from its roots after fire. Cultivated plants are re-seeders whereas certain ecotypes of wild *A. Linearis* are slower growing re-sprouters. Re-sprouting wild plants store carbohydrate reserves in its underground lignotuber which enhances its ability to survive droughts and re-grow after fire. It has been observed that the cultivated Nortier type tea does not have the same resistance to droughts and pests compared to wild types (Archer et al., 2009). In addition, harvesting techniques employed by small-scale farmers to ensure sustainable growth of wild *A. Linearis* are also dictated by this distinction between re-seeders and re-sprouters. Wild populations of *A. linearis* have a narrow geographic range within the Fynbos Biome and are largely confined to mountain ranges of the far south western part of the Northern Cape Province and Cederberg mountains of the Western Cape.

Rooibos has successfully made the transition from wild resource to an agriculturally important plant. Rooibos production has traditionally encompassed the mountainous part of the Fynbos biome but has progressively expanded into lowland areas in the south and the west of the CFR where wild rooibos does not occur. The Cederberg region, being one of the traditional mountainous growing regions, is a semi-arid environment where conventional agricultural production is limited by low and erratic rainfall, high evapotranspiration rates and nutrient poor soils (Rebelo et al., 2006). The area is bounded by the Atlantic Ocean on its west side and the Cederberg mountain range in the east while Nieuwoudtville in the Northern Cape Province and the Berg River form its northern and southern boundaries (Fig. 2).

Its Mediterranean climate is characterized by a strong seasonal pattern of rainfall, with marked aridity during summer months (December-February) and most of the annual rainfall falling during the winter period (June-August). However, the topographically diverse nature of the region ensures that the climate is by no means uniform. Rainfall varies from as little as 150 mm per annum on the coast and lowlands to over 1000 mm on the interior plateaus of the Cederberg mountain range (over 2000 m.a.s.l.). Winter rainfall is mainly associated with rain bearing mid-latitude frontal systems, while summer convective precipitation events contribute to annual rainfall in the far north east. It is a drought prone environment with regular and recurrent dry spells (Rouault and Richard, 2003). According to the (IPCC, 2014) Mediterranean ecosystems such as the CFR are particularly exposed and vulnerable to the impacts of climate change.

2.4. Environmental requirements

The rooibos production area is mainly located in the north-western CFR (Fig. 2), which is characterized by marked summer drought, with lower annual rainfall and winter temperatures compared to the rest of the CFR. Although an annual rainfall of at least 300-350 mm is considered necessary (Dahlgren, 1984), rainfall distribution throughout the growing season is particularly important for rooibos growth. The seeds of commercially propagated rooibos are sown during February/March in well prepared, irrigated seed-beds. Seedlings are usually transplanted during July when enough soil moisture is available. Good follow-up rain is then crucial to sustain active growth throughout the early spring season. Some summer rainfall is again critical during the hot summer months to ensure the survival of the plant into the next cycle. Rooibos is adapted to endure large fluctuations in temperature; from occasional snow and frost during winter to exceeding 40 °C in summer. Rooibos with its characteristic deep tap root is thus well adapted to the hot and very dry summers of the region. During the winter months of June to August, seedlings are transplanted into cultivated fields and do not receive any additional water. Hence, sufficient late winter and spring rainfall is critical to ensure initial establishment of seedlings during winter and will enhance the ability of plants to survive the first summer drought (Richards and Lamont, 1996). The onset of the rainy season and distribution of winter and late winter rainfall is therefore critical in the recruitment of non-sprouting wild and cultivated plants.

Apart from rainfall, strong wind is an important stress factor during the regeneration phase, since young plants and germinating seeds are very sensitive to wind damage. The reproductive cycle of flowering and fruiting activity occurs from October to January, while the active growth phenophase for rooibos including leaf elongation and shoot growth commences in spring. Shoots continue to grow towards midsummer after which growth gradually declines, being followed by a period of dormancy during the winter months (Louw, 2006)

Aspalathus linearis is a nodulating legume which is able to form symbiotic relationships with both rhizobial bacteria, (specifically *Bradyrhizobium* species (Dakora and Phillips, 2002) and arbuscular mycorrhizal fungi. The species grows mainly in nutrient poor, highly acidic and well-drained, sandstone-derived soils (pH 3-5.3) typical of the mountainous areas in the area (Muofhe and Dakora, 2000). Yet, *A. linearis* and its associated microsymbionts have managed to establish a functional N_2-fixing symbiosis which can tolerate the extremities of soil acidity and low nutrient stress by fixing high levels of N. Due to its unique soil and climatic requirements rooibos has not been successfully cultivated in other parts of the world. All demand is supplied from a single production area that is approximately 200 x 100 kilometres in extent.

2.5. Quantifying water use, yield and water-use efficiency/ productivity of crops

Before exploring existing research regarding water use of rooibos tea, it is necessary to review the concept of evapotranspiration and methodological approaches towards quantifying water-use efficiency. Several definitions for water-use efficiency can be found in the literature, depending on the application and crop assessed. Singh et al. (2011) review water-use efficiency as follow:

- WUET is the amount of dry matter or marketable yield produced per unit of water taken up (transpiration) by plants. This is also known as transpiration efficiency or transpiration ratio (yield/transpiration) or Water Productivity (WP).
- WUEET is the amount of dry matter or marketable yield produced per unit of evapotranspiration (ET) by the crop (yield/ET). ET is the sum of soil evaporation and transpiration by the crop during the season.
- WUEI is the amount of dry matter or marketable yield produced per unit of irrigation amount applied to the crop (yield/irrigation). Sometimes this is also referred to as water

application efficiency (WAE).

- WUER is the amount of dry matter or marketable yield produced per unit of rainfall received by the crop or cropping system (yield/rainfall). This is also known as rainfall use efficiency (RUE).
- WUE(ET/R) is the ratio of water used (ET) to the amount of rainfall received by the crop or cropping system during the growing period (ET/rainfall). It is also expressed as percent of rainfall.
- WUE(R+I) is the amount of dry matter or marketable yield produced per unit of rainfall plus irrigation [yield/(rainfall+irrigation)] received by the crop or cropping system during the cropping period.

In the biophysical sense, sustainable production refers to maximum crop yield per unit of water being applied or used by the crop, but in the economic sense, it is maximum net income per unit of water applied or used or monetary input to the crop.

In rain-fed crop systems the available energy which influences the evaporative demand of the atmosphere and the available soil moisture play a significant role in water productivity. The available energy and aerodynamic factors impose an evaporative demand on vegetation and soil surfaces and cause moisture loss from these surfaces. The extent to which this occurs is influenced by atmospheric temperature, humidity, and wind speed, which together determine the atmospheric evaporative demand, the maximal rate at which the atmosphere can vaporize water from a free-water surface.

These conditions are external to the evaporating body and only influenced by meteorological factors. This is equivalent to the reference crop evapotranspiration which is defined by the FAO as evapotranspiration (ETo) from a short (0.12 m) grass surface that is healthy, actively growing, uniformly covering the ground and not short of water (Allen et al., 1998).

2.6. Review of water use and water productivity of crops in the Western Cape

In irrigated crops such as deciduous crops (e.g. apples, pears, wine grapes, peaches) and citrus, water productivity is a critical success factor. The accurate quantification of water use is important for irrigation scheduling in order to optimize yield, growth and quality. Over the years, the Water Research Commission (WRC) has supported many projects on the water use of crops and some of the studies were done in the Western Cape Province. This was in an effort to avail information to develop tools that can assist water managers and growers to improve water management, particularly irrigation scheduling (Singels et al., 2010). Crops studied in the Western Cape include mainly irrigated tree crops, e.g. citrus (Taylor et al., 2014), deciduous fruit trees, e.g. apples (Dzikiti et al., 2017; Gush et al., 2019), peaches and plums and grapevines (Lategan and Howell, 2016), among others. There have also been national scale studies that have estimated the extent of the irrigated land area in the country and the associated water use by the crops using remote sensing methods (e.g. Van Niekerk et al., 2018).

In 2015 a study was undertaken by Dzikiti et al. (2018) to determine the water use, yield and quality of selected high performing apple cultivars from planting to full-bearing in selected climatic zones and specific soils. The specific aim was to model the water balance of apple orchards and then determine the water productivity in terms of crop yield and quality. The study was conducted in the main apple growing areas of the Koue Bokkeveld (KBV) and the Elgin/ Grabouw/ Vyeboom/ Villiersdorp (EGVV) regions. These regions fall within the winter rainfall region of the Western Cape and have a Mediterranean type climate where cold wet winters and warm dry summers dominate. Orchard evapotranspiration (ET) was measured/quantified using the open path eddy covariance method, the soil water balance approach and lastly by deriving ET data from satellite images through the remote sensing "FruitLook" product. Additional data collected include the orchard leaf area index (LAI – m^2 of leaf area per m^2 of ground area), volumetric soil water content at various depths and wet/dry spots in some orchards, soil properties, orchard floor evaporation, tree water status, leaf stomatal conductance and gas exchange rates, yield and fruit quality. Using this data and based on both measured tree transpiration and modelled orchard evapotranspiration the water productivity, defined as kg fruit per m^3 of water used was calculated. The maximum unstressed seasonal transpiration of mature high yielding 'Cripps' Pink' and 'Golden Delicious' orchards was in the range 6 000 to 8 000 m^3 ha^{-1} depending on canopy cover. The maximum orchard ET varied from 9 000 to just over 10 000 m^3 ha^{-1} $season^{-1}$. In young orchards seasonal total transpiration ranged from 1 330 m^3 ha^{-1} in the low density plantings in EGVV to 2 710 m^3 ha^{-1} in the high density orchards in KBV. Seasonal ET was very high (> 5 000 m^3 ha^{-1}) in all the young orchards.

In a study by Myburgh (2016)), the focus was on estimating water use of whole grapevines under field conditions. The specific objectives of this study were (i) to determine the effects of viticultural and atmospheric conditions on diurnal sap flow in field-grown grapevines and (ii) to develop a model for estimating daily transpiration at the whole-plant level. The study used sap flow measurements in vineyards with a soil evaporation model to estimate vineyard evapotranspiration. In the case of this study the objective was not to correlate water use with yield but rather assess water use in terms of leaf area per grapevine and reference evapotranspiration.

Vahrmeijer et al. (2015) looked at water use of citrus [*Citrus sinensis* (L.) Osbeck] in South Africa and included the area of Citrusdal in the Western Cape as a study site. In this study, sap flow measurements of the trees were done using the heat pulse velocity method while reference evapotranspiration (ETo) was determined from weather parameters recorded at the nearest weather station. A clear seasonal pattern for reference evapotranspiration (ETo) was obtained with a sharp increase in ETo during the hot dry summer months. The highest monthly ETo was recorded for January (215 mm). ETo decreases during the winter months when temperatures drop and the rainfall season starts with the lowest monthly ETo recorded for June (35 mm). Transpiration data also followed a seasonal pattern with the highest monthly transpiration measured for December (72 mm). During the winter months transpiration decreases with the lowest value recorded for June (29 mm). During conditions of low atmospheric demand (winter months) a good correlation existed between transpiration and ETo. However, the increase in transpiration during the summer months (high atmospheric demand) did not have the same strong seasonal effect as ETo. The total amount of water transpired for the season was around 660 mm and ETo was almost twice as much at about 1 367 mm.

Both of these studies used *in situ* methods to establish actual evapotranspiration, whereas Dzikiti et al. (2018) also used the ETLook remote sensing model to calculate the actual (ET) and potential evapotranspiration rates (ETpot) from satellite imagery. This is the most widely applied model in South Africa to assess water productivity in irrigated crops. Several studies have used this method to assess irrigated sugarcane, vineyards, apple orchards.

.

2.7. Review of water relations in rooibos

Both honey bush and rooibos are rain-fed crops and therefore not irrigated except during seedling stage. However, in recent years an increasing number of rooibos producers in the West Coast Sandveld area have started to convert center pivot fields (where they normally plant potatoes) into rooibos fields. This is however not standard practice at present, as there are many questions and issues related to soil fertility, soil health and pest and diseases that influence the successful cultivation of rooibos on old potato fields.

Until recently, very little information in the published literature existed on water-use relations in either rooibos or honey bush tea. The majority of herbal tea research in South Africa has been focused on the health benefits of the plant and optimizing the tea quality. Recent studies have been conducted under field conditions to investigate the effect of fertilization, soil depth and residue management on the soil water balance (SWB), biomass water-use efficiency (WUEB) and plant nutrient cycle and growth of rooibos ((Nieuwoudt, 2017; Van Heerden, 2019; Van Schalkwyk, 2018). Van Schalkwyk (2018) conducted an experimental trial in the area of Clanwilliam to assess the effect of fertilized vs unfertilized treatments (on deep and shallow soils) on soil water use and plant root physiology in cultivated rooibos plants. On the one site she used fertilizer (20 mg.kg^{-1} N, 30 mg.kg^{-1} P and 20 mg.kg^{-1} K) and this was compared to an unfertilised treatment with rooibos plants, as well as a bare unplanted site. For all three treatments she monitored soil chemical status, soil water content, biomass production, root system characteristics and biomass water-use efficiency of the plants over the growing season from July 2016 to April 2017. Soil water content was determined using a capacitance probe (Diviner 2000, Sentek Sensor Technologies Inc, Stepney, Australia) as well as the ECH2O soil moisture sensors installed at different soil depths. The evapotranspiration or evaporation was calculated for each treatment using the equation: $ET = \Delta S + P$ where: ET = evapotranspiration (mm), ΔS = change in soil water content (mm) and P = precipitation or rainfall (mm). The results of her study indicated that fertilisation and soil depth played an important role in root growth. Root biomass was negatively impacted by the fertilizer due to high P concentrations which reduced the root growth. Biomass water-use efficiency was also higher on the unfertilized site. In terms of soil depth, the root growth in the deep soils was better compared to the shallow soils. This was expected because shallow soils restricted the root growth and caused distortion. This study indicated that the specific combination of fertilizer application used in the research may actually restrict plant growth and performance.

According to Van Schalkwyk (2018) the soil water balance derived ET for rooibos for the period July 2016 to April 2017 was in the range 108 to 121 mm. These somewhat low water-use rates probably reflect the sharp rainfall gradients that occur across the Western Cape Province. For example, other researchers measured much higher ET rates on fynbos but at sites where water is readily available. (Dzikiti et al., 2014) used the surface energy approach incorporating a large aperture boundary layer scintillometer at three sites across the province. The first site was on Atlantis Sand Plain fynbos at Riverlands Nature Reserve near the town of Malmesbury where they recorded annual ET of close to 1 000 mm. However, these plants were in an area with relatively high rainfall (~ 450 mm/yr) and a shallow groundwater level. Similarly high ET rates were observed on Sandstone fynbos growing along the a tributary of the Palmiet river at Kogelberg Nature Reserve which is a high rainfall area exceeding 800 mm/yr. Evapotranspiration data collected on Swartland alluvial fynbos at the Elandsberg Nature Reserve was lower and close to 500 mm/yr (Dzikiti et al., 2019, 2014; Majozi et al., 2017). Overall, the ET rates of fynbos appeared to be highly dependent on the availability of water and similar trends are likely with rooibos, but this still needs to be confirmed.

Another study by Van Heerden (2019) focused on understanding the type and rate of fertilizer (commercial brands of compound NPK organic and mineral fertilizers) that would improve the production and performance of rooibos plants. Another study therefore focused on understanding what type and rate of fertilizer (commercial brands of compound NPK organic and mineral fertilizers) would improve the production and performance of rooibos plants (Van Heerden, 2019). The study was conducted on one-year old rooibos plants under Nieuwoudtville field conditions in the Northern Cape. Most importantly it also focused on understanding the availability of NPK in the soil during the winter months, when rooibos plants usually accumulate nutrients for the dry summer growth period. In this study the field trials were established during a prolonged drought in June 2017. The rooibos plants were fertilised with three different NPK ratios and application rates. Parameters measured include climate, soil water content and temperature, soil pH, electrical conductivity (EC), exchangeable cations, Bray II P, micronutrients, total carbon and nitrogen, foliar macro and micronutrient concentrations, plant survival and tea yields. The results of the study indicated that during winter months the organic fertilizers failed to mineralise due to cold soil temperature limiting microbial activity. However, mineral fertilizers were more effective in cold conditions in the short-term as it provided plant-available nutrients during the nutrient uptake season of rooibos plants.

As the study was conducted during a drought event where only 19.3% of the annual winter rainfall fell, it had a significant impact on the soil water content. The research therefore also gave interesting results in terms of the effect of drought conditions on the plant accumulation of nutrients. With low soil water content, foliar nutrient concentrations decreased showing the negative effect of drought on plant accumulation of nutrients. The addition of mineral fertilizers under drought conditions however, ensured that nutrients were more readily available for plant uptake as soon as the soil water content increased. Foliar NPK concentrations peaked in July due to increased soil water content. The prevailing drought conditions reduced the time for nutrient uptake with a decline in foliar nutrient concentration in August due to warmer and drier conditions stimulating plant growth. Foliar NPK concentration was highest in the mineral 3:1:5 fertilizer, indicating that the higher nutrient application increased plant uptake. Nutrient recovery was highest in the mineral 2:3:2 fertilizer with higher application of N and K lost through leaching.

In a study by (Nieuwoudt, 2017), the emphasis was on understanding the impact that different mulching treatments have on the rooibos plant nutrient cycle (uptake and nutrient pools). The study monitored soil chemical properties, plant nutrient uptake and soil water content under four different mulch treatments; a bare soil (leaf residue removed) treatment, an added rooibos mulch, a natural leaf mulch and an enriched rooibos mulch. The results indicated that all the mulch treatments showed a higher uptake of P, K and Mg by the plants. It also showed that during dry periods, mulch treatment conserved more water for longer. The mulched treatments also moderated the soil temperature by increasing the daily minimum temperature and decreasing the daily maximum temperature at a soil depth of 20 cm.

A few other studies offer some insight into water use of rooibos plants, albeit as part of studies on climate variability, sustainable harvesting and biodiversity guidelines. (Archer et al., 2009) indicated that climate change would place significant additional pressure on rooibos production in an area where rainfall is already low and variable. Projections for the main production area are that temperatures will increase alongside a decline in rainfall during critical months. This means that that critical threshold in terms of water and heat stress may occur more often under future climate scenarios. In follow up research regarding climate change and rooibos, (Lötter, 2015) assessed historical climate trends over the rooibos distribution area and performed several experimental studies to improve the knowledge of plant physiological functioning of *A. linearis* under changing climate conditions. The study used gas exchange measurements and leaf carbon isotope ratios to monitor water-use efficiency in wild and cultivated plants. Both methods revealed better water-use efficiency as adaptive strategy in wild plants under dry conditions.

In a study directed at investigating the possible co-occurrence of wild rooibos with threatened vegetation types, (Hawkins et al., 2011) also addressed water-use efficiency in wild rooibos and cultivated type rooibos. The study indicated that rooibos ecotypes growing in relatively drier areas had a greater water-use efficiency compared to those growing in wetter areas, while they found no difference in water-use efficiency between cultivated and wild rooibos from the same rainfall area. They used the carbon isotope discrimination method (discrimination (Δ) of the stable isotope of carbon, 13C, relative to the more abundant 12C) to determine integrated water-use efficiency.

2.8. Climate change over the study area

In a study on historical climate trends in the Greater Cederberg region (Lötter, 2015), it was found that there is strong evidence of accelerated temperature increase and spatially localized changes in rainfall characteristics during the recent past over the greater Cederberg region. Maximum temperatures have significantly increased by more than 2° C over 50 years with the most significant increases being observed during March, April and May (MAM). Several other studies have indicated significant increases in maximum and minimum temperatures, as well as temperature extremes over the Western Cape in the last 50 years (Kruger and Nxumalo, 2017; Kruger and Sekele, 2013). The largest change in maximum temperatures coincides with the warmest and driest time of the year which is Dec-Mar. These changes in temperature are further associated with an increase in frequency of hot extremes which may contribute to the intensification of heat stress and low water availability during summer months when rainfall is limited.

Regional climate projections, although subject to the specific emissions scenario, project a further increase in annual temperatures for the Western Cape of between 2 and 3°C by 2040-2060 (Engelbrecht et al., 2015). These annual average temperatures may increase up to 5°C for the period 2080-2100. This would lead to a net drop in water availability leading to prolonged periods of drought in summer and reducing the amount of peak water available in autumn and winter.

