Relationship between *Aspalathus linearis* (Burm. F.) R. Dahlgren (rooibos) growth and soil moisture in a glasshouse and in the DSSAT-CSM crop model

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DECLARATION

I know the meaning of plagiarism and declare that all the work in the dissertation, save that which is properly acknowledged, is my own.

Signed by candidate

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ABSTRACT

Climate change and drought pose a major threat to agriculture and water resources globally and for rooibos (*Aspalathus linearis* (Burm. F.) R. Dahlgren) production in the Western Cape province of South Africa. Rooibos is adapted to the coarse, nutrient poor, acidic, well-drained, deep sandy soil of the Fynbos biome. The region has a Mediterranean climate, which is characterised by wet cold winters, with an average annual rainfall of about 375 mm, and dry summers. The growth of rooibos peaks in the summer months, implying a reliance on soil moisture. The current study aims to investigate the relationship between rooibos growth and soil moisture. The objectives of the study were: 1) to determine the effect of soil moisture on growth and evapotranspiration in rooibos under glasshouse conditions, 2) to adapt the CROPGRO model in DSSAT to simulate the shoot biomass yield of rooibos, using the rooibos CROPGRO model, 3) to investigate the effect of rooibos growth on soil moisture, and 4) to determine the effect of different levels of mulching and irrigation on rooibos yield and soil moisture. Some of the results obtained in the glasshouse study in Objective 1 and observational field data from the literature were used in the adaptation of the CROPGRO model.

The glasshouse study was carried out at the University of Cape Town, using soils from Clanwilliam and Citrusdal sites to grow rooibos seedling for 16 weeks in pots before exposing them to drought treatments. The pots were arranged on trays in the glasshouse using a completely randomized design. Two drought treatments were used: moderate drought stress (MDS), set at 20% FC, and severe drought stress (SDS), during which watering was completely withdrawn, were applied to 10 pots per treatment per site. Data on plant growth, root morphology, evapotranspiration, soil moisture, chlorophyll fluorescence and leaves to determine chlorophyll and carotenoid concentration were collected from the plants in the

glasshouse after 10 days of these drought treatments. The SDS plants were re-watered for 8 weeks for recovery, and together with the MDS and control plants were transferred into a growth chamber for measurement of gas exchange parameters and biomass. The CROPGRO model in DSSAT was adapted for rooibos by changing some parameters in a pigeon pea (*Cajanus cajan* L. Millspaugh) CROPGRO model. The adapted rooibos model was used to set up an experiment that compared the cumulative evapotranspiration and soil moisture from the rooibos field and bare soil under rainfed conditions. Also, in a simulation experiments, the model was used to determine the effect of three levels of mulching by means of wheat residue at 8000 kg/ha, 4000 kg/ ha and 2000 kg/ha and drip irrigation at 25.4mm and at 12.5mm once a week from December to March, both separately and in combination, on rooibos shoot biomass and soil moisture.

The results from the glasshouse study showed a 40% decrease in biomass under MDS conditions for 12 weeks, while SDS plants could not survive beyond 10 days in the glasshouse. Root morphological features changed under severe drought stress, resulting in longer and thinner roots relative to the control plants. The reduced biomass accumulation under drought conditions was followed by reduced photosynthesis, stomata conductance, transpiration, and concentration of chlorophyll and carotenoids. Changes in both maximum quantum efficiency of photosystem II (*Fv/Fm*) and fluorescence quantum yield (*Fq'/Fm'*) were observed in the later stages of the SDS plants (days 9 and 10) compared to the control plants but were unaltered in the MDS plants. The soil moisture correlated negatively with evapotranspiration and stomata conductance in control plants, while these relationships were absent in MDS plants. Changes in temperature in the glasshouse correlated positively with stomata conductance and transpiration in the control plants, but these correlations were also absent in MDS plants. However, changes in temperature correlated negatively with soil moisture in both the control plants and the MDS treated plants.

The CROPGRO model in DSSAT was successfully adapted to simulate shoot biomass in rooibos under field conditions and the rooibos model had an agreement of 94% with observational shoot biomass under field conditions. Furthermore, the model simulated cumulative evapotranspiration in rooibos plants in the field, with an agreement of 56%. The simulated experiments showed that cumulative evapotranspiration from the rooibos field was 33% higher than that of bare soil, and showed that rooibos plants extract moisture from deep soil layers to a depth of about 2 m. Furthermore, rooibos growth in deep soil, and in mulched or irrigated treatments, produced higher shoot biomass than control plants. In deep soil, the simulated irrigated rooibos plants, which received 25.4 mm water weekly from December to March, produced a higher biomass yield than only rainfed or mulched plants. However, the combined treatments of mulching at 8000 or 4000 kg/ha and irrigation at 12.5 mm was similar to irrigation at 25.4mm. The average extractable soil moisture was greater in deep soil for all the treatments and control plants compared to shallow soil.