Future rainfall climate change scenarios project drying across all seasons over the Western Cape with biggest rainfall reductions occurring during June, July and August (JJA). These trends are consistent with the projected physical changes in the regional climate system over South Africa, which indicates a displacement of frontal rain bands towards the south, which are unfavourable for rainfall over the winter rainfall region of South Africa (Engelbrecht et al., 2009; Hewitson and Crane, 2006). (Hewitson and Crane, 2006) also linked drying during the winter period to atmospheric circulation changes, through a systematical southward displacement of frontal systems during JJA. Given that the area is already water-limited, an annual average temperature increase of 2 to 4°C, coupled with less rainfall, could significantly impact the hydrological and climate regime of the region.

CHAPTER 3

3. MATERIALS AND METHODS

3.1. Study sites

Several field trips in the Cederberg area and meetings with rooibos industry representatives were undertaken to identify suitable sites for the field work. Scoping of suitable sites were based on geographical and climatological differences within the rooibos production region. Within this production area there is significant variation in the soil, climate characteristics and height above sea level. Although the dominant geological characteristic of the area is that of Cape Sandstone (Table Mountain Sandstone), which are the main soils used for the cultivation of rooibos, there are location specific differences in the characteristics of the soils. The altitude at which plants are grown varies between 300-600 metres above sea level. Due to these altitude differences, winter rain varies between 180 to 500 mm per annum while air temperatures vary between 0 and 48°C. There is a significant rainfall gradient from the Cederberg to the west coast with a long-term average rainfall around 100 mm/yr. along the coast rising to 400 mm pa in the western mountains and rising to over 700 mm in the central Cederberg. The decision was therefore made to select a site along the southern boundary of the rooibos production region for the first year of field work followed by a site in the central to northern part of the rooibos production region in the second year of field work.

The main criteria for choosing the rooibos field sites were:

- the site must be well-managed and have a good yield history;
- the site should be large in spatial extent (to allow use of micrometeorological instrumentation);
- the site should be secure (for equipment safety);
- have good cooperation from the farmer;
- and the site should be relatively easily accessible for vehicles to facilitate equipment installation and site visits.

3.1.1. Porterville

The first field work site was located just outside the town of Porterville as it ascribed to all the mentioned requirements. This site is less than 5 km outside Porterville (coordinates 33° 2'17.20"S, 18°58'13.18"E) on the Jakkalskloof road to Piketberg which is situated about 150 km to the north of Cape Town Metropolitan (see Fig. 1). This site is situated towards the southern margin of the rooibos production area and it is considered to be a higher rainfall area with a long term annual average around 483 mm. However, it seems as if production areas are expanding even further southwards as the northern production areas are getting drier and the demand for the crop is increasing.

Data were collected in a 25 ha rooibos field which was planted in 2015 and the first harvest was in 2016. The crop was planted in north-south oriented rows with a spacing of 1.5 m x 0.60 m giving a plant density of about 11 111 plants per hectare. Soils at the study site were nutrient poor sandy acidic soils of the fernwood form (Soil Classification Working Group, 1991) derived from the Cape Sandstone geological formation. Detailed physical properties of the soils are summarized in Table 2. The terrain was relatively flat with a slope less than 3 degrees.

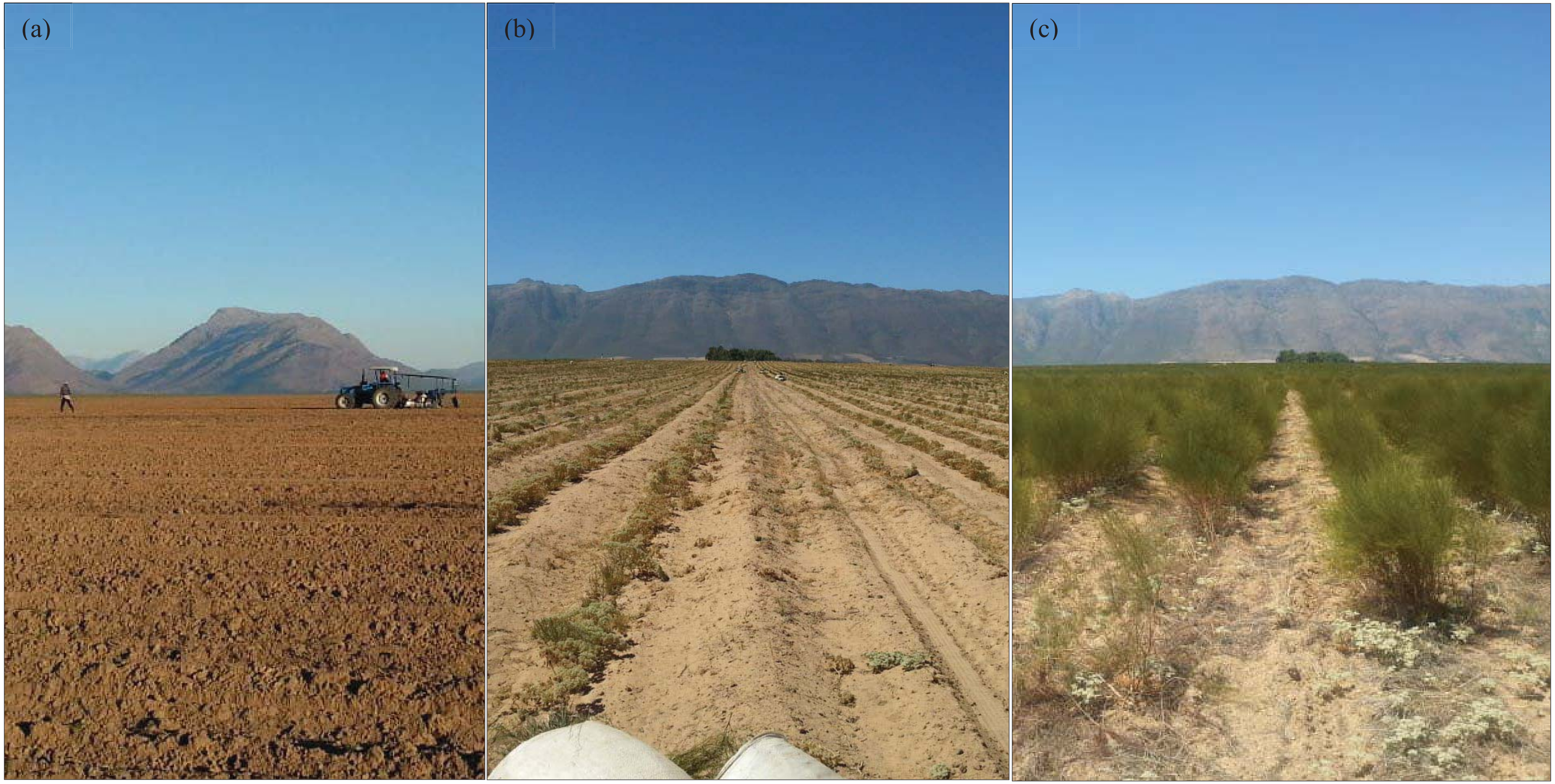

Figure 16. Land preparation at the rooibos growing sites namely; a) ploughing, b) ridging and c) an established rooibos crop.

3.1.2. Clanwilliam

The second site that was identified and selected for field data collection is located approximately 8 km outside Clanwilliam north of the R364 road towards Graafwater and Lambert’s Bay (Fig. 1). The site is located on the farm Ysterfontein (coordinates 32° 9'52.86"S, 18°48'39.03"E) which belongs to Mr Willie Nel. This area is considered to be in the heart of the traditional rooibos production area as Clanwilliam is referred to as the rooibos capital. The average annual rainfall is around 230 mm while maximum temperatures often exceed 40 degrees Celsius in summer. This site is therefore somewhat drier than the site that was used during the first year of data collection near Porterville. The rooibos crop at the Clanwilliam study site was established in the winter of 2018 when seedlings were transplanted into cultivated fields. About 10 months after planting the rooibos was harvested for the first time. This first harvest delivered a very small yield but it stimulated the main stem to subdivide to form a number of strong side-shoots. The first proper harvest took place 18 months after planting. Thereafter the plants were harvested annually. The field is approximately 225 ha in size and is relatively flat and homogenous across its extent. The soils were deep (>1000 cm), predominantly sandy and well drained.

Figure 17. View of the study site with the Cederberg mountains showing in the distance.

3.2. Weather and soil measurements

Weather data for this study was collected from automatic weather stations operated by the Agricultural Research Council. The weather stations were located within 5 km of both the Clanwilliam and Porterville study sites, respectively. Data collected by the stations included the maximum and minimum air temperature, maximum and minimum relative humidity, wind speed and direction, rainfall, and solar irradiance. The data were collected hourly throughout the study period. The weather stations were located on short grass surfaces and the sensors were mounted at 2.0 m height above the ground. The climatic variables were used to calculate the daily reference evapotranspiration (ETo). In this study we defined the reference evapotranspiration as evapotranspiration from a short grass surface that is healthy, actively growing, not short of water and uniformly covering the surface according to the FAO 56 (Allen et al., 1998).

Soil samples were collected from the fields and analyzed for the physical and chemical characteristics at Bemlab in Somerset West, Western Cape. The samples were taken at depths of 20 cm, 40 cm, 60 cm and 100 cm down soil profiles. Detailed physical properties of the soils at the two study sites are summarized in Tables 2 and 5.

3.3. Transpiration measurements

The dynamic flow of water through the tea crop stems were monitored using the heat balance sap flow gauges (Dynamax, Houston. TX, USA). Figure 18 shows a typical representation of the heat balance sap flow sensor. In this technique, a known constant power, P_{in}, is applied to the plant segment encircled by a small flexible heater, typically a few centimetres in width, wrapped around the organ where sap flow is to be measured (Smith and Allen, 1996). The energy balance equation for that segment is then solved for the amount of heat taken up by the moving sap stream under steady state conditions. This energy is then used to calculate the mass flow of sap. Given the need for steady state conditions, it is essential that the heater is the sole source of energy and thus insulation of the gauge to cut out energy inputs from the environment is crucial.

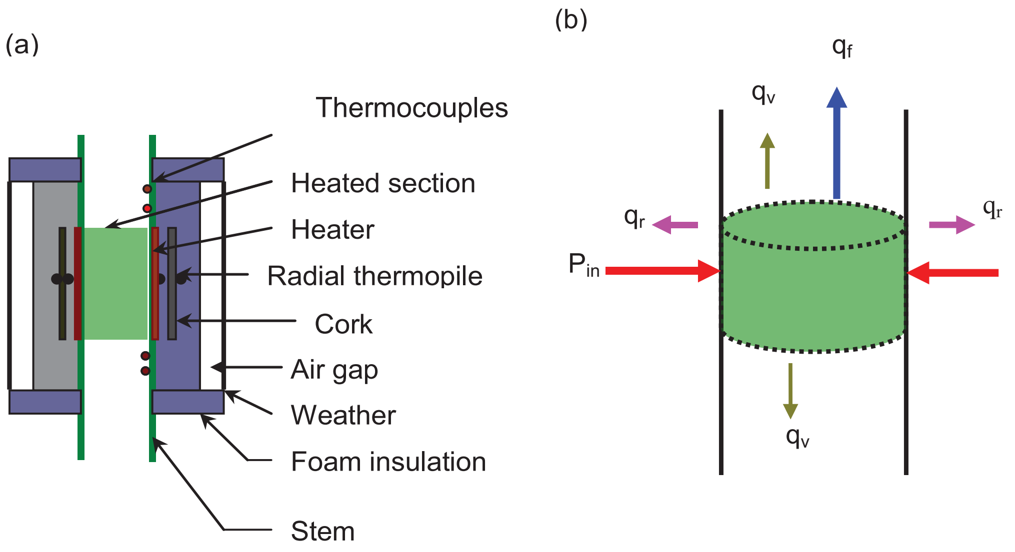

Figure 18. Schematic representation of the heat balance sap flow gauge (Dynamax, Houston, TX, USA). (a) Vertical section through the stem heat balance sap flow gauge. (b) Energy balance components of the heat balance sap flow sensor.

Suppose the power input to the plant organ (e.g. the stem in Fig 18) is P_{in}, then the heat balance of the stem according to (Sakuratani, 1981) and (Baker and Van Bavel, 1987) can be written as

$$P_{in} = q_v + q_r + q_f \qquad \text{(W)} \qquad (1)$$

where q_v is the rate of vertical heat loss by conduction, q_r is radial heat loss by conduction through the sensor, and q_f is heat uptake by the moving sap stream. The value of q_f is obtained by subtracting q_v and q_r from P_{in} which all can be measured. If ΔT_a and ΔT_b are the temperature gradients measured by the axial thermocouples above and below the heater and ΔT_r is the radial temperature gradient, then applying Fourier's law for one dimensional heat flow, q_v is calculated using

$$q_v = A_{st} k_{st} \left(\frac{\Delta T_b - \Delta T_a}{x} \right) \qquad \text{(W)} \qquad (2)$$

where A_{st} is the cross sectional area of the heated section, k_{st} is the thermal conductivity and x is the distance between the two thermocouple junctions on each side of the heater. The radial component of the stem heat balance, q_r, is determined from ΔT_r using

$$q_r = K_{sh} \Delta T_r \qquad \text{(W)} \qquad (3)$$

where K_{sh} is the effective thermal conductance of the sheath of materials surrounding the heater. The value of K_{sh} is unknown and depends on the thermal conductivity of the insulating sheath and stem diameter. This is determined from the energy balance equation during periods when q_f is zero. This condition is approached at predawn.

Sources of error in sap flow measurements using the heat balance technique include the influence of the changes in the heat storage of the gauged section of the plant which is often neglected and errors in the determination of K_{sh}, among others. Most reliable methods for checking the accuracy of sap flow measurements are expensive and time consuming, e.g. use of lysimeters.

At each field site, three rooibos plants were chosen randomly, where after stems were measured with a caliper to ensure that the diameters were within the range of the specific gage. Three miniature stem heat balance sap flow gauges, model SGB13 and SGB16 (Dynamax, Houston, USA) (Baker and Van Bavel, 1987) were installed on the plants. Given that each rooibos bush had multiple stems, one sap flow gauge was installed per branch on a selected shrub. A total of four sap flow sensors were installed in the field. More plants could not be instrumented due to equipment limitations. To avoid further stressing the plants which already grew under very hot conditions, the sap flow sensors were moved from one plant to another once a month. The stem diameter of the first plant was measured at the midpoint of the gage installation and recorded for loading as a stem parameter into the software later. The heater impedance found on the sensor serial number label as well as the cable number corresponding to the sensor/plant were also recorded for use in the software. Before installing the sensors the branches had to be prepared for installation by very gently sanding the branch to ensure it is was smooth and flat for optimal contact with the sensors thermocouples. However, this proved not necessary as the bark on the rooibos plant was very thin, so sanding of the branches were not necessary. The branches were cleaned and sprayed with canola release spray which prevents the sensors from sticking to the stems. Subsequently, the gauges were installed and tightened so that they sat firmly on the branches. The O-rings were fitted and the whole system was covered with a plastic sheet to keep out the rain. A second weather shield (aluminum bubble foil) was also placed over the entire Dynagage sensor to keep out the sun and to maintain steady state conditions around the sensor. The Dynagage sensors remained on the three plants for one month after which they were removed and reinstalled on three other branches. After relocation of the sap flow sensors, the branch leaf area (Ai) was measured destructively using the Li-3000 leaf area meter (LICOR Inc., NEBRASKA, USA) in the laboratory.

Figure 19. Installation procedures for the stem heat balance sap flow gauge monitoring transpiration rates in rooibos crop.

Given that tea crops such as rooibos have multiple stems, the sap flow was measured on a few selected stems then scaled up to the whole field level. For example, if SF_i was the sap flow (in cm^3/h) of a single plant stem whose leaf area was A_i, then the total transpiration (T_c, in mm) by the field could be calculated as:

$$T_c = \sum_i \frac{SF_i}{A_i} \times LAI_c \qquad (\text{mm d}^{-1}) \qquad (4)$$

where LAI_c is the leaf area index (m^2 of leaf area per m^2 of ground area) of the crop.
Soil evaporation (E) could be determined as

$$E = ET - Tc \qquad (\text{mm d}^{-1}) \qquad (5)$$

This relationship allowed the distinction between the beneficial (e.g. transpiration used to grow the tea) and non-beneficial water uses. The leaf area index (LAIc) was measured using a leaf area meter (Model LAI – 2000; LiCor Inc., USA) at sunset when the rooibos leaves behaved like black bodies. Data were collected on 10 plants per field once every month. Canopy dimensions and plant height were also measured monthly.

3.4. Evapotranspiration measurements

3.4.1. Eddy Covariance Method

The eddy covariance method is the most widely used micrometeorological technique for quantifying evapotranspiration over large fields. It is based on the principle that fluxes of momentum, heat and mass over crop canopies are due to the swirling movement of small pockets of air called eddies that cause air turbulence (Campbell and Norman, 1998). These fluxes can be determined by taking measurements of air temperature (T_a) and vertical wind speed (ω) at high frequencies, typically 10-20 Hz, and by calculating the covariance between them:

$$\boldsymbol{H = \rho C_p \Sigma (\omega - \bar{\omega})(T_a - \overline{T_a})} \qquad (6)$$

where H is the sensible heat flux (i.e. energy used to warm up the air), ρ is the density of air, C_p is the specific heat capacity of air at constant pressure and T_a is the air temperature. The wind speed ω and T_a are measured using sonic anemometers and there are various types that are available commercially. The latent heat flux (λE) which is the energy equivalent of evapotranspiration (ET) can be calculated in two ways. First as a residual of the surface energy balance equation if all other terms are measured

$$R_n - G = H + \lambda E \tag{7}$$

where all terms are usually expressed in Wm^{-2}. The R_n term is the net radiation which is the algebraic sum of the net shortwave and net longwave radiation components at the Earth's surface. The G term represents the soil heat flux transferred into or out of the Earth's surface and it usually accounts for 5-32% of the energy balance (Monteith, 1973; Kustas and Daughtry, 1989) and R_n-G represents the available energy. Use of Eq. 2 assumes surface energy balance closure (Burba and Anderson, 2010) which is not always achieved in practice. So secondly, direct measurement of ET using the eddy covariance method can also be done through the covariance of the vertical wind speed and the atmospheric water vapor concentration (e) measured using an infrared gas analyser (IRGA) as:

$$\lambda E = \lambda \frac{M_w / M_a}{P_a} \rho_a \overline{\omega' e'} \tag{8}$$

where M_w and M_a are the molar masses of water vapor and air (g mol^{-1}), P_a is the atmospheric pressure (kPa), ω' is the instantaneous deviation of the vertical wind speed, and e' is the air's vapor pressure. Main sources of error with the eddy covariance method include sensors' time delays, spikes and noise, un-levelled instrumentation, and air density fluctuations, among others. Post-processing of the data is therefore critical to correct for these errors.

The schematic of an eddy covariance station is depicted in Fig. 20. Eddy covariance systems often include measurements of CO_2 fluxes such as those in the FluxNet network (Baldocchi, 2008)

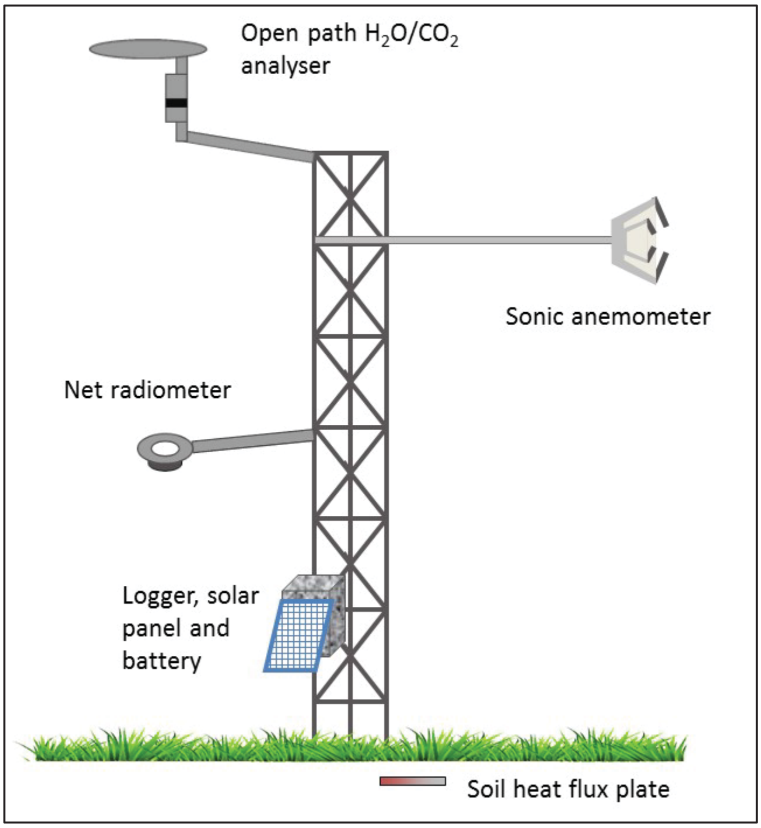

Figure 20. Schematic representation of an eddy covariance micrometeorological station (after Jovanovic et al., 2013)

In this study, evapotranspiration (ET) from the rooibos fields was quantified using an open path eddy covariance system. The system comprised of a sonic anemometer (Model: CSAT3, Campbell Sci. Inc., Utah, USA) which measured the wind speed in 3D. The concentration of atmospheric water vapor and carbon dioxide were measured using an infrared gas analyzer (IRGA) (Model: LI-7500A, LI-COR Inc., Nebraska, USA). All the sensors were connected to a CR5000 data logger, manufactured by Campbell Scientific. The high frequency data, collected at 10 Hz, were stored on 2 GB memory cards. Additional sensors included a CNR1 net radiometer (Kipp & Zonen, The Netherlands), two clusters of soil heat flux plates (Hukseflux, The Netherlands) installed at 8 cm depth below the surface. Soil averaging thermocouples (Model: TCAV, Campbell Sci. Inc., Utah, USA) were installed above the soil heat flux plates at 2 and 6 cm depths from the surface to correct the measured fluxes for the energy stored by the soil above the plates. The IRGA and sonic anemometers were installed at about 3.0 m above the ground. Vegetation height was measured at monthly intervals to ensure that the sensors were above the surface roughness sublayer and that there was adequate fetch around the sensors. Advanced processing of the high frequency eddy covariance data were done using the EddyPro v 6.2.0 software (LI-COR Inc., Nebraska, USA) to correct for fluctuations in air density, lack of sensor levelness (coordinate rotation), etc. Lastly, the eddy covariance data were corrected for lack of energy balance closure using the Bowen ratio method as described by (Cammalleri et al., 2014).

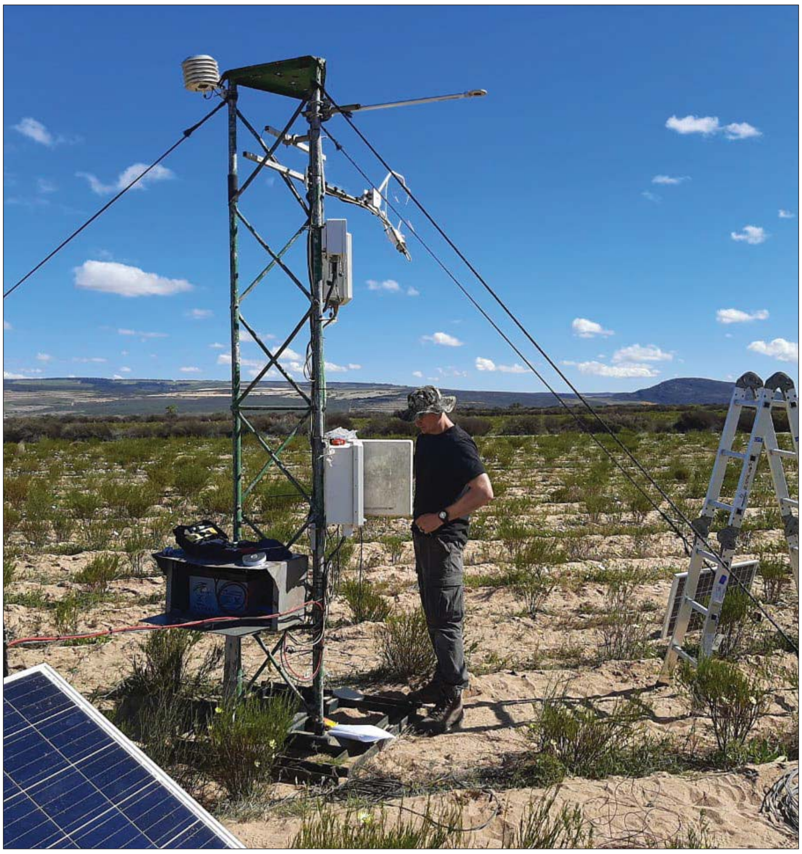

Figure 21. Installation of open path eddy covariance and surface renewal systems in rooibos.

3.4.2. Surface renewal

Another micrometeorological technique used in this study was the surface renewal method. This method was used as a back-up to the eddy covariance technique in case of data losses. The surface renewal method is a relatively new method which is a lot simpler than the eddy covariance method. The surface renewal method allows the sensible heat flux component (H) in equation 6 to be estimated from measurements of air temperature at a single level using fine wire thermocouples. In this study we used a single Type E thermocouple mounted at the same height as the sonic anemometer. With this method, air temperature data were also collected at high frequency, typically 10 Hz and positive or negative temperature ramps were studied involving (i) quiescent periods for which there is no change in air temperature with time, and (ii) ramping periods for which the air temperature ramp with a given amplitude. Because this method only measures H, it is important that the net radiation and soil heat flux are also measured. In this study, these sensors were mounted on a CR1000 data logger. The sensible heat flux, in practice is calculated with this technique as:

$$H = \frac{\alpha \rho z \delta Ta}{\delta t} Cp \quad (9)$$

where α is a calibration parameter that is determined by calibrating the surface renewal method against the eddy covariance method and z is the height of measurement of the air temperature. However, because the height of the rooibos was constantly changing, the crop height data were monitored monthly and it was used in the calculation of H.

3.5. Soil water balance

To estimate the actual evapotranspiration of the tea crops, we used the universal soil water balance approach as illustrated in Fig. 22 (Allen et al., 1998). The study fields gain water through rainfall since they are not irrigated. Capillary rise was not feasible in areas where the water table was deep, but this can cause a complication with these methods for fields that have high water tables.

Using the principle of conservation of mass, the rainwater is lost from the field through evapotranspiration (ET), deep percolation (DP), surface run off (RO), and changes in the water stored within the soil profile (±Δθ). For simplicity we often assume runoff to be zero especially for fields on flat terrain and also with predominantly sandy soils. Deep percolation is often negligible, but in situations where this is significant, models such as Hydrus 1/2D may be used for an accurate determination of the field water balance.

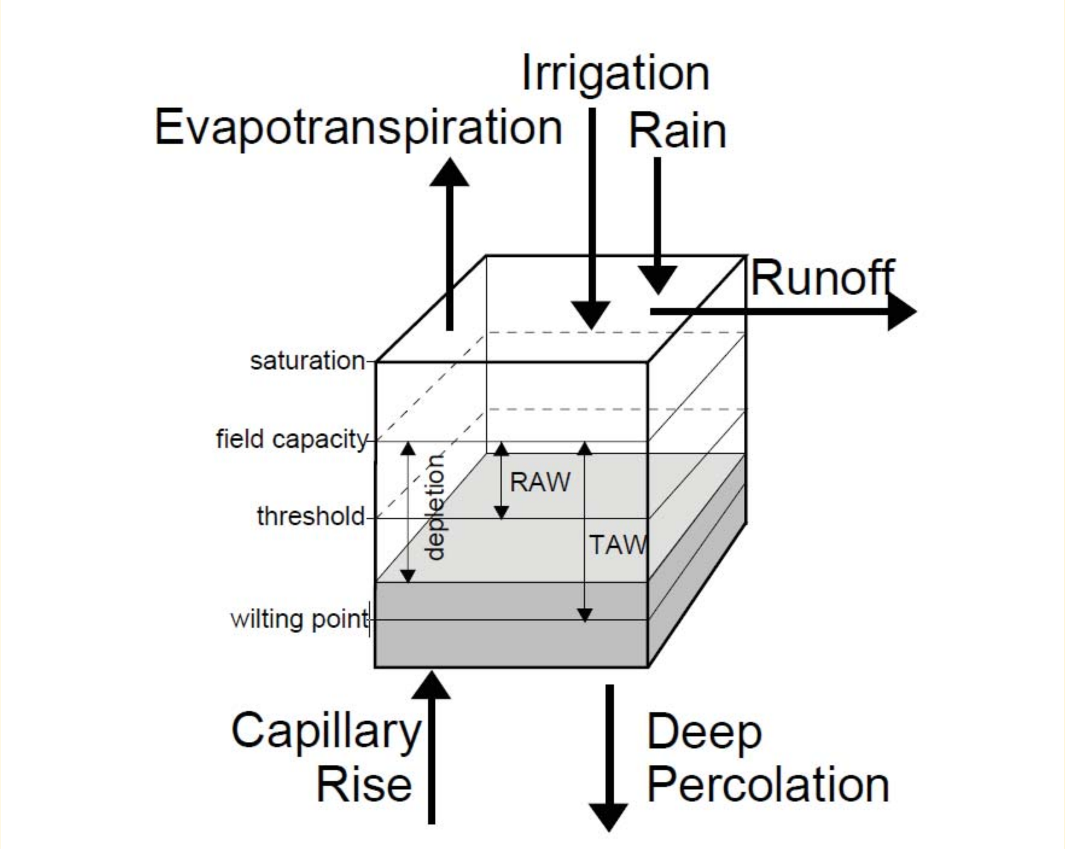

Figure 22. Components of the soil water balance in the root zone of plants (after Allen et al., 1998)

Soil water content was measured and monitored throughout the year using soil moisture sensors (Model CS616, Campbell Sci. Ltd, USA) that were installed at four depths (20 cm, 40 cm, 60 cm and 80 cm) down in the root zone of the plants (Fig. 23). Two profile pits were dug and the sensors were located in two positions namely within the plant rows and in the open spaces between the rows. These sensors monitored the volumetric soil water content at hourly intervals throughout the study period. A tipping bucket rain gauge was also installed nearby to quantify the rainfall received by the field. The universal soil water balance equation was used to provide estimates of daily ET from the soil water content measurements and the rainfall according Allen et al. (1998).

Figure 23. Installation of soil moisture sensors to monitor the volumetric soil water content in the root zone of the rooibos crop

3.6. Plant and soil sampling

Ten rooibos plants were randomly selected in the field to monitor their growth. The plants were numbered and the same plants were measured each month for height, canopy breadth and width.

The field LAI was measured using the LAI-2000 leaf area meter at monthly intervals throughout the growing season. The LAI data was collected either at sunset, early in the morning before sunrise or during overcast conditions when the plant leaves behaved like black bodies.

Figure 24. Measuring LAI in the rooibos field during overcast conditions

Crop management practices across the rooibos production region are not uniform. In some areas, especially towards the southern boundary of the region, farmers do not remove weeds between the crop rows as these weeds usually die-off towards the end of the rainy season. In an effort to quantify the contribution of the weeds to the evapotranspiration measurements it was necessary to collect data on the actual land area that weeds covered. The LAI of the weeds was therefore quantified by randomly cutting the weeds to ground level in four quadrants each measuring 50 cm x 50 cm on the field floor. The actual leaf area of the weeds in each quadrant was measured in the laboratory using a leaf area meter (Model: Li-3000, Li-COR Inc., Nebraska, USA). The leaf area index of the weeds was calculated as the ratio of the measured leaf area to the grid area.

Figure 25. Soil profile for characterizing the soils at the Porterville study site

As part of the soil water balance calculation, information on the field capacity of the soil is necessary. Hence, soil samples were taken at intervals of 30 cm depth along the soil profile. Four samples were taken and kept at 15°C until analyzed. These soil samples were sent for a full soil analysis and a texture – 5 fraction analysis to Bemlab.

3.7. Modeling water use by rooibos crops

3.7.1. Model description

The daily evapotranspiration (ET) by the rooibos crop was modelled using a simple combination Penman-Monteith equation in which

$$ET = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{Ta+273}u_2(e_s - e_a)}{\Delta + \gamma(1+\frac{r_s}{r_a})} \qquad \text{(mm/d)} \qquad (10)$$

where Δ (kPa/K) is the slope of the saturation vapor pressure vs air temperature curve, R_n is the net all wave radiation (MJ/m^2/d), G is the soil heat flux (MJ/m^2/d), γ is the pyschrometric constant (kPa/K), T_a is the average air temperature (°C), u_2 is the daily average wind speed measured at 2 m height (m/s), e_s and e_a are the daily average saturation and actual vapor pressure (kPa), r_s is the surface resistance of the field incorporating both the crop and soil and r_a is the aerodynamic resistance (s/m).

The slope of the saturation vapor pressure vs temperature curve was calculated as

$$\Delta = 4098\frac{[0.6108\times e^{\frac{17.27Ta}{237.3}}}{(Ta+237.3)^2} \qquad \text{(kPa/K)} \qquad (11)$$

The daily total net radiation on the rooibos field was calculated as

$$R_n = R_{ns} + R_{nl} \qquad \text{(MJ/m}^2\text{/d)} \qquad (12)$$

where

$$R_{ns} = (1-\alpha)R_s \qquad \text{(MJ/m}^2\text{/d)} \qquad (13)$$

where R_{ns} is the net daily shortwave radiation, R_s is the daily total shortwave radiation measured at the weather station, and α is the surface albedo which was considered to be a constant at 0.23. R_{nl} is the daily net long wave radiation which was calculated according to Allen et al. (1998) as

$$R_{nl} = \sigma\left[\frac{{T_{max,K}}^4 + {T_{min,K}}^4}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}} - 0.35\right) \qquad \text{(MJ/m}^2\text{/d)} \quad (14)$$

where σ is the Stefan-Boltzmann constant (4.903 x 10^{-9} MJ K^{-4} m^{-2} d^{-1})

T_{max}, K is the daily maximum air temperature in Kelvin

T_{min}, K is the daily minimum air temperature in Kelvin

e_a is the actual vapor pressure of the air (kPa)

R_{so} is the clear sky shortwave radiation calculated according to Allen et al. (1998).

The soil heat flux was assumed to be 0.1 x R_n. The aerodynamic resistance was calculated using the equation for a logarithmic wind profile as

$$r_a = \frac{ln\left(\frac{z_m - d}{z_{om}}\right) \times ln\left(\frac{z_h - d}{z_{oh}}\right)}{k^2 \times u_2} \qquad \text{(s/m)} \qquad (15)$$

where z_m is the height of measurement of wind speed (~ 2 m), z_h is the height of measurement of relative humidity which was also set at 2.0 m, d is the zero plane displacement height which was calculated as d = 0.67 x H; where H is the height of the rooibos crop, z_{om} is the roughness length governing momentum transfer, z_{oh} is the roughness length governing heat and humidity transfer which were calculated as z_{om} = 0.123 x H and z_{oh} = 0.1 x H, respectively.

The surface resistance was considered to be variable influenced by two stress factors namely the soil water deficit f(θ) and the vapor pressure deficit of the air f(VPD). Both stress factors have values between 0 and 1. The functional form of the surface resistance equation was expressed according to Jarvis et al. (1976) as

$$g_s = g_m \times f(\theta) \times f(VPD) \qquad \text{(mm/s)} \qquad (16)$$

where g_s is the surface conductance (g_s = 1/r_s), g_m is the maximum unstressed surface conductance which was obtained by model optimization. The stress factors were calculated as:

$$f(VPD) = e^{-K_{vpd} \times VPD} \qquad (17)$$

$$f(\theta) = \left[\frac{\theta - \theta_{WP}}{\theta_{FC} - \theta_{WP}}\right]^{\beta} \qquad (18)$$

where θ is the average volumetric soil water content over the entire root zone for a given day. θ_{FC} is the volumetric soil water content at the field capacity, θ_{WP} is the volumetric soil water content at the permanent wilting point and β is a curvature function for the soil water stress factor. The model was calibrated using data collected from the Porterville site and validated using the data from Clanwilliam.

Accumulation of the wet and dry biomass of the rooibos during the growing season was monitored by harvesting and weighing three to four plants on 06 October 2020, 05 November 2020, and 23 December 2020. Yield data was obtained from the farm in tons per hectare at the end of the growing season. Estimates of the yield were modelled via a linear relationship between the yield and the accumulated ET.

3.7.2. Climate change scenarios

Climate change data were obtained from climate model simulations spanning the historic and future climate (1960-2100). These simulations were performed at a quasi-uniform 50 km horizontal globally using the conformal-cubic atmospheric model (CCAM) developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) (McGregor and Dix, 2005). The CCAM model is a variable-resolution global climate model (GCM) and it is relied upon, in this study, to realistically simulate the climate system teleconnection to Southern Africa.

The CCAM-CABLE model global runs use bias-adjusted sea surface temperatures (SSTs) and sea-ice concentration from six GCM models as lower boundary forcings (McGregor, 2001). The used GCMs go under the names: the Community Climate and Earth-System Simulator (ACCESS1-0); National Centre for Meteorological Research Coupled Global Climate Model, version 5 (CNRM-CM5); the Geophysical Fluid Dynamics Laboratory Coupled Model (GFDL-CM3); the Max Planck Institute Coupled Earth System Model (MPI-ESM-LR); the Norwegian Earth System Model (NorESM1-M); and the Community Climate System Model (CCSM4). All the GCM outputs, used as CCAM-CABLE forcing data, formed part of the Coupled Model Intercomparison Project Phase Five (CMIP5) and the Assessment Report Five (AR5) of the Intergovernmental Panel on Climate Change (IPCC). The forcing CMIP5 models were based on their ability to represent a good representation of the El Niño-Southern Oscillation (ENSO) attributes.

All model runs were performed with CCAM-CABLE prescribed with atmospheric greenhouse gas (CO_2, sulphate and ozone) concentration trajectories under the Representative Concentration Pathway 8.5 (RCP8.5). The scenario is commonly referred to as the "business as usual" scenario representing the 90th percentile of the policy scenarios used in CMIP5.

RCP8.5 is also associated with high baseline emissions and low mitigation for the 21st century. The extraction of site-specific meteorological data including near air surface (2 m) temperature, wind speed and precipitation from gridded modelled fields was achieved through an inverse distance weighted remapping using climate data operator (CDO).

The model developed using the measured water use and environmental data was applied under potential scenarios of future climate change in the rooibos producing areas in the Western Cape. Six coupled climate change models, i.e. ACS 85, CCS 85, CNR 85, MPI 85, NOR 85, and GFD 85, which assume the RCP 8.5 emission scenario were used to estimate potential changes in the future water requirements and yield of rooibos as the climate changes. According to Lotter and Le Maitre (2014), the RCP8.5 emission scenario is most appropriate for the rooibos growing area as it reflects the actual trajectory of emissions that are already ahead of the higher end of the emissions scenario. The six coupled climate models were dynamically downscaled for Southern Africa by means of the conformal – cubic atmospheric model (CCAM; Engelbrecht et al., 2011) obtained from the climate modelling group at the Council for Scientific and Industrial Research in South Africa. These data were used to simulate future changes in crop water requirements between the baseline period (1960-1969) and the far future scenarios (2089-2099) for each of the six models. Assumptions made in these simulations are that the seasonal changes in vegetation height and soil moisture regimes were similar for all scenarios. So changes in the crop water requirements were a result of changes in climatic conditions only. Changes due to crop growth variations were not taken into account to ensure model simplicity. In addition, solar radiation is generally not produced by climate change models. This had to be calculated using the approach by Allen et al. (1998) as:

$$R_s = K_{RS}\sqrt{T_{max} - T_{min}}R_a \qquad \text{(MJ/m}^2\text{/d)} \qquad (19)$$

Where K_{RS} is a constant which was taken as 0.16, T_{max} and T_{min} are the maximum and minimum air temperature in degrees Celsius, R_a is the solar radiation at the top of the atmosphere calculated according to Allen et al. (1998).

CHAPTER 4

4. RESULTS: PORTERVILLE (2019-2020)

4.1. Weather conditions

Typical daily trends in key climate driving variables at Porterville during the 2019-2020 growing season are summarized in Fig. 26. The maximum daily solar radiation ranged from a peak around 12.0 MJ/m^2/d in winter (July 2019) to just over 32.0 MJ/m^2/d in mid-summer (December 2019). The air temperature peaked at just over 41°C while the lowest value was around 2.7°C, recorded in winter as summarized in Table 1. Wind speeds at this site were fairly strong presumably due to the funneling effect of the mountains on either side of the study area. The daily average wind speeds for most months was higher than 1.5 m/s with strong gusts approaching 10 m/s recorded on occasion.

The atmospheric evaporative demand, depicted by the reference evapotranspiration (ETo), was quite high in summer reaching up to 8.4 mm/d. The annual total ETo from 01 May 2019 to 30 April 2020 was about 1 447 mm which was more than four times greater than the rainfall which was only 334 mm. About 74% of the rain was received in the winter months from May to August. February was the driest month that received only 0.3 mm of rainfall. Only 5% of the annual rainfall was received in from November to March. Compared to other years, the 2019-2020 growing season was somewhat drier receiving 31% lower rainfall than the long-term average rainfall for the area which is around 480 mm/year (SAWS).