Overall, the rooibos crop model shows that an increased supply of soil moisture enhances the production of biomass yield in rooibos in the field. Also, rooibos extracts moisture from a deeper soil layer, which enables it to hydrate its leaves and to transpire during the summer period for better growth and biomass production. Water loss through evapotranspiration was high in rooibos fields, and thus mulching of the plants would be beneficial for increased biomass production. However, even better rooibos yields were obtained when mulching was combined with irrigation. The glasshouse experiments showed a yield decrease of rooibos biomass by about 40% when the moisture supply was reduced by about 50% of the adequate conditions. The thinner and longer roots of rooibos, among other drought tolerance traits, most likely enable it to cope with low rainfall and drought conditions, which are prevalent in the Cederberg region of the Western Cape. The production of rooibos in the farms is prone to water

loss through evapotranspiration, and thus soil moisture conservation technologies such as mulching would greatly enhance its biomass yield.

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DEDICATION

To the Almighty GOD (the Alpha and Omega)

To the Holy Spirit, my teacher and comforter through this journey

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LIST OF ACRONYMS

ARCISCW	Agricultural Research Council's Institute for Soil, Climate and Water
B (element)	Boron
C (element)	Carbon
Ca (element)	Calcium
Ci	Intracellular concentration of carbon dioxide
Cu	Copper
CCR	Core Cape Subregion
CFR	Cape Floristic Region
DAFF	Department of Agriculture, Forestry and Fisheries
DEA	Department of Environmental Affairs
DS	Deep soil
DSSAT-CSM	Decision Support System for Agrotechnology Transfer Cropping System Model
DWS	Department of Water and Sanitation
EM-FL	Emergence and flowering
ET	Evapotranspiration
FC	Field capacity
HSD	Honest significant difference
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
MDS	Moderate drought stress
Mn (element)	Manganese

Na (element)	Sodium
P (element)	Phosphorus
PPFD	Photosynthetic photon flux density
PSII	Photosystem II
PWUE	Photosynthetic water use efficiency
RRMSE	Relative root mean square error
RWC	Relative water content
SDS	Severe drought stress
SM	Soil moisture
SML	Soil moisture layer
SPAC	Soil Plant Atmosphere Continuum
SPEI	Standard Precipitation Evapotranspiration Index
SPI	Standard Precipitation Index
SS	Shallow soil
SWC	Soil water content
USA	United States of America
Vpdl	Vapour pressure deficit based on leaf temperature
Zn (element)	Zinc

CHAPTER ONE

General Introduction

1.1 Background of study

Aspalathus linearis (Burm. F.) R. Dahlgren (rooibos), which was initially and traditionally collected as a wild plant by the Khoisan tribe, is now commercially cultivated in the Western Cape. The plant is used to make a mild-tasting tea that contains no caffeine, very little tannin and large amounts of polyphenol antioxidants – all attributes that are associated with important health benefits and medicinal value (Van Heerden et al., 2003; Joubert and de Beer, 2011). Also, the rooibos plant is the only source of Aspalathin, which is an antioxidant that assists in the fight against cancer (Joubert and Schulz, 2006). As a result of all these health benefits, the demand for rooibos has increased both locally and internationally (SARC, 2016). This has led to the development of an industry that provides both an income and employment for many people. Hence, it also contributes significantly to the prosperity and wellbeing of local communities and the economy of the Western Cape more generally (Van der Bank, 1995; Hawkins et al., 2011).

The Western Cape, which is one of the main parts of the Core Cape Subregion (CCR), contributes significantly to agriculture, economy and biodiversity of South Africa (Manning and Goldblatt, 2012; Western Cape Government, 2014; Zwane, 2019). This is largely because of its unique Mediterranean climate (Hoffman and Harrrison, 2018), which allows crops that cannot be planted in the subtropical, temperate or arid climates of other regions of South Africa to be planted in the Western Cape. As a result, the Western Cape is the largest producer of crops, such as oats, barley, grapes, apples and other deciduous fruits in South Africa (Department of Agriculture, Forestry and Fisheries [DAFF], 2017). Presently, the Western Cape also generates and contributes the largest amount of income from commercial farming,

like the production of grapes, wine and dry fruits than other provinces in South Africa (Census of Commercial Agriculture, 2017). Apart from its agricultural significance, the Western Cape is home to the biodiversity hotspot of the CCR, which is characterised by particularly high plant diversity, density and endemism (Manning and Goldblatt, 2012).

The Western Cape region is predominantly a semi-arid region (Cowling et al., 1996; Malgas et al., 2010). The climate of the region is Mediterranean, and thus characterised wet cold winters and dry summers. It receives an average annual rainfall of about 375 mm that is below the national average (Lötter and Le Maitre, 2014). Rain falls mostly during the winter months of May to August, with average maximum temperatures ranging from 15 to 32°C (Rundel and Cowling, 2013; Lötter and Le Maitre, 2014). Due to the semi-arid nature of this region, water is an important resource, and can be scarce at times, especially in years when the annual rainfall is below average.

In addition to the fact that the Western Cape is a semi-arid region, drought and climate change also pose a major threat to water resources for agricultural, industrial, economic, household and domestic uses. A lack of precipitation over a region for a period of time (which is referred to as a meteorological drought) can lead to a reduction in available water resources from both surface and sub-surface reservoirs and dams (referred to as a hydrological drought), which severely affects not only the agricultural sector (crop and animal production), but also socio-economic activities (industrial and economic activities) (Wilhite, 2000; Mishra and Singh, 2010; WMO and GWP 2016). Furthermore, Midgley et al. (2005) estimated that the CCR