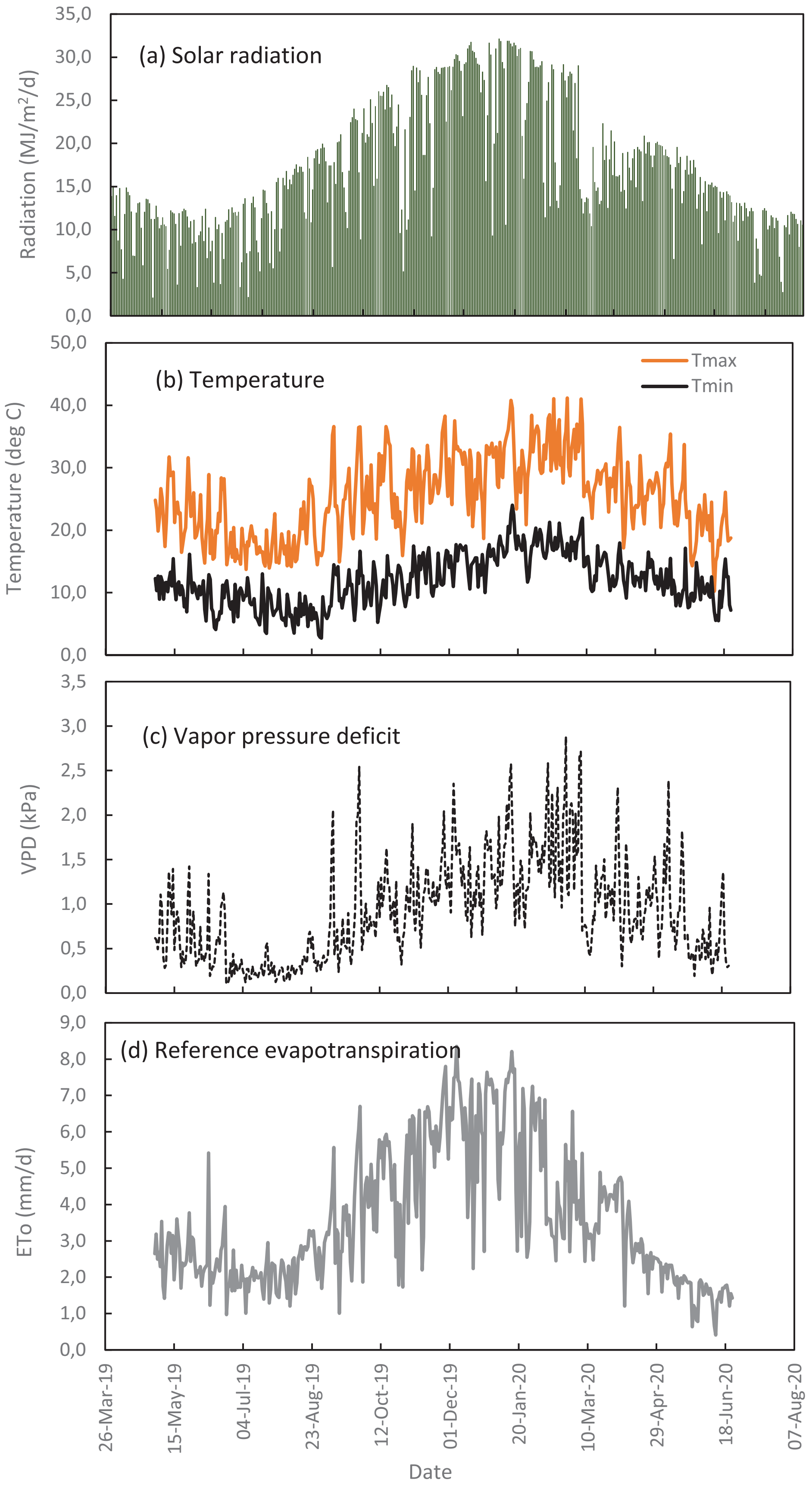

Figure 26. Seasonal variations in key climatic variables namely; (a) daily total solar irradiance, (b) maximum and minimum air temperatures, (c) vapor pressure deficit of the air, and (d) the short grass reference evapotranspiration.

Table 1. Summary of monthly climate variables including the daily average solar irradiance (R_s), maximum and minimum air temperatures (T_{max}, T_{min}), average wind speed (u_2), relative humidity (RH) and short grass reference evapotranspiration (ET_o).

	Rs (MJ/m²/d)	T_{max} (°C)	T_{min} (°C)	u_2 (m/s) (m/s)	Rain (mm)	RH (%)	ET_o (mm)
May-19	11,2	31,7	6,9	1,6	52,1	66	82,2
Jun-19	9,7	28,9	4,1	1,7	55,6	73	70,8
Jul-19	9,5	22,7	3,5	1,9	87,8	83	59,8
Aug-19	14,0	28,2	2,7	1,2	21,6	78	75,0
Sep-19	17,6	36,6	5,5	1,7	29,2	65	110,5
Oct-19	21,2	36,6	5,2	1,9	19,2	59	138,0
Nov-19	25,7	38,3	9,0	2,3	3,3	54	176,4
Dec-19	27,6	37,5	10,0	2,9	5,8	52	195,6
Jan-20	24,6	40,8	11,7	2,5	5,5	55	184,1
Feb-20	18,8	41,2	15,2	2,4	0,3	50	144,1
Mar-20	18,0	41,0	10,2	1,8	2,5	58	118,7
Apr-20	15,8	36,5	9,1	0,9	52,1	56	92,3
Total					334,8		1447,5

4.2. Soil properties and water content dynamics

The soil profile comprised course sand in the top horizons (0 to 60 cm) and the clayey content increased with depth. The soil texture was predominantly sandy clay in the 80 to 100 cm depth with a clayey layer beyond this depth. The depth to the water table in the area was not determined, so we had no way of establishing whether or not the plants used groundwater. However, it is evident from Fig. 27 that there were clear differences in the soil water content regimes between the rows (Fig. 27a) and within the rows of the plants (Fig. 27b). The soil water content declined sharply for the probes that were installed within the rows than those that were between the rows indicating active plant water uptake. A few heavy storms infiltrated the entire soil profile up to the 100 cm depth for both sets of probes. But negligible changes in the soil water content were observed within the rows after small rain events as the soil profile had become quite dry with volumetric water contents typically less than 5%. The soil water content was highest at the 60 cm depth which was located just above the clayey layer possibly because of the constraining effect of the impermeable layer. Despite this, there was evidence of water uptake by the rooibos at this depth as shown in Fig. 27b.

Table 2. Soil physical properties for the rooibos field in Porterville.

Depth (cm)	Clay %	Silt %	Sand %	Fine Sand %	Medium Sand %	Course Sand %	Stone % (v/v)	Classification	Water holding Capacity -10 kPa %		
									-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	7,12	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

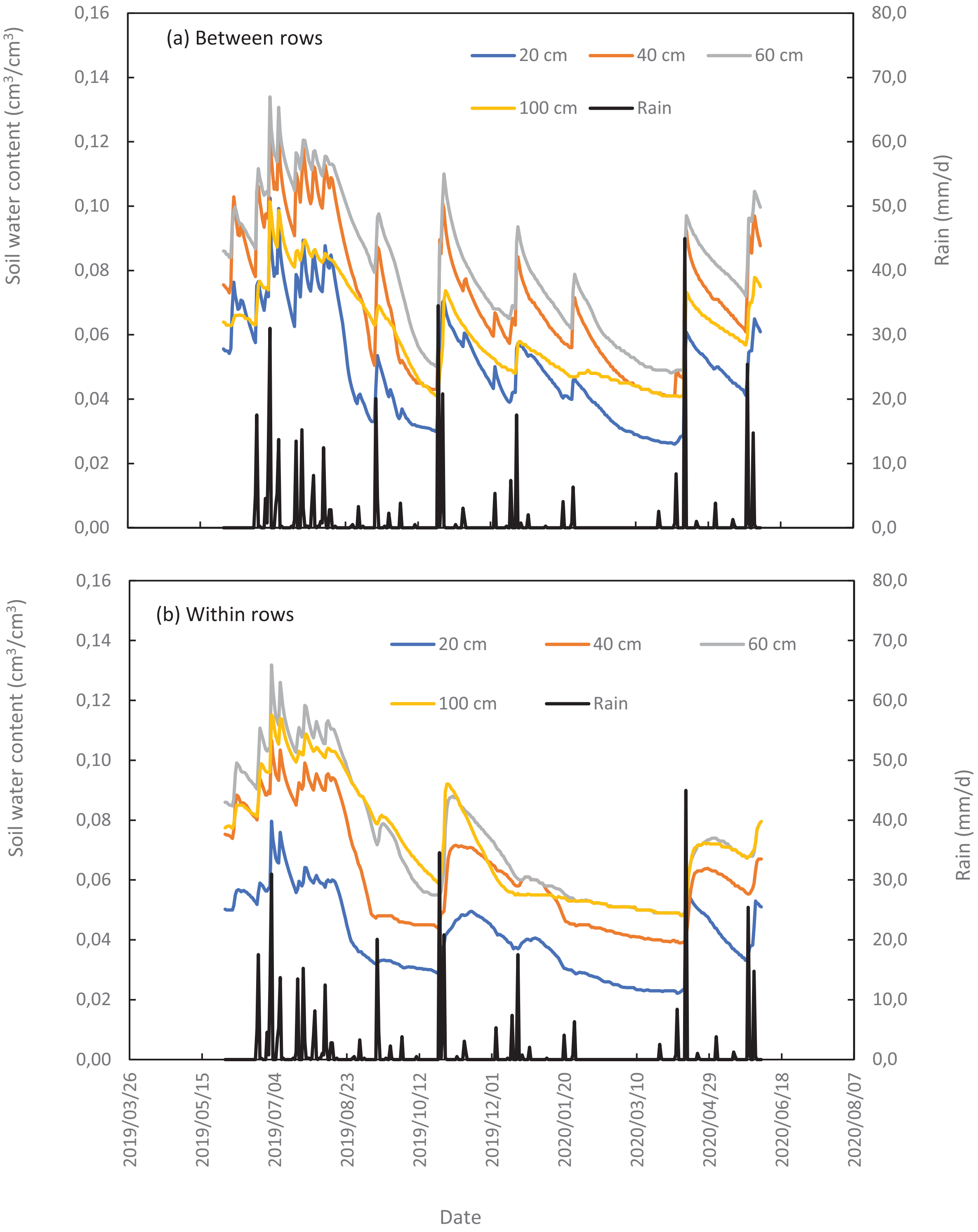

Figure 27. Soil water content dynamics and rainfall time series; (a) between, and; (b) within plant rows.

4.3. Surface energy balance and canopy growth

Average crop height was just over 1.0 m when the study commenced in in May 2019 with the corresponding leaf area index around 0.28 (Fig. 28). The growth rate for the rooibos, determined from the monthly increases in average crop height, ranged from around 1.0 cm per month in winter (June-July) accelerating to a peak of about 12 cm per month in early summer (October-November). The leaf area index measured in January 2020 just before harvest was about 1.56 while the average crop height approached 1.60 m. Harvesting of the rooibos crop was done between 12 and 15 February 2020. The average fresh mass of the crop was about 0.84 tons per hectare.

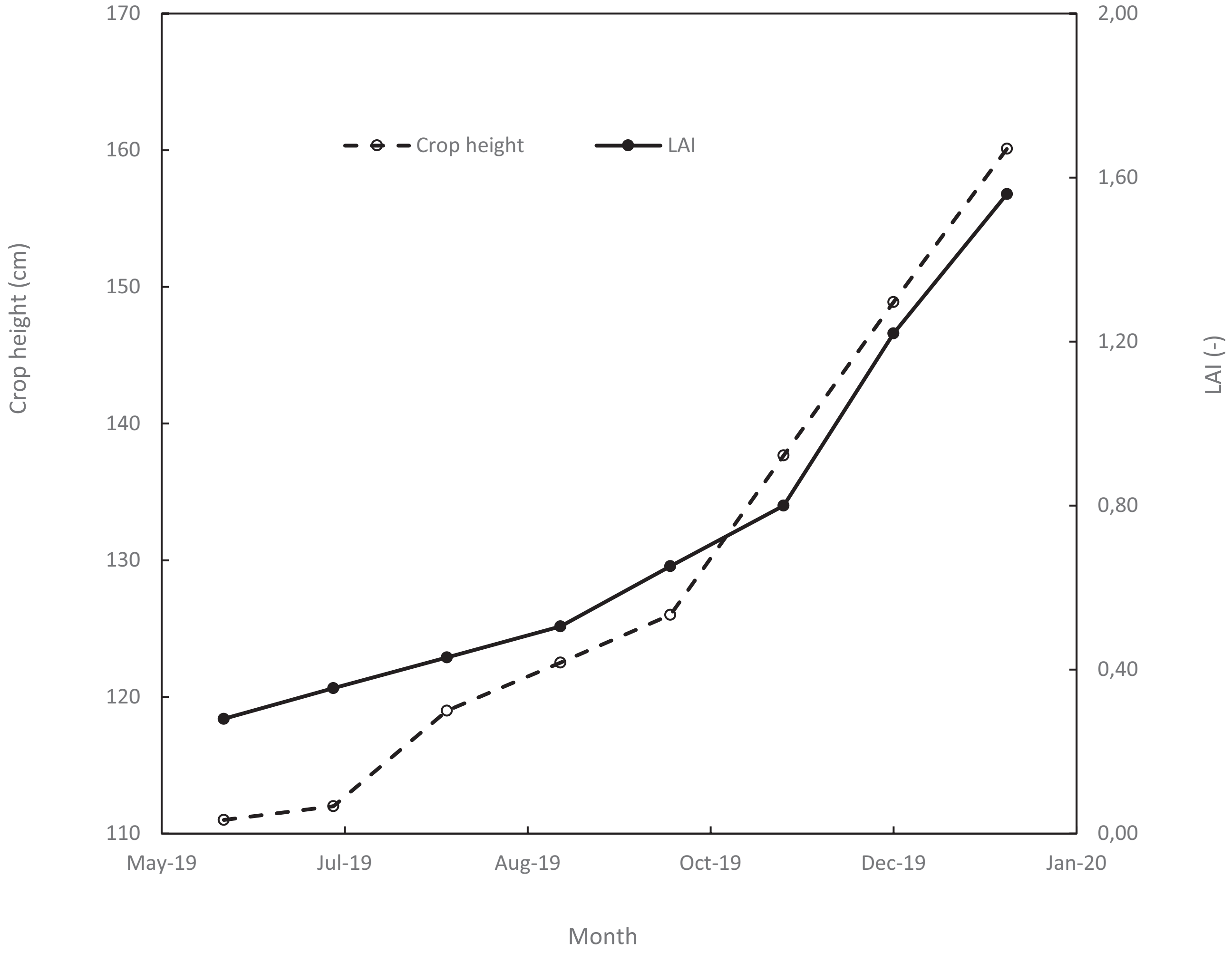

Figure 28. Changes in the leaf area index of the rooibos field over a typical growth cycle from May 2019 to January 2020. The crop was harvested in February 2020

The typical energy balance for the rooibos field in summer on 10 January 2020, about one month before the crop was harvested is shown in Fig. 29. At this time, canopy cover was at its maximum. It is clear in Fig. 29a that, under clear sky conditions, more than 80% of the available energy was dissipated as sensible heat and a small fraction was used to evaporate the water. This asserts the fact that the rooibos crop had very low water-use rates despite the extensive canopy cover.

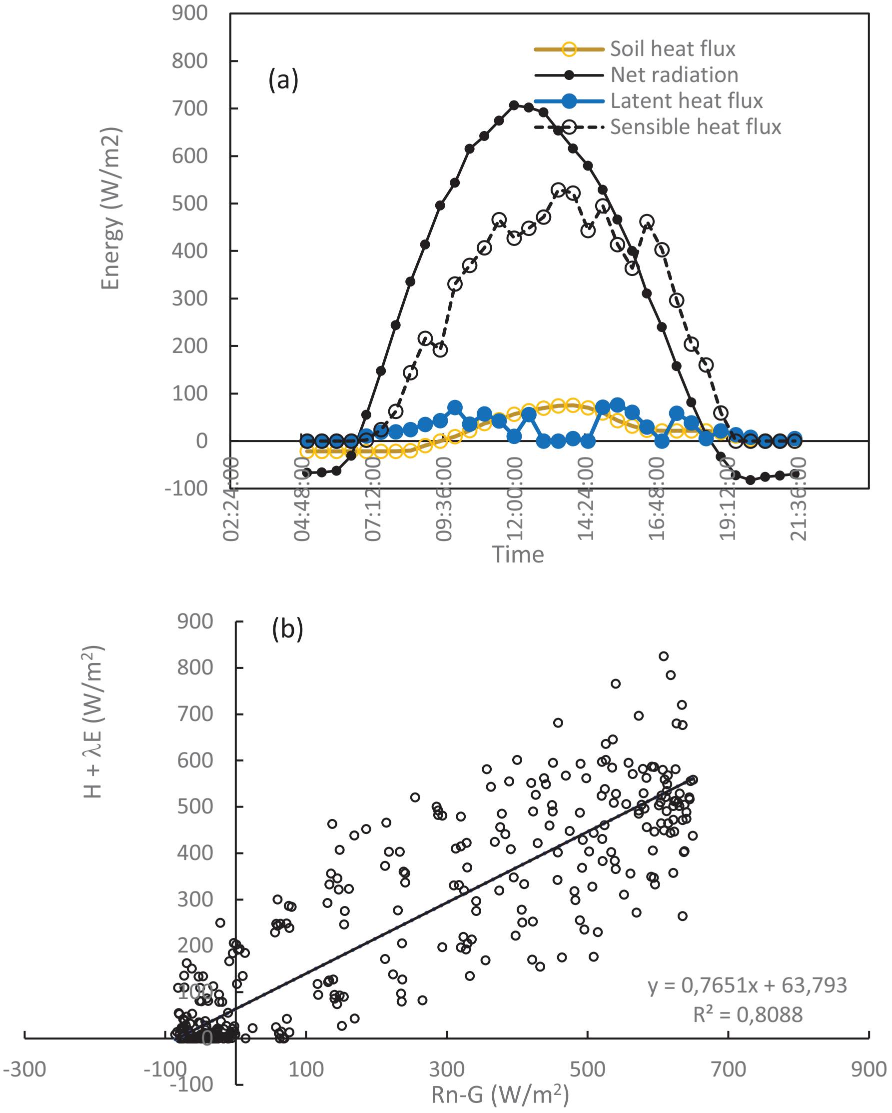

Figure 29. (a) Components of the surface energy balance of a rain-fed rooibos crop on a typical clear day in summer. (b) Energy balance closure for the rooibos crop measured using the eddy covariance method

The latent heat flux (blue line in Fig. 29a) was of the same order of magnitude as the soil heat flux (open yellow circles in Fig. 29a). In addition, a midday decline in the latent heat flux is apparent in Fig. 29a suggesting that the rooibos possibly closed its stomata to minimize water losses in the middle of the day when the atmospheric evaporative demand was maximum. This trend was confirmed by the sap flow measurements (data not shown). The energy balance closure for the rooibos field is illustrated in Fig. 29b. There was substantial deviation from the one to one relationship and therefore the energy balance closure correction described in section 3.4 was implemented to derive the field evapotranspiration.

4.4. Crop water use, yield and water productivity

The partitioning of water-use fluxes in the rooibos field is illustrated in Fig. 30(a). The peak of the actual evapotranspiration (ET) and the reference evapotranspiration (ETo) were out of phase with ET reaching a maximum in spring (September to early October) while the ETo peaked much later in mid-summer (i.e. December-January). This trend can be attributed to the high water use by the dense weed cover from May to September. During this time, the rooibos canopy cover was still very small as illustrated in Fig. 28 and by the transpiration trend in Fig. 30a. Significant winter rains stopped on 30 July 2019 (Fig. 30b). However, high ET rates, reaching up to 3.0 mm/d at times, were sustained until mid-September 2019 (Fig. 30a). This period coincided with a rapid decline in the soil water content (Fig. 27) as the weeds depleted the water reserves. The annual total ET for the field was about 338 mm with about 61% of this water consumed mostly by the weeds in the period May to September as shown in Table 3.

Daily transpiration by the rooibos crop peaked in October (Fig. 30a) with the maximum recorded value approaching 2.0 mm/d. From late October onwards, the measured transpiration was of the same order of magnitude as the measured ET suggesting that rooibos transpiration was the major source of evaporation after the weeds had died down.

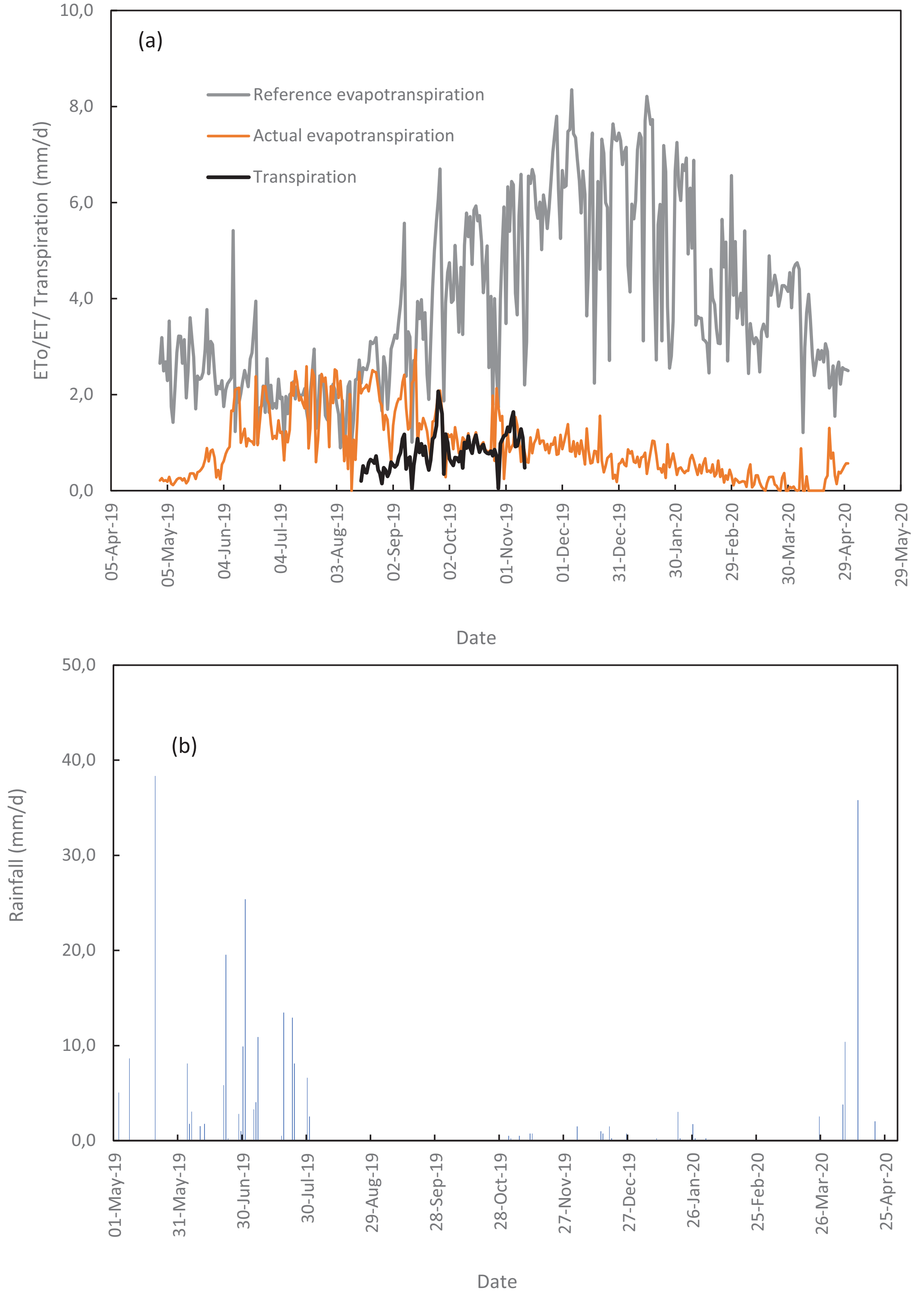

Figure 30. (a) Seasonal variations in actual evapotranspiration, reference evapotranspiration and rainfall on the rooibos crop. (b) Daily rainfall during the 2019/20 growing season

Atmospheric factors, mainly the solar radiation and the vapor pressure deficit (VPD) of the air were the main drivers of rooibos transpiration (Fig. 31) with VPD having the strongest effect ($R^2 > 0.69$). Although wind speeds were fairly strong at the site, this did not have a significant effect on the rooibos transpiration ($R^2 < 0.05$). Similarly, the soil water deficit had a week effect on the plant transpiration ($R^2 < 0.05$) suggesting that the crop could have accessed other water sources, e.g. water stored in deep soil layers given the rather deep tap root of rooibos which can exceed up to 2.0 m deep in some places.

Table 3. Water use and the driving climate variables over one full growing cycle

	Rain (mm)	ETo (mm)	ET (mm/d)	T (mm/d)	SWC (cm^3/cm^3)
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		

The annual total ET was slightly higher than the rainfall received at the site as shown by the cumulative fluxes in Fig. 32 confirming that the rooibos likely accessed other water sources.

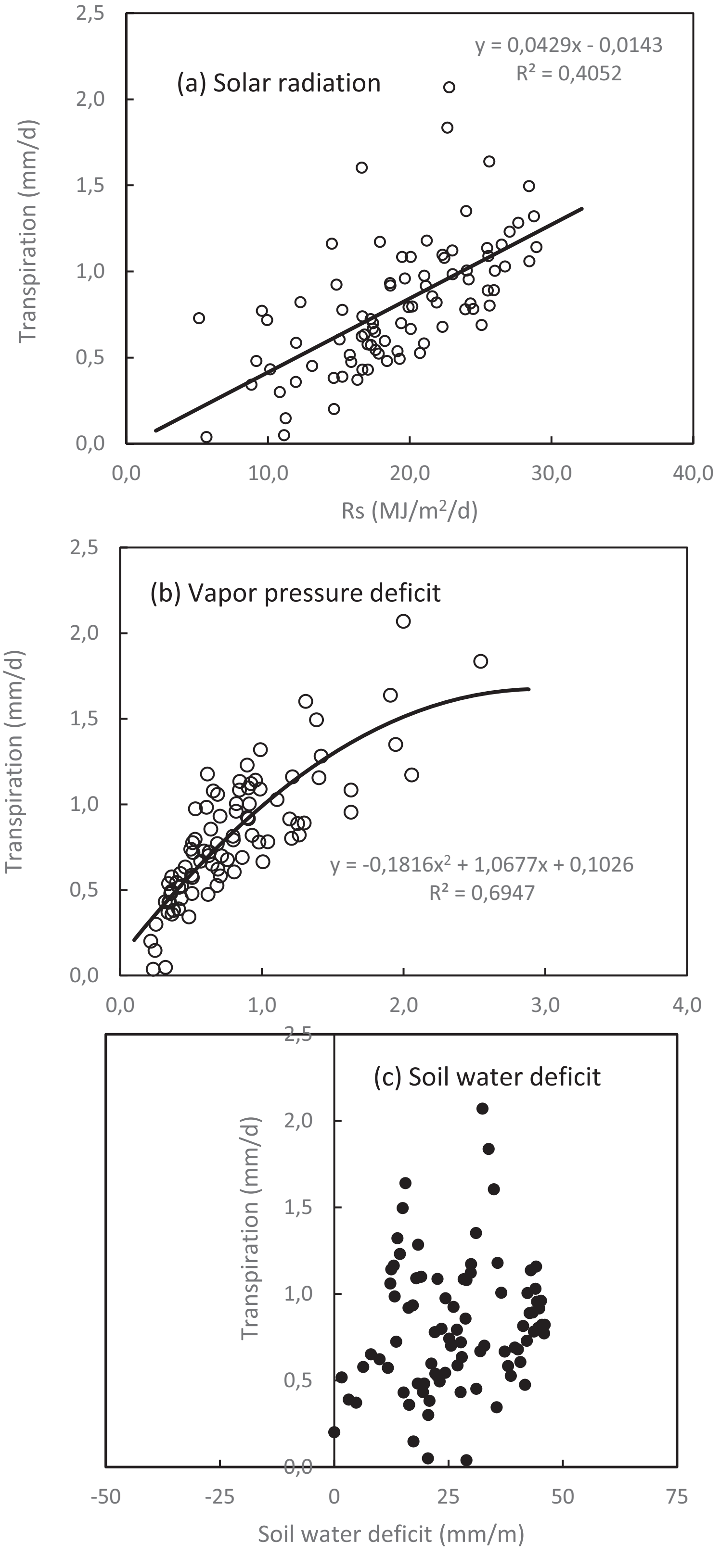

Figure 31. Effect of the climate driving variables, i.e. (a) solar radiation and (b) vapor pressure deficit of the air and (c) soil water deficit on the transpiration of rooibos crop

The total crop yield was about 21 tons over the whole field which translated to about 0.84 tons per hectare. The water productivity, calculated here as the ratio of the yield to the annual ET was about 0.25 kg of rooibos per m^3 of water consumed.

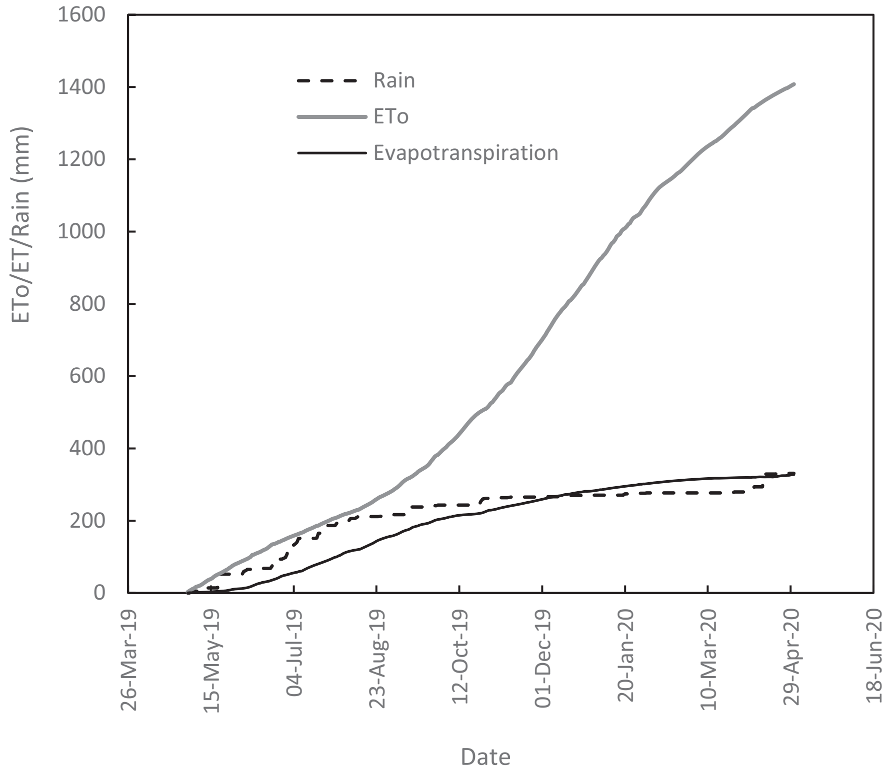

Figure 32. Cumulative rainfall, reference and actual evapotranspiration of the rooibos field during the 2019/20 growing season

CHAPTER 5

5. RESULTS: CLANWILLIAM (2020-2021)

5.1. Weather conditions

Typical trends in the daily solar radiation, maximum and minimum air temperature, maximum and minimum relative humidity, reference evapotranspiration and rain fall at Clanwilliam are shown in Fig 33 (a-d). These data were collected from August 2020 to July 2021. The maximum clear sky daily solar radiation was slightly higher than at Porterville peaking at around 32 MJ/m^2/d while the lowest was in winter averaging about 10.5 MJ/m^2/d. The maximum air temperature was around 43°C reached in February 2021 while the lowest value was about 0.8°C reached in July 2021. The minimum relative humidity frequently dropped below 10% indicating the extremely dry conditions experienced in the study area, especially in the summer months. Peak reference evapotranspiration was around 8.0 mm/d. June 2021 was the wettest month receiving approximately 36 mm of rainfall while no rain was recorded in December 2020 and February 2021, respectively. The atmospheric evaporative demand was greatest in January 2021 totaling 202 mm. The annual total reference evapotranspiration was about 1 400 mm which was almost 12 times greater than the rainfall total of only 113 mm. A summary of the monthly weather conditions is given in Table 4.

5.2. Soil properties and water content dynamics

The physical properties of the soils at Clanwilliam are summarized in Table 5 below. The volumetric soil water content in the root zone of the rooibos crop was generally low (Fig. 34) since the soils were mostly sandy and with a low water holding capacity (Table 5).

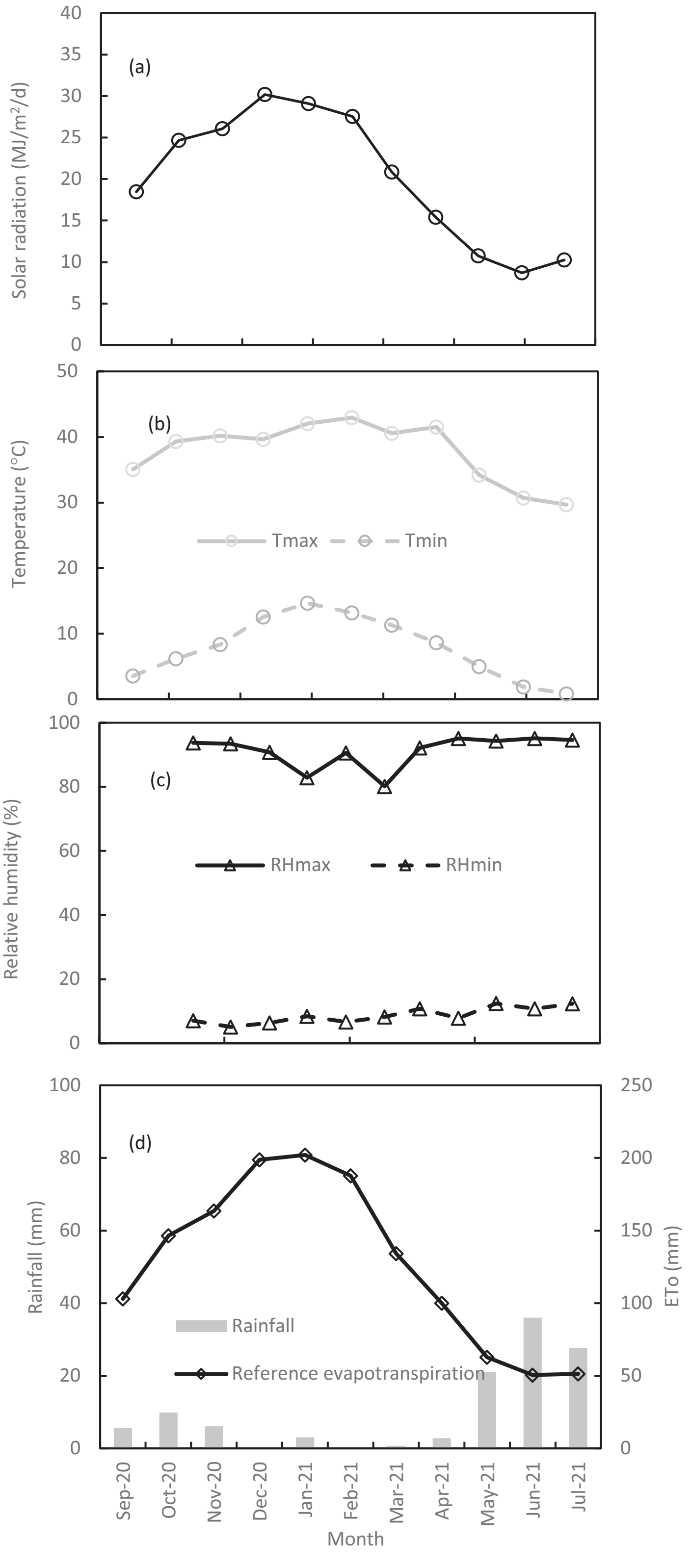

Figure 33. Weather conditions during the 2019 and 2020 growing season at Clanwilliam. (a) daily average total solar radiation, (b) maximum and minimum temperatures, (c) maximum and minimum relative humidity, (d) daily total rainfall and reference evapotranspiration over the course of the growing season

Table 4. Summary of the monthly weather conditions at Clanwilliams during the 2020-2021 rooibos growing season.

Month	Tmax (°C)	Tmin (°C)	RHmax (%)	RHmin (%)	Rs (MJ/m²/d)	U (m/s)	Rain (mm)	ETo (mm)
Sep-20	35.1	3.5	94	7	18.4	1.2	5.6	102.9
Oct-20	39.3	6.2	93	5	24.7	1.5	9.9	146.4
Nov-20	40.2	8.4	91	6	26.1	1.9	6.1	163.5
Dec-20	39.6	12.6	83	8	30.2	1.9	0.0	198.7
Jan-21	42.0	14.6	91	7	29.1	1.9	3.0	202.0
Feb-21	43.0	13.2	80	8	27.6	1.8	0.0	187.8
Mar-21	40.6	11.3	92	11	20.8	1.5	0.8	134.0
Apr-21	41.5	8.6	95	8	15.4	1.0	2.8	100.0
May-21	34.2	5.0	94	12	10.7	0.9	21.1	62.7
Jun-21	30.7	1.9	95	11	8.7	1.1	36.0	50.6
Jul-21	29.7	0.8	95	12	10.2	0.8	27.6	51.4
		Total					**112.9**	**1400**

Table 5. Physical properties of the soils at Clanwilliam

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Fine sand (%)	Medium sand (%)	Course sand (%)	Stone % (v/v)	Classification	Water holding capacity		
									-10 kPa	-100 kPa	mm/m
30	7	0	93	42.4	31.6	19.0	0.9	SAND	17.67	8.30	93.73
60	7	0	93	41.6	32.5	18.9	0.9	SAND	17.38	8.18	91.96
90	5	2	93	41.4	31.6	20.0	0.7	SAND	17.90	8.47	94.25
120	7	0	93	41.0	32.6	19.4	0.9	SAND	17.29	8.20	90.99

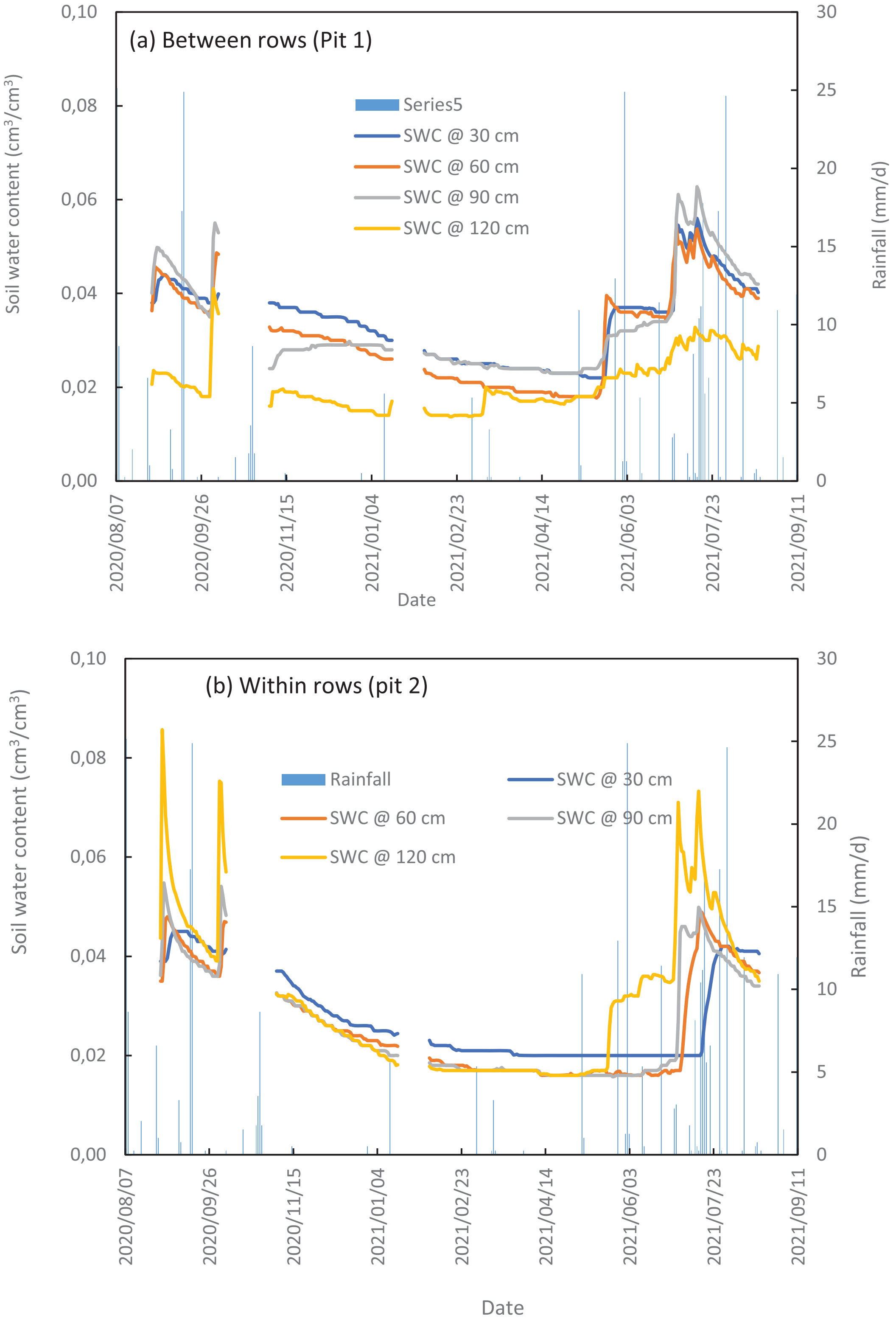

Figure 34. Changes in the soil water content in the root zone of the rooibos measured (a) between, and b) within plant rows

Changes in the water content responded to the precipitation pulses although the trends for the sensors between the rows (Fig. 34a) and within the rows (Fig. 34b) were somewhat different. As expected, shallower sensors gave the lowest soil water content. But for the within row sensors, the water contents at the four depths were almost similar especially during the dry summer season indicating substantial uptake of water by the rooibos crop right down the profile (Fig. 34b). Gaps in the data from 03 October to 09 November and again from 16 January to 06 February 2021 indicate periods when power supply to the data logger failed. In future deliverables, the soil water content and rainfall data will be used to provide an independent data set of evapotranspiration calculated using the soil water balance approach.

5.3. Surface energy balance and canopy growth

The seasonal changes in the surface energy balance early in the growing season in spring (September2021) and towards the end of the growing season in summer (January) are shown in Fig. 35a and b. The available energy (R_n – G) is either converted to sensible heat (H) used to warm the air or it is converted into the latent heat flux (λE), i.e. the energy equivalent of evapotranspiration, assuming that energy storage and that used to support physiological processes like photosynthesis is negligible. It is apparent in Fig. 35a that in spring, the available energy is partitioned almost equally between the sensible and latent heat fluxes. Evapotranspiration rates are fairly high supported by evaporation from the relatively well soils and the dense cover of weeds. Energy balance closure was around 70% (Fig. 35b) and this was corrected according to the approach by (Cammalleri et al., 2014)

However, as the soil dried and the weeds senesced in summer, it is clear from Fig. 35c that most of the available energy was converted to the sensible heat flux and very little was used as evapotranspiration despite the fact the rooibos cover was increasing as shown in Fig. 36. This suggests that water use by the rooibos crop itself is very little.

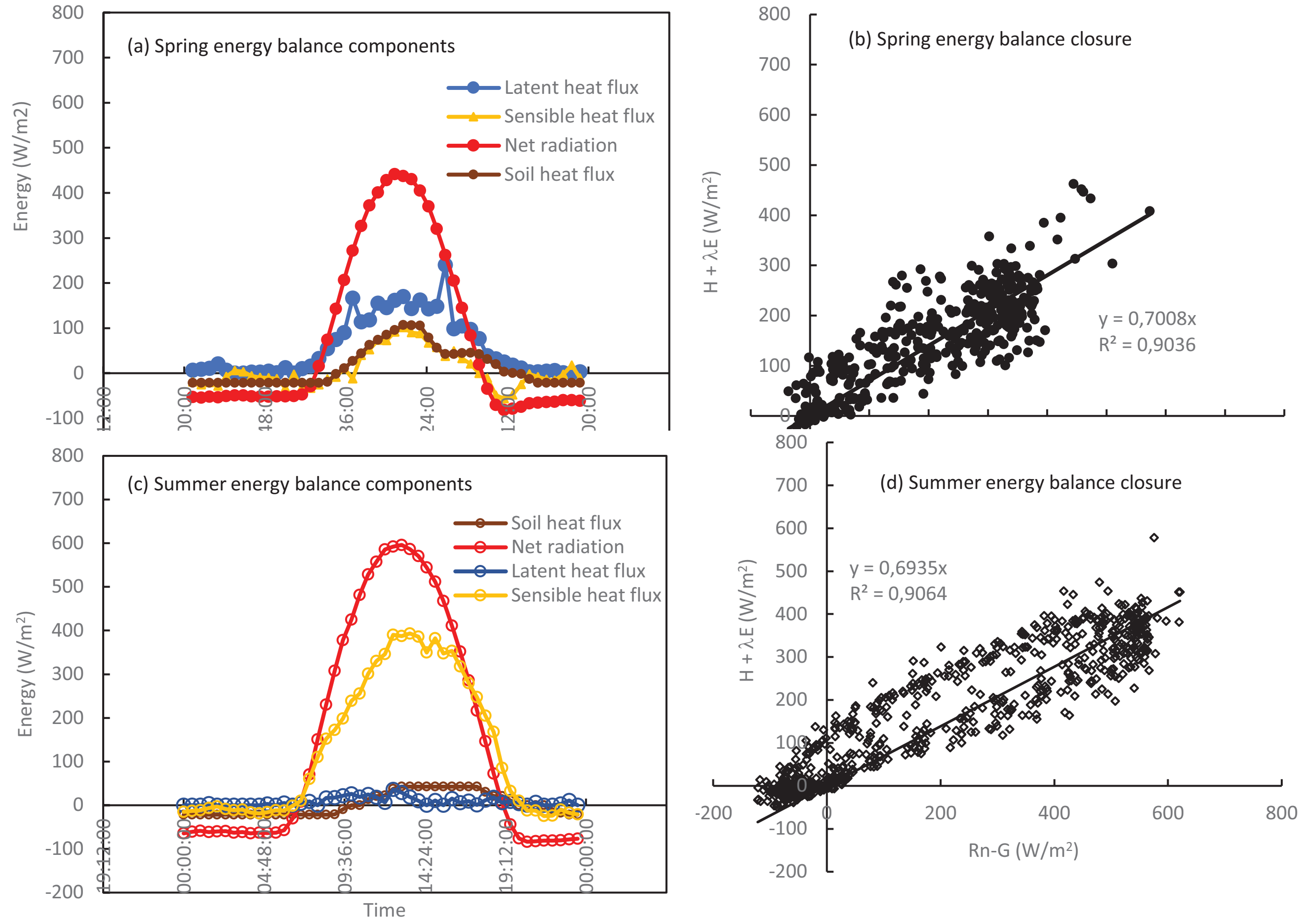

Figure 35. (a) Typical surface energy balance for a rooibos field for a clear day in spring on 10 September 2020 in Clanwilliam, (b) energy balance closure for the rooibos in spring from 28 August to 30 October 2020. (c) Surface energy balance for the rooibos field for a typical clear summer day on 17 December 2020 and; (d) energy balance closure for the summer season from 01 December 2020 to 31 January 2021.

Most of the evapotranspiration measured emanated from the soil and weeds early in the growing season. The order of magnitude the latent heat flux was similar to that of the soil heat flux in summer (Fig. 35c). In addition, the energy balance closure in summer showed a significant hysteresis effect (Fig. 35d) between the morning to afternoon and afternoon to evening trends. This could be a result of significant energy storage under the hot and dry conditions experienced in summer in the growing region.

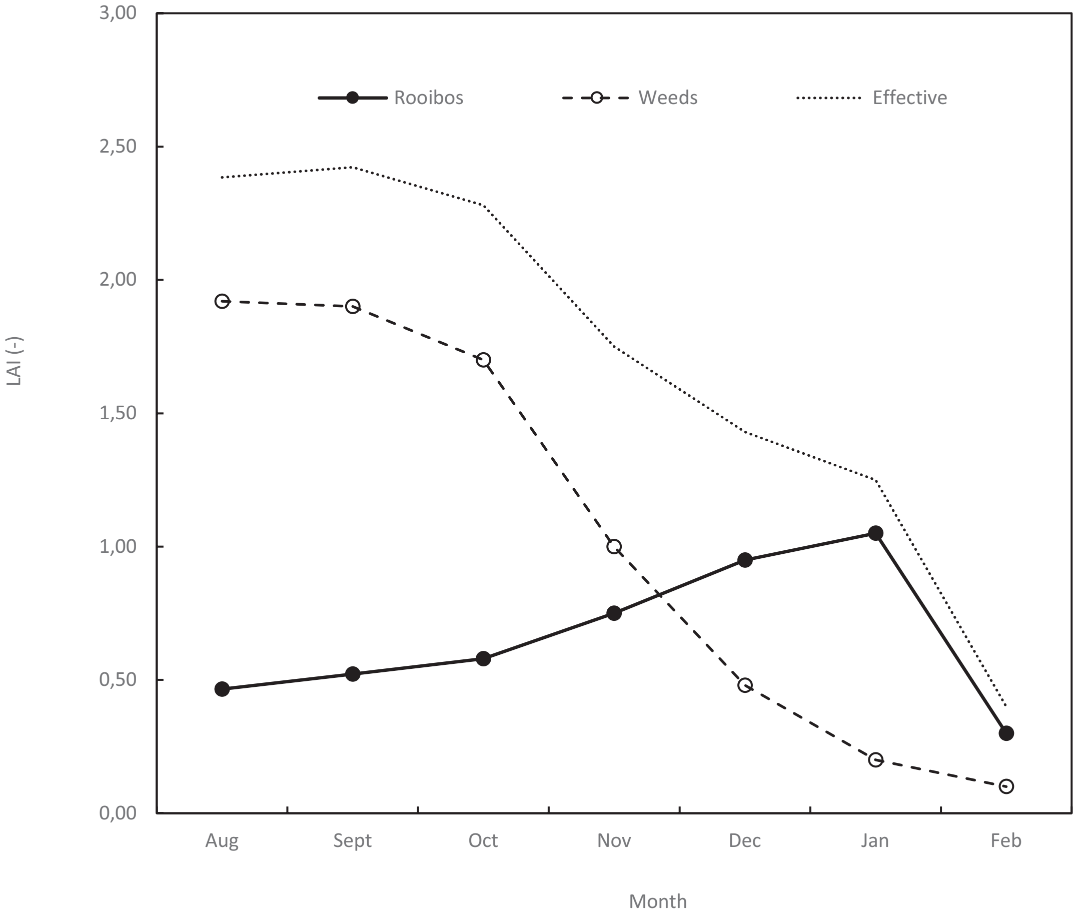

Figure 36. Seasonal changes in the leaf area index of the rooibos and weeds. The dotted line shows the effective leaf area index calculated as an algebraic sum of the weeds and rooibos LAI, respectively.

The maximum leaf area index of the field (~2.5) was measured in spring mostly due to the dense weed cover. Early in the season the LAI of the rooibos was less than 0.50 rising to just over 1.0 in summer (Fig. 36). The effective LAI was calculated as the algebraic sum of the rooibos and weeds LAI.

5.4. Crop water use, yield and water productivity

The daily trend in water use and reference evapotranspiration of the rooibos field from August 2020 to August 2021 is shown in Fig. 37a. The seasonal course of the atmospheric evaporative demand, depicted by the reference evapotranspiration, did not match that of the rooibos transpiration and the actual evapotranspiration (ET). The actual ET peaked early in the growing season (in spring) driven by the residual moisture from the winter rains that resulted in higher soil water content (Fig. 37b). The moist soil and transpiration from the dense cover of weeds were the major source of evapotranspiration. The contribution of the actual rooibos transpiration to the total ET early in the growing season was negligible as evident in Fig. 37a.

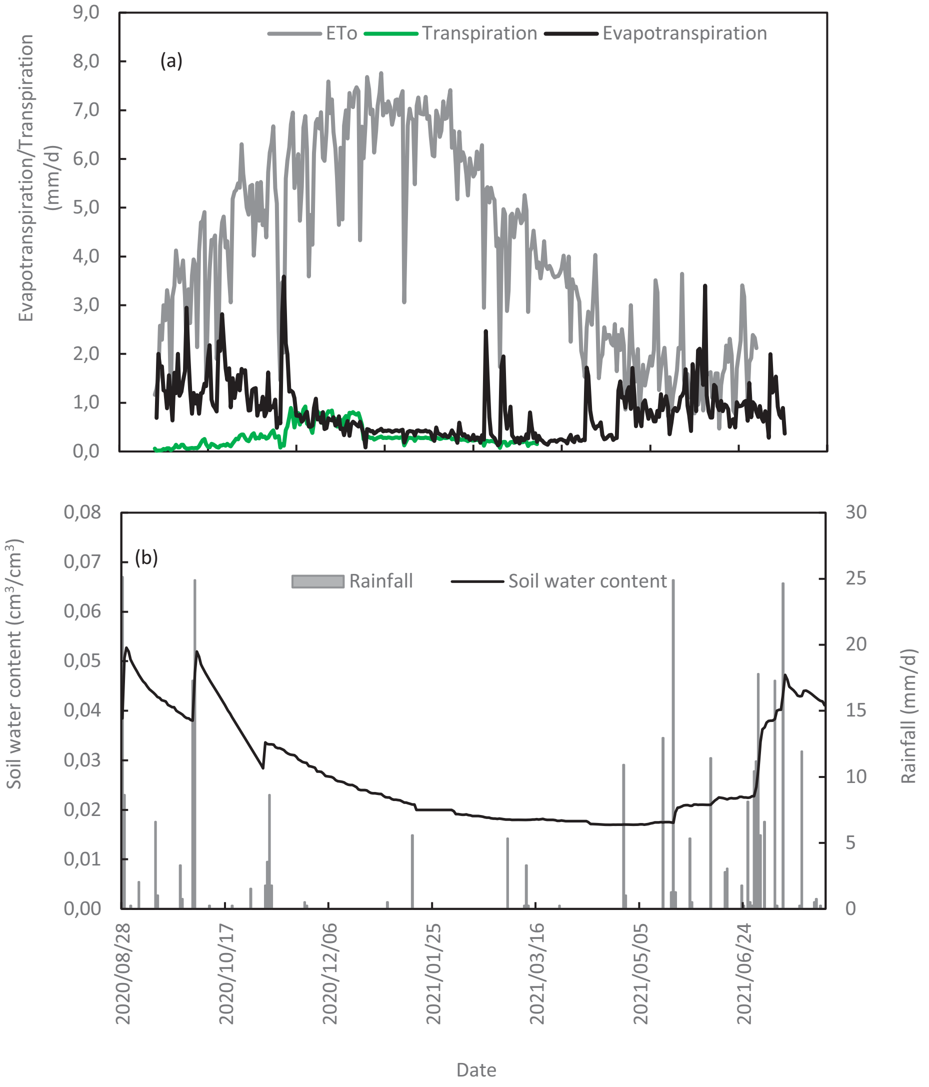

Figure 37. (a) Seasonal dynamics in the reference evapotranspiration, actual evapotranspiration and transpiration by the rooibos crop over a period of one year from August 2020 to July 2021 at Clanwilliam. (b) Average soil water content in the root zone and the corresponding rainfall.

The peak rooibos transpiration was reached in mid-December at values close to 1.0 mm/d before the average soil water content in the root zone dropped below 4% (Fig. 37b). These data are for the Clanwilliam study site and similar results were observed for Porterville. There was a non-linear relationship between the transpiration and the driving climate and soil variables (Fig. 38). The data in Fig. 38a shows that transpiration of the rooibos increased as the radiation intensity increased suggesting that the stomata of the plant opened with rising light levels. Transpiration rates increased at low VPD levels, but there was evidence of the stomata closing at the threshold VPD values between 1.5 and 2.0 kPa (Fig. 38b). Although the rooibos plant has a deep root system, it appears the transpiration declined with increasing soil water deficit (Fig. 38c). This observation is supported by the data in Fig. 38b where the transpiration declined from late December until harvest in February even though canopy cover was increasing (Fig. 36). Beyond December 2020, the order of magnitude of the rooibos transpiration matched that of the evapotranspiration (Fig. 38a) suggesting that the rooibos transpiration was the dominant contributor to the whole field evapotranspiration. Occasional spikes in ET were measured in summer after rain events as a result of evaporation from the wet soil surface and from intercepted rain water. The cumulative evapotranspiration and fresh above ground biomass were linearly related as shown in Fig. 39. The water productivity was 5.5 kg of rooibos (fresh mass) produced per cubic metre of evapotranspiration.

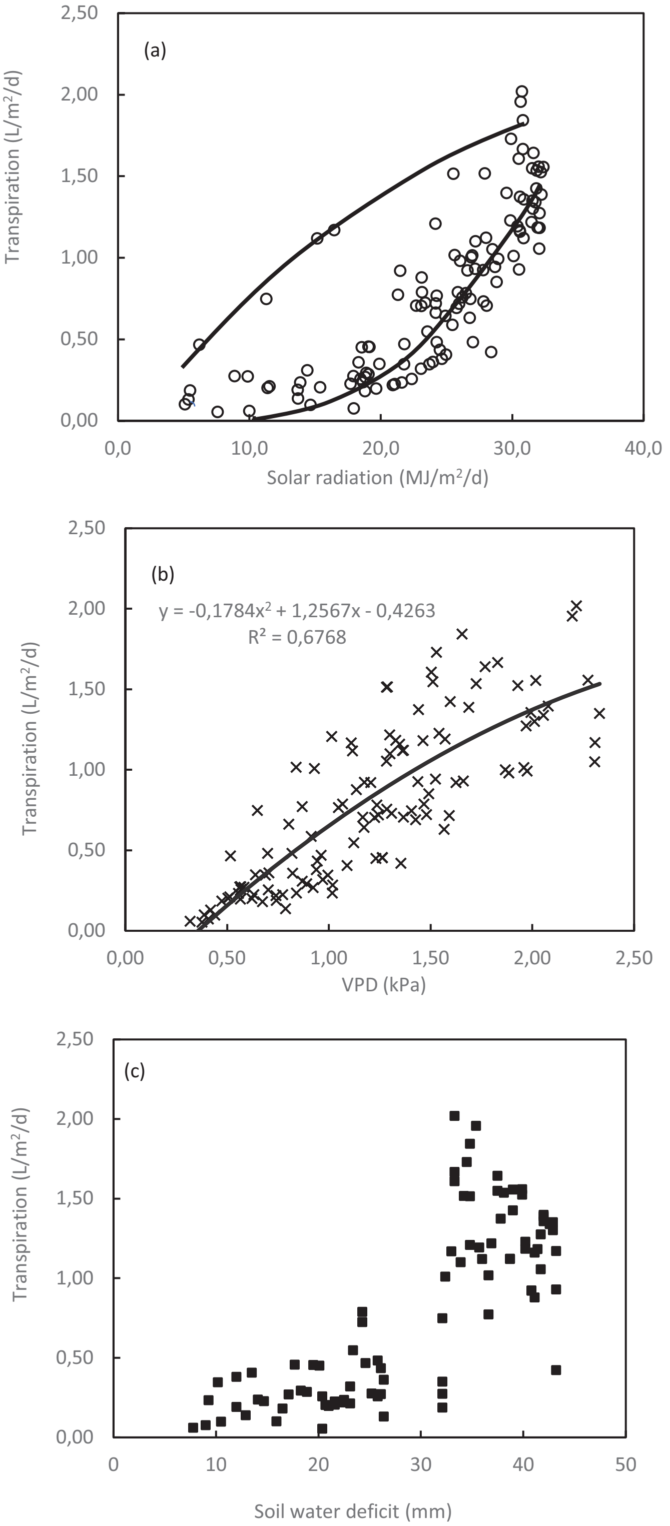

Figure 38. Rooibos transpiration and its drivers namely; (a) the solar radiation, (b) vapor pressure deficit of the air, and (c) soil water deficit in the root zone.

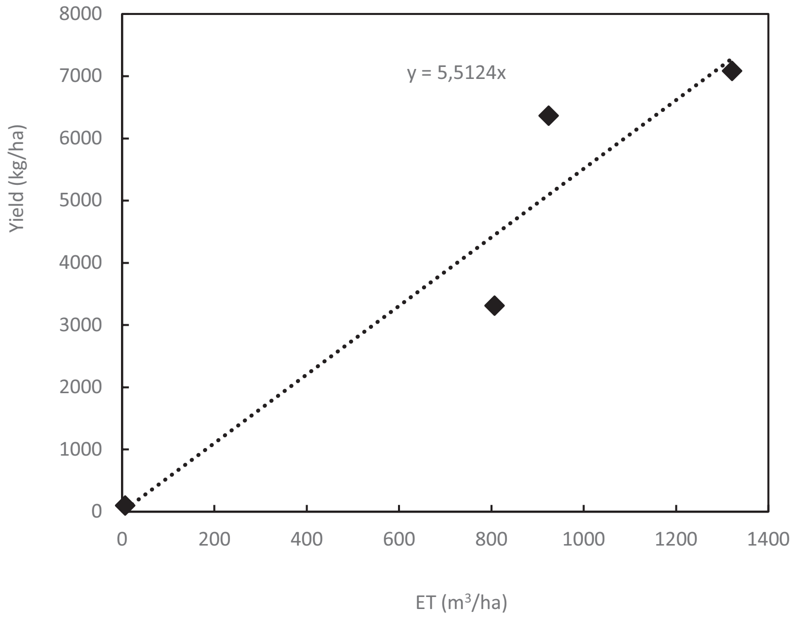

Figure 39. The water-use yield relationship for rooibos tea crop.

5.5. Modelling rooibos water use and climate change

Comparison of the measured and modelled ET for the rooibos field is shown in Fig. 40 with the grey line indicating the measured values and the associated error margins. Overall, the modelled ET were within 15% of the measured values. However, significant errors occurred after rainfall events due to difficulties in accurately modelling the surface conductance term when ET spiked. In addition, the small values of the ET fluxes made the daily simulations to be quite difficult, so we present the data as weekly totals.

All the six climate change models predict an increase in both the maximum and minimum air temperatures for the study area between the baseline period (1961 to 1970) and the far future (2089 to 2099). Expected increases are in the range 4 to 5 degrees Celsius and this will inevitably increase the atmospheric evaporative demand quite significantly. The reference evapotranspiration is projected to rise by between 11 and 18% while the actual ET is expected to increase by between 7 and 13% (Fig. 41). The increase in actual ET is expected to be slightly lower than that of ETo because of the projected higher VPD brought about by the rising air temperatures and the declining relative humidity. The VPD stress is therefore expected to increase thereby reducing the ET. Predicted yield increases are between 8 and 15% as summarized in Table 6. Higher increases are possible if the CO_2 enrichment of the atmosphere is taken into account. We did not include this aspect in our simulations as we did not have adequate input data.

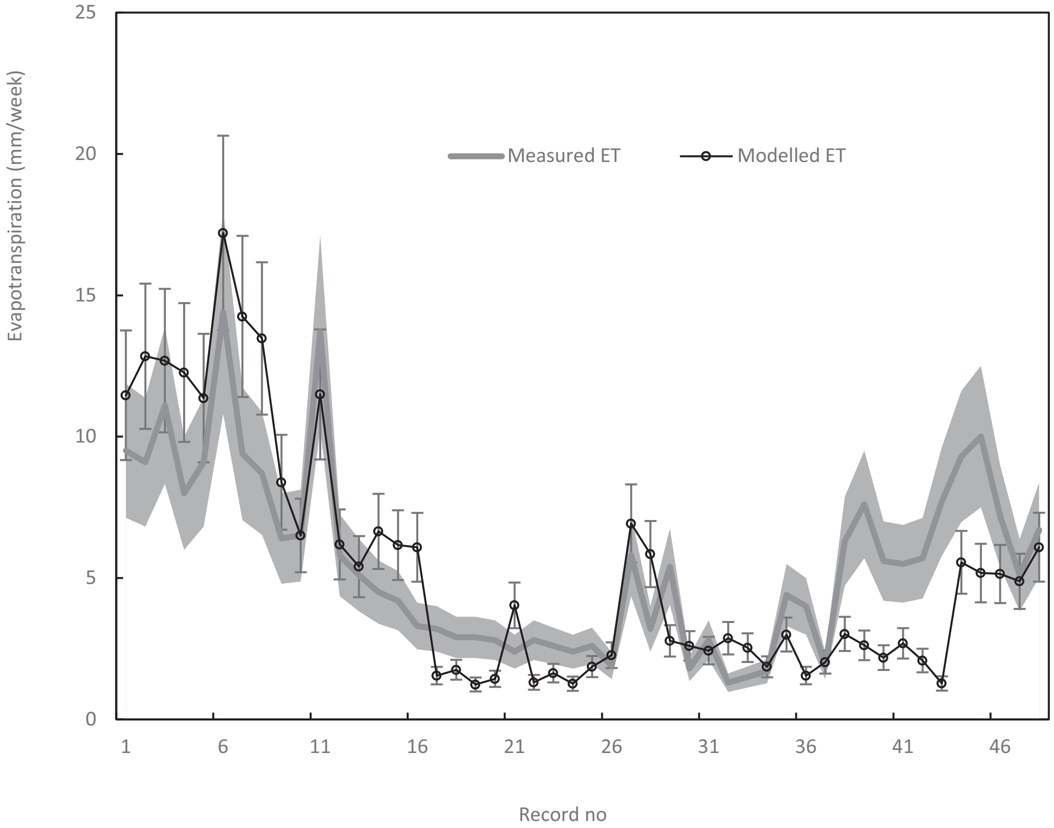

Figure 40. Comparison of the measured and modelled weekly evapotranspiration for the rooibos crop at Clanwilliam.

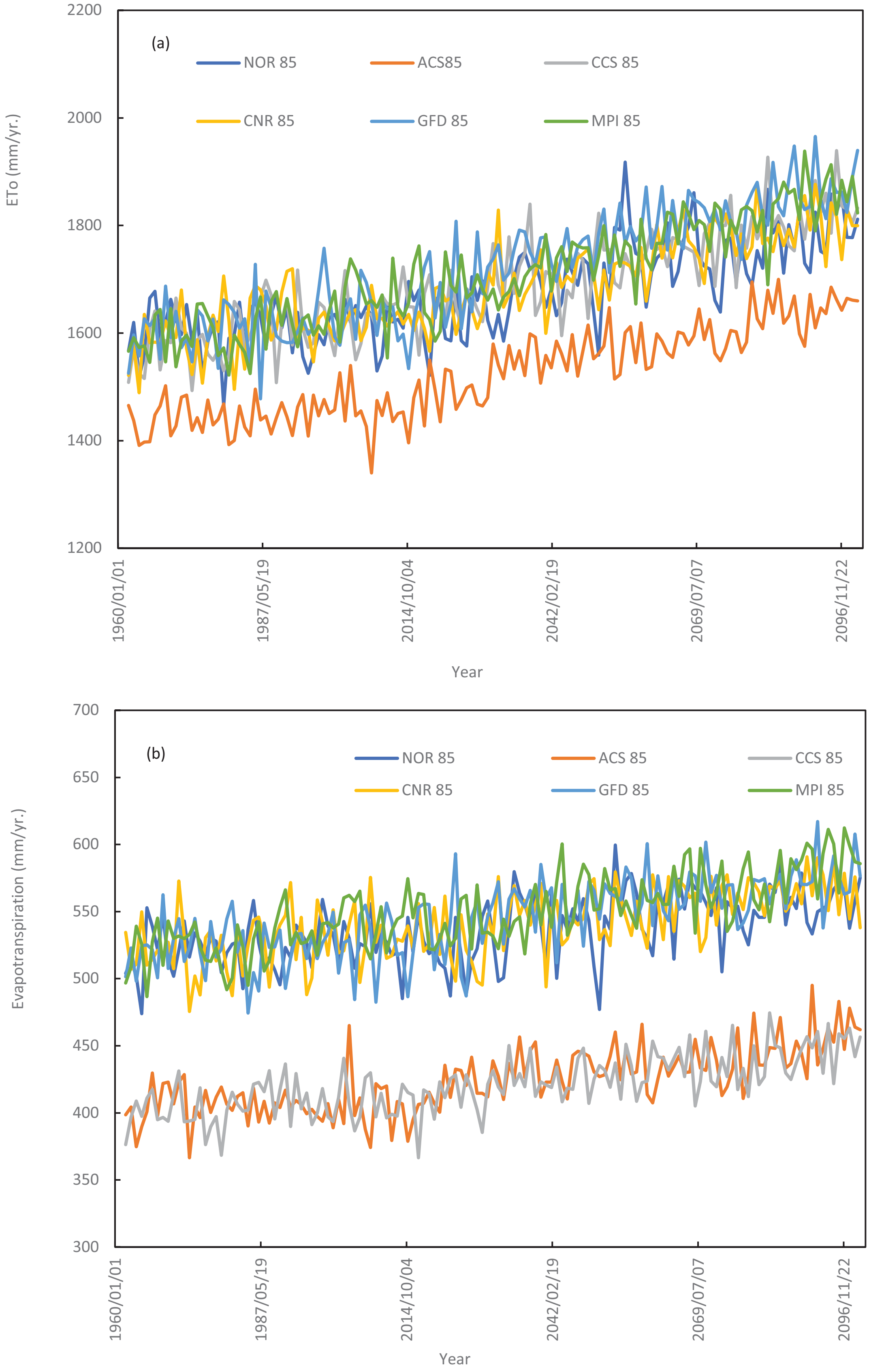

Figure 41. Projected (a) reference evapotranspiration and (b) actual evapotranspiration using 6 climate change models for the period 1961 to 2099 for the Clanwilliam site.

Table 6. Changes in the water requirements of rooibos fields under different climate change models between the first decade (1961-1971) and the last decade (2089-2099).

Model	**ΔETo(%)**	**ΔET(%)**	**Yield increase (%)**
NOR 85	11	7	8
ACS 85	15	13	15
CCS 85	17	12	13
CNR 85	14	8	8
GFD 85	17	11	11
MPI 85	18	13	13

CHAPTER 6

6. GENERAL DISCUSSION

The rooibos industry is critical for driving the economy of the South Africa, particularly the Western Cape where the species is endemic. It is a huge driver of job creation in the province while some indigenous communities derive their livelihoods from picking the wild types for income generation. Yet the sector is highly vulnerable to climate change and variability since all production is under rain-fed conditions. Climate change in the prime rooibos growing areas, is projected to get warmer and drier and this is expected to have a huge effect on crop production.

Studies have been done to quantify the effects of climate change and variability on commercial fruit production, cereal production, e.g. maize and wheat, production of biofuel crops, e.g. sugarcane, sugar beet, and sorghum and pastures, among others (DEA, 2013b; SmartAgri, 2015). In most instances irrigation is the most effective adaptation strategy to cope with climate change in areas where the frequency and severity of droughts are increasing as in the Mediterranean regions. The predicted warmer and drier conditions in the prime rooibos growing areas raise questions about the future sustainability of production of this crop.

The crop has not been successfully grown under irrigation and neither has it been successfully cultivated outside its natural habitat in the Cape Floral Region (Lötter, 2015). In this study we, for the first time, quantified the water-use dynamics of rooibos plants; established its seasonal dynamics, and how it is related to crop growth and yield. While rooibos can indeed grow under harsh conditions, this studied showed that its transpiration can decrease substantially with increasing soil water deficit in the root zone. Numerous studies have demonstrated that there exists a positive correlation between crop yield and cumulative transpiration (Dzikiti et al., 2018; FAO, 2013; Myburgh, 2016) because plants open their stomata to transpire in exchange for CO_2 gain. Therefore, higher soil water deficits, often associated with droughts, can indeed lead to substantial reduction in rooibos yield as confirmed by the severe droughts of 2016 to 2018 in the Western Cape Province in South Africa.

While rooibos is not produced under irrigation, this study shows that significant quantities of water stored in the soil profile are depleted early in the growing season before the rooibos crop reaches peak growth rate. The water is lost through soil evaporation and as transpiration by the weeds. Therefore, water demand management practices that reduce water loss from the field floor are important to conserve soil water which can sustain crops later in the growing season. Examples of the water demand management practices include the use of green mulches between the plant rows which must be maintained short to reduce transpirational losses (SmartAgri, 2015). Weeds can consume large quantities of water (Ntshidi et al., 2020) especially where they are allowed to thrive in poorly managed fields. Therefore, removing the weeds early in the growing season before rooibos transpiration levels rise is very important to preserve the residual soil moisture from the winter rains. Contour ridges on sloping terrain can also trap substantial amounts of runoff which can later be utilized by the plants.

Being a sclerophylous shrub that is adapted to dry environments, the rooibos crop itself has very low water requirements. But its growth and production can be significantly impacted by prolonged dry spells. Independent evidence of the low water consumption is presented by the surface energy balance data. In spring, the latent heat flux is a significant proportion of the available energy due to relatively wetter soils and the presence of mostly weeds that consume significant volumes of water. The weeds dry out in early summer causing a significant drop in the latent heat flux. By mid-summer, most of the available energy is dissipated as sensible heat and the order of magnitude of the latent heat flux is similar to that of the soil heat flux. These trends are not expected given the lush green cover that characterizes most rooibos fields before harvest. Establishing the mechanisms by which the rooibos crop is able to grow and thrive not only under extremely dry conditions, but also under nutrient poor soils is beyond the scope of this study.

All the six climate change models applied to the rooibos producing areas suggest significant increases in air temperature and the atmospheric evaporative demand in the coming decades. The big-leaf Penman-Monteith model applied in this study suggests that the crop water requirements will possibly rise but at a slower rate than the atmospheric evaporative demand. This will be as a result of the increased crop stress levels leading to reduced stomatal conductance due to higher VPDs arising from higher temperatures and lower relative humidity (Jarvis et al., 1976). Ecological studies on the suitability of different regions in the Cape Floral Region to grow rooibos under climate change suggest a substantial shrinkage in the area where rooibos will be able to grow in future as the growing conditions become unfavorable (Lötter and le Maitre, 2014). Similar findings were reported for the fynbos biome in the Cape Floral Region which is in the same family as rooibos (Midgley et al., 2002). The present study however, sheds light on the possible impacts of climate change on the water requirements of rooibos and the effects on yield. The model was developed using measured data of evapotranspiration, transpiration and environmental variables namely the climate and soil factors.

CHAPTER 7

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

This study has for the first time presented actual evapotranspiration (ET) and energy balance data for the rooibos crop over a complete growing cycle. With this continuous dataset it was possible to quantify seasonal changes in rooibos water use and how this is related to crop growth and yield and establish a baseline for assessing the consequences of climate change for cultivated rooibos tea.

There is consensus amongst a range of climate models for a significant increase in average temperatures, but also extreme temperatures and heat waves over the Greater Cederberg region. Moreover, future climate projections also point to changes in the temporal and spatial variation in rainfall with rainfall events that will become more sporadic appearing at more irregular intervals in time. This study has shown that these changing climate conditions will cause increased crop stress levels in rooibos plants with concomitant effects on yield.

This study has also indicated that the severity of impacts will not be spatially homogeneous. The rooibos production region varies in topography with rainfall from as little as 150 mm per annum on the west coast and lowlands to over 1000 mm on the interior plateaus of the Cederberg mountain range. Cultivation in sub-optimal locations or marginal areas is likely to decrease rapidly under the influence of accelerated global climate change. These represent the most vulnerable areas and reflect the differences between the lowland areas and the mountain sites, and also between the north-western and southern range of the production area. In the lowlands along the west coast and the northern periphery of the production area areas, the occurrence of optimum cultivation conditions will become erratic as the suitable areas tend to expand south-eastwards in the future.

Although rooibos as sclerophylous plant is adapted to semi-arid environments, future climate conditions may induce a climate regime beyond the adaptive mechanisms of cultivated rooibos plants. There may however be significant differences in the extent to which cultivated and wild plants will be able to persist in a more arid climate. Previous studies have indicated that wild populations of rooibos tea might have an adaptive advantage to tolerate increased aridity.

7.2. Recommendations

Climate change will increasingly challenge rooibos producers to manage their crops in the same manner as they have done in the past. Commercial producers could potentially offset some of the consequences of climate change by implementing water demand management practices such as the use of green mulches between the plant rows and removing the weeds early in the growing season to preserve the residual soil moisture from the winter rains. Contour ridges on sloping terrain can also trap substantial amounts of runoff which can later be utilized by the plants.

Other useful adaptation measures include improving soil fertility, retaining natural vegetation and minimum tillage. Although these adaptation strategies could mitigate climate change effects in optimal growing areas, farmers in marginal areas may progressively opt to convert to crops more suited to the new conditions. Commercial producers could also potentially offset some of the consequences of climate change by relocating or expanding crops to more suitable areas towards the southern parts of the growing region.

Given the findings of other studies regarding the ability of wild populations of tea to tolerate environmental stress, it would be useful for the Rooibos industry to initiate a similar study and further investigate the water use of wild rooibos as opposed to commercially grown rooibos. Such a study might support suggestions that further selection through wild types may indeed improve the resilience of cultivated tea to drought and heat stress.

8. REFERENCES

ALLEN, R.G., PEREIRA, L.S., RAES, D., SMITH, M., 1998. Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56.

ARCHER, E., CONRAD, J., MÜNCH, Z., OPPERMAN, D., TADROSS, M., VENTER, J., 2009. Climate change, groundwater and intensive commercial farming in the semi-arid northern Sandveld, South Africa. Journal of Integrative Environmental Sciences 6, 139-155. https://doi.org/10.1080/19438150902916589

BAKER, J.M., VAN BAVEL, C.H.M., 1987. Measurement of mass flow of water in the stems of herbaceous plants, in: Plant, Cell & Environment. https://doi.org/10.1111/1365-3040.ep11604765

BALDOCCHI, D., 2008. TURNER REVIEW No. 15. "Breathing" of the terrestrial biosphere: Lessons learned from a global network of carbon dioxide flux measurement systems. Australian Journal of Botany. https://doi.org/10.1071/BT07151

BOND, P., GOLDBLATT, P., 1984. Plants of the Cape Flora. A Descriptive Catalogue. Journal of South African botany / Supplementary volume.

CAMMALLERI, C., ANDERSON, M.C., KUSTAS, W.P., 2014. Upscaling of evapotranspiration fluxes from instantaneous to daytime scales for thermal remote sensing applications. Hydrology and Earth System Sciences 18, 1885-1894. https://doi.org/10.5194/HESS-18-1885-2014

CHENEY, R.H., SCHOLTZ, E., 2015. Rooibos Tea, A South African Contribution to World Beverages1.

CODD, L.E., 1983. Southern African species of *Mentha* L. (Lamiaceae). Bothalia. https://doi.org/10.4102/abc.v14i2.1155

CONRADIE, B., KNOESEN, H., 2009. A survey of the cultivation and wild harvesting of fynbos flowers in South Africa 1-19.

DAFF, 2016. Honeybush tea production guideline, Notes. Pretoria, South Africa.

DAHLGREN, R., 1984. A new species of Aspalathus (Fabaceae) from the Prince Albert District. South African Journal of Botany. https://doi.org/10.1016/s0022-4618(16)30037-7

DAKORA, F.D., PHILLIPS, D.A., 2002. Root exudates as mediators of mineral acquisition in low-nutrient environments. Plant and Soil. https://doi.org/10.1023/A:1020809400075

DE VYNCK, J.C., VAN WYK, B.E., COWLING, R.M., 2016. Indigenous edible plant use by contemporary Khoe-San descendants of South Africa's Cape South Coast. South African Journal of Botany 102, 60-69. https://doi.org/10.1016/j.sajb.2015.09.002

DEA, 2013a. Long-Term Adaptation Scenarios Flagship Research Programme (LTAS) for South Africa. Climate Change Implications for the Agriculture and Forestry Sectors in South Africa, LTAS Phase Technical Report.

DEA, 2013b. Full technical report on the implications of climate change for the Agriculture Sector in South Africa 1-50.

DZIKITI, S., GUSH, M.B., TAYLOR, N.J., VOLSCHENK, T., MIDGLEY, S., LÖTZE, E., SCHMEISSER, M., DOKO, Q., 2017. Measurement and modelling of water use by high yielding apple orchards and orchards of different age groups in the winter rainfall areas of South Africa. Acta Horticulturae. https://doi.org/10.17660/ActaHortic.2017.1150.5

DZIKITI, S., JOVANOVIC, N.Z., BUGAN, R., ISRAEL, S., LE MAITRE, D.C., 2014. Measurement and modelling of evapotranspiration in three fynbos vegetation types. Water SA. https://doi.org/10.4314/wsa.v40i2.1

DZIKITI, S., JOVANOVIC, N.Z., BUGAN, R.D., RAMOELO, A., MAJOZI, N.P., NICKLESS, A., CHO, M.A., LE MAITRE, D.C., NTSHIDI, Z., PIENAAR, H.H., 2019. Comparison of two remote sensing models for estimating evapotranspiration: algorithm evaluation and application in seasonally arid ecosystems in South Africa. Journal of Arid Land. https://doi.org/10.1007/s40333-019-0098-2

DZIKITI, S, VOLSCHENK, T., MIDGLEY, S., GUSH, M., TAYLOR, N., LOTZE, E., ZIREBWA, S., NTSHIDI, Z., MOBE, N., SCHMEISSER, M., DOKO, Q., 2018. Quantifying water use and water productivity of high performing apple orchards of different canopy. Water research commission 1-312.

DZIKITI, S., VOLSCHENK, T., MIDGLEY, S.J.E., LÖTZE, E., TAYLOR, N.J., GUSH, M.B., NTSHIDI, Z., ZIREBWA, S.F., DOKO, Q., SCHMEISSER, M., JARMAIN, C., STEYN, W.J., PIENAAR, H.H., 2018. Estimating the water requirements of high yielding and young apple orchards in the winter rainfall areas of South Africa using a dual source evapotranspiration model. Agricultural Water Management. https://doi.org/10.1016/j.agwat.2018.06.017

ENGELBRECHT, C.J., ENGELBRECHT, F.A., DYSON, L.L., 2013. High-resolution model-projected changes in mid-tropospheric closed-lows and extreme rainfall events over southern Africa. International Journal of Climatology. https://doi.org/10.1002/joc.3420

ENGELBRECHT, F., ADEGOKE, J., BOPAPE, M.J., NAIDOO, M., GARLAND, R., THATCHER, M., MCGREGOR, J., KATZFEY, J., WERNER, M., ICHOKU, C., GATEBE, C., 2015. Projections of rapidly rising surface temperatures over Africa under low mitigation. Environmental Research Letters 10. https://doi.org/10.1088/1748-9326/10/8/085004

ENGELBRECHT, F.A., MCGREGOR, J.L., ENGELBRECHT, C.J., 2009. Dynamics of the conformal-cubic atmospheric model projected climate-change signal over southern Africa, in: International Journal of Climatology. https://doi.org/10.1002/joc.1742

FAO, 2013. Crop Yield Forecasting: Methodological and Institutional Aspects 241.

GOLDBLATT, P., MANNING, J.C., 2002. Plant Diversity of the Cape Region of Southern Africa. Annals of the Missouri Botanical Garden. https://doi.org/10.2307/3298566

GUSH, M., DZIKITI, S., VAN DER LAAN, M., STEYN, M., MANAMATHELA, S., PIENAAR, H., 2019. Field quantification of the water footprint of an apple orchard, and extrapolation to watershed scale within a winter rainfall Mediterranean climate zone. Agricultural and Forest Meteorology. https://doi.org/10.1016/j.agrformet.2019.02.042

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. https://doi.org/10.1016/j.sajb.2010.09.014

HEERDEN, F.R. VAN, WYK, B. VAN, VILJOEN, A.M., 2006. Phenolic variation in wild populations of Aspalathus linearis (rooibos tea) 31, 885-895. https://doi.org/10.1016/S0305-1978(03)00084-X

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, 1315-1337. https://doi.org/10.1002/JOC.1314

HIGGINS, S.I., TURPIE, J.K., COSTANZA, R., COWLING, R.M., LE MAITRE, D.C., MARAIS, C., MIDGLEY, G.F., 1997. An ecological economic simulation model of mountain fynbos ecosystems. Ecological Economics. https://doi.org/10.1016/s0921-8009(97)00575-2

IPCC, 2014. Climate Change 2014 Synthesis Report Summary Chapter for Policymakers. Ipcc. https://doi.org/10.1017/CBO9781107415324

JOUBERT, E., DE BEER, D., MALHERBE, C.J., 2017. Herbal teas – Exploring untapped potential and strengthening commercialisation. South African Journal of Botany. https://doi.org/10.1016/j.sajb.2017.01.204

JOUBERT, E., JOUBERT, M.E., BESTER, C., DE BEER, D., DE LANGE, J.H., 2011. Honeybush (Cyclopia spp.): From local cottage industry to global markets – The catalytic and supporting role of research. South African Journal of Botany 77, 887-907. https://doi.org/10.1016/j.sajb.2011.05.014

JOUBERT, E., SCHULZ, H., 2006. Production and quality aspects of rooibos tea and related products. A review 144, 138-144.

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. https://doi.org/10.5772/53405

KINFE, H.H., LONG, H.S., STANDER, M.A., VAN WYK, B.E., 2015. The major phenolic compound of the roots and leaves of Rafnia amplexicaulis (Fabaceae), a liquorice substitute and traditional tea used in Cape Herbal Medicine. South African Journal of Botany 100, 75-79. https://doi.org/10.1016/j.sajb.2015.05.014

KRUGER, A.C., NXUMALO, M., 2017. Surface temperature trends from homogenized time series in South Africa: 1931-2015. International Journal of Climatology 37, 2364-2377. https://doi.org/10.1002/JOC.4851

KRUGER, A.C., SEKELE, S.S., 2013. Trends in extreme temperature indices in South Africa: 1962-2009. International Journal of Climatology 33, 661-676. https://doi.org/10.1002/JOC.3455

LATEGAN, E.L., HOWELL, C.L., 2016. Deficit irrigation and canopy management practices to improve water use efficiency and profitability of wine grapes. Pretoria.

LÖTTER, D., 2015. Potential implications of climate change for Rooibos (A. linearis) production and distribution in the greater Cederberg region, South Africa. University of Cape Town.

LÖTTER, D., LE MAITRE, D., 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. https://doi.org/10.1002/ece3.985

LOUW, R., 2006. Sustainable harvesting of wild rooibos (Aspalathus linearis) in the. University of Cape Town.

MACALISTER, D., MUASYA, A.M., CRESPO, O., OGOLA, J.B.O., MASEKO, S., VALENTINE, A.J., OTTOSEN, C.O., ROSENQVIST, E., CHIMPHANGO, S.B.M., 2020a. 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

MACALISTER, D., MUASYA, A.M., CRESPO, O., OGOLA, J.B.O., MASEKO, S.T., VALENTINE, A.J., OTTOSEN, C.O., ROSENQVIST, E., CHIMPHANGO, S.B.M., 2020b. Effect of temperature on plant growth and stress tolerant traits in rooibos in the Western Cape, South Africa. Scientia Horticulturae 263. https://doi.org/10.1016/j.scienta.2019.109137

MAJOZI, N.P., MANNAERTS, C.M., RAMOELO, A., MATHIEU, R., MUDAU, A.E., VERHOEF, W., 2017. An intercomparison of satellite-based daily evapotranspiration estimates under different eco-climatic regions in South Africa. Remote Sensing. https://doi.org/10.3390/rs9040307

MALGAS, R., OETTLE, N., 2007. The sustainable harvest of Wild Rooibos.

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 Bokkeveld Plateau. South African Journal of Botany. https://doi.org/10.1016/j.sajb.2009.07.004

MCGREGOR, G.K., 2017. Guidelines for the sustainable harvesting of wild honeybush.

MIDGLEY, G.F., HANNAH, L., MILLAR, D., RUTHERFORD, M.C., POWRIE, L.W., 2002. Assessing the vulnerability of species richness to anthropogenic climate change in a biodiversity hotspot. Global Ecology and Biogeography. https://doi.org/10.1046/j.1466-822X.2002.00307.x

MOOLLA, A., VILJOEN, A.M., 2008. “Buchu” – Agathosma betulina and Agathosma crenulata (Rutaceae): A review. Journal of Ethnopharmacology. https://doi.org/10.1016/j.jep.2008.07.036

MORRISON, M., 2008. Aspects of Honeybush Tea (Cyclopia Species).

MUOFHE, M.L., DAKORA, F.D., 2000. Modification of rhizosphere pH by the symbiotic legume Aspalathus linearis growing in a sandy acidic soil. Australian Journal of Plant Physiology.

MYBURGH, P.A., 2016. Estimating Transpiration of Whole Grapevines under Field Conditions. South African Journal of Enology and Viticulture 37, 47-60. https://doi.org/10.21548/37-1-758

NIEUWOUDT, S.F., 2017. The effect of residue management on the nutrient cycle in the production of rooibos (Aspalathus linearis) at. University of Stellenbosch.

REBELO, T., BOUCHER, C., HELME, N., MUCINA, L., RUTHERFORD, M., SMIT, W., POWRIE, L., ELLIS, F., LAMBRECHTS, J., SCOTT, L., RADLOFF, G., JOHNSON, S., RICHARDSON, D., WARD, D., PROCHES, S., OLIVER, E., MANNING, J., JUERGENS, N., MCDONALD, D., JANSSEN, J., WALTON, B., LEROUX, A., SKOWNO, A., TODD, S., HOARE, D., 2006. Fynbos Biome, in: The Vegetation of South Africa, Lesotho and Swaziland.

RICHARDS, M.B., LAMONT, B.B., 1996. Post-fire mortality and water relations of three congeneric shrub species under extreme water stress – A trade-off with fecundity? Oecologia. https://doi.org/10.1007/BF00582234

ROOIBOS COUNCIL, 2019. Rooibos industry fact sheet: 2019.

ROUAULT, M., RICHARD, Y., 2003. Intensity and spatial extension of drought in South Africa at different time scales. Water SA.

SAKURATANI, T., 1981. A Heat Balance Method for Measuring Water Flux in the Stem of Intact Plants. Journal of Agricultural Meteorology. https://doi.org/10.2480/agrmet.37.9

SANBI, 2020. PlantZAfrica [WWW Document]. http://pza.sanbi.org.

SINGELS, A., ANNANDALE, J.G., JAGER, J.M. DE, SCHULZE, R.E., INMAN-BAMBER, N.G., DURAND, W., RENSBURG, L.D. VAN, HEERDEN, P.S. VAN, CROSBY, C.T., GREEN, G.C., STEYN, J.M., 2010. Modelling crop growth and crop water relations in South Africa: Past achievements and lessons for the future. South African Journal of Plant and Soil 27, 49-65. https://doi.org/10.1080/02571862.2010.10639970

SINGH, P., WANI, S.P., PATHAK, P., SAHRAWAT, K.L., SINGH, A.K., 2011. Increasing crop productivity and water use efficiency in rainfed agriculture. Integrated Watershed Management in Rainfed Agriculture 315-347. https://doi.org/10.1201/b11424-11

SMARTAGRI, 2015. A Status Quo Review of Climate Change and the Agriculture Sector of the Western Cape Province.

SMITH, C.A., 1966. Common Names of South African Plants. Memoirs of the Botanical Survey of South Africa.

SMITH, D.M., ALLEN, S.J., 1996. Measurement of sap flow in plant stems. Journal of Experimental Botany. https://doi.org/10.1093/jxb/47.12.1833

SOIL CLASSIFICATION WORKING GROUP, 1991. Soil classification : a taxonomic system for South Africa, 2nd rev. ed. ed. Dept. of Agricultural Development, Pretoria South Africa.

TAYLOR, N.J., ANNANDALE, J.G., VAHRMEIJER, J.T., GUSH, M.B., 2014. Understanding the dynamics of citrus water use. Acta Horticulturae.

TURPIE, J.K., HEYDENRYCH, B.J., LAMBERTH, S.J., 2003. Economic value of terrestrial and marine biodiversity in the Cape Floristic Region: Implications for defining effective and socially optimal conservation strategies. Biological Conservation. https://doi.org/10.1016/S0006-3207(02)00398-1

VAHRMEIJER, J.T., ANNANDALE, J.G., GUSH, M.B., TAYLOR, N.J., 2015. Citrus water use in South Africa. Acta Horticulturae 1065, 1719-1724. https://doi.org/10.17660/ActaHortic.2015.1065.220

VAN HEERDEN, F.R., VAN WYK, B.E., VILJOEN, A.M., STEENKAMP, P.A., 2003. Phenolic variation in wild populations of Aspalathus linearis (rooibos tea), in: Biochemical Systematics and Ecology. https://doi.org/10.1016/S0305-1978(03)00084-X

VAN HEERDEN, S., 2019. Organic and Mineral Fertilizer Field Trial on Rooibos Tea under Northern Cape Climatic Conditions. University of Stellenbosch.

VAN NIEKERK, A., JARMAIN, C., GOUDRIAAN, R., MULLER, S.J., FERREIRA, F., MÜNCH, Z., PAUW, T., STEPHENSON, G., GIBSON, L., 2018. An earth observation approach towards mapping irrigated areas and quantifying water use by irrigated crops in South Africa. Pretoria.

VAN SCHALKWYK, R., 2018. Soil water balance and root development in Rooibos (Aspalathus linearis) plantations under Clanwilliam field conditions. University of Stellenbosch.

VAN WYK, B.E., 2011a. The potential of South African plants in the development of new food and beverage products. South African Journal of Botany. https://doi.org/10.1016/j.sajb.2011.08.003

VAN WYK, B.E., 2011b. The potential of South African plants in the development of new medicinal products. South African Journal of Botany. https://doi.org/10.1016/j.sajb.2011.08.011

VAN WYK, B.E., 2008. A broad review of commercially important southern African medicinal plants. Journal of Ethnopharmacology. https://doi.org/10.1016/j.jep.2008.05.029

VAN WYK, B.E., GORELIK, B., 2017. The history and ethnobotany of Cape herbal teas. South African Journal of Botany. https://doi.org/10.1016/j.sajb.2016.11.011

VAN WYK, B.E., GORELIK, B., 2017. The history and ethnobotany of Cape herbal teas. South African Journal of Botany 110, 18-38. https://doi.org/10.1016/j.sajb.2016.11.011

VILJOEN, A., 2010. South Africa’s medicinal flora – abundant opportunities and daunting challenges. Planta Medica. https://doi.org/10.1055/s-0030-1264200

ANNEXURE A

CAPACITY BUILDING

Capacity building on this project was achieved in the form of students training, staff community and institutional development. These will be detailed below.

1 Staff development

This research project contributed significantly towards broadening the research staff's skills. As a climate change scientist being primarily involved in crop modelling, Dr Daleen Lötter gathered valuable experience in applying micro-meteorological methods to quantify water use in crops. This will enable her to use similar methods in future projects and broaden her scope of study.

Dr. Sebinasi Dzikiti is an agrometeorological scientist with skills in applying micrometeorological methods to quantify water use in irrigated crops, especially deciduous crops. In this study, however, it was the first time he was involved in rainfed crops that resemble fynbos shrubs. This gave him valuable insight into the indigenous tea industry and would support his work in similar future projects. He also had the chance to work with climate simulations and using those projections to model future water use, which allowed him to better understand climate change data.

Mr. Sarel Haasbroek is a senior electrical engineer in the Smart Mobility cluster at the CSIR. Sarel specializes in technical aspects of meteorological equipment and data loggers. He was included on the project to help with the practical aspects of setting up the equipment in Clanwilliam. By involving him on this project he gained significant experience in micro-meteorological methods, outside his field of expertise and he will be able to assist in future similar projects.

2 Community development

During this project the project team had several informal engagements with rooibos farmers, discussing the project and giving feedback to the industry. By involving the farmers in the project, they gained valuable insight into monitoring rooibos fields and understanding the drivers of water use. Conversely, the project team also learned a lot from the farmers and established important connections for future work.

3 Institutional development

The CSIR team had informal discussions and feedback on the research at a meeting in Clanwilliam which was attended by representatives of the Rooibos Council. It was decided that the results of the study will be presented at the Rooibos Information Day, held by the Rooibos Council in October 2021. However, this meeting was postponed by the Council and will now take place in April 2022.

4 Students on course for graduation

Ms. Wasanga Mkhanzi

The 1st MSc candidate is Ms. Wasanga Mkhanzi and is registered in the MSc program with the Institute for Water Studies, Department of Environmental and Water Science at the University of the Western Cape. She is being supervised by Prof. D Mazvimavi and the title of her thesis is:

"Investigating the influence of meteorological factors on the water-use patterns of rooibos tea crops in the Western Cape Province of South Africa" She mainly focuses on studying the water-use patterns of the rooibos crops in the area of Porterville in the Western Cape Province under present day growing conditions. Wasanga enrolled for her MSc study in 2019 and the expected completion date was December 2020. However, due to Covid restrictions she had to spent significant time away from the university during the lockdown period. According to her main supervisor she has produced a Draft Thesis which was reviewed, and comments were provided end of 2021. Her supervisor at UWC suggested that she includes a brief analysis of how climate change may impact on the rooibos production region, including the severity of this impact at selected locations. Wasanga will have to register again in 2022 in order to submit her revised thesis and be able to graduate.

The following tasks has been completed:

- Registering of thesis title
- Installation of equipment to conduct study
- Proposal complete
- Literature review complete
- Study area complete
- Methodology complete
- Data collection complete
- Analysis of data complete

- Results, discussion, conclusion complete
- First draft of full thesis complete

Ms. Elbe Du Toit

Ms. Elbe du Toit is the other MSc candidate and she is enrolled at the University of Stellenbosch, in the Botany Department. As part of the additional student support funding provided by the WRC, she was awarded funding to the amount of R120 000 over two years. The title of her research proposal is "Seasonal resilience of rooibos soil-root nutrition during natural drought conditions" and the supervisors will be Prof. Alexander Valentine (US), Dr. Aleysia Kleinert (ARC/ US) and Dr. Daleen Lotter (CSIR). Her research will look at how the increase in dry spells during climate change will cause a restriction in the N and P soil access in rooibos plants in their natural habitats. This project will investigate N and P acquisition and metabolism in rooibos plants under conditions from dry to wet seasons. The study will employ methods of field ecophysiology, soil biology and biochemistry and laboratory-based assays. Her study area coincides with our existing field site on the project.

The rooibos project is almost completed. All her lab work is completed, which consists of 8 different assays: GDH-A, GDH-D, GS, NR, Phytase, RNAse, Pi and APase. These assays have been conducted on all plant samples collected for summer and plant and soil samples collected for winter. All soil microbial community tests have also been completed (as presented last year at the progress report). These results have also been statistically analysed with interesting significant differences and trends throughout summer and winter and changes in the plants P and N acquisition and recycling in different organs for the two seasons. All of the lab work has been sent away, which includes soil samples and amino acid metabolite analysis. The soil sample data has come back and has been analysed and there is a clear difference between the two soils, especially in composition (clay, silt and sand percentages), organic matter content and also water holding capacity.

She is currently waiting for the results of the amino acid metabolite analysis, which will specifically indicate amino acids that are linked to drought conditions such as proline which will give us an indication of the drought stresses taking place during the different seasons and if the soil influence these.

Other than that, she is currently in the process of writing up all the results and putting together a first draft for her thesis. All of the statistical analysis for the results already received has been completed and graphs and tables have already been made, all that is currently necessary in the writing of the thesis.

ANNEXURE B

KNOWLEDGE DISSEMINATION & TECHNOLOGY TRANSFER

1 Scientific articles

D Lotter, S Dzikiti, W Mkhanzi. 2020 Water use and productivity of rain-fed rooibos tea (*Aspalathus Linearis*) under semi-arid Mediterranean conditions. Paper submitted to the SA Journal of Botany, 2020.

S. Dzikiti*, D Lotter, S Mpandeli, L Nhamo. 2022. Assessing the energy and water balance dynamics of rain-fed rooibos tea crops (*Aspalathus linearis*) under changing Mediterranean climatic conditions. Paper under review by the Agricultural Water Management journal.

2 Popular articles

Rooibos fact sheet series: a series of short communications on climate change and rooibos for the rooibos industry. In progress

3 Selected presentations

Warmer and drier – what are the implications for Rooibos water use? Presentation to the Rooibos industry and information day.

4 Technology transfer to industry

4.1 ArcGIS story maps

ArcGIS story maps, use Geographic Information System (GIS) tools to combine geospatial data with photos, video, audio, and text to visualize a theme or sequential events. Story maps are designed for nontechnical audiences with access to the Internet; users do not need experience with GIS software to read or use story maps.

In this project we created a customised story map of the research project for use by the rooibos community (Rooibos industry, rooibos producers and other stakeholders). The website is still under development and will be shared with stakeholders once it is approved.

The system that we use is an online cloud-based mapping platform using the latest geospatial server technology at the backend. This technology forms the backbone of the CSIR’s Geospatial Data Infrastructure and is supporting most research initiatives that relies on disseminating data of a spatial nature. It has proven to be a reliable and effective way to communicate and disseminate research output and geospatial data.

5 Other activities

The CSIR team had informal discussions and feedback on the research at a meeting in Clanwilliam which was attended by representatives of the Rooibos Council. It was decided that the results of the study will be presented at the Rooibos Information Day, held by the Rooibos Council in October 2021. However, this meeting was postponed by the Council took place on 4 May, 2022 on the Bo-Bergvlei farm in the areas of Citrusdal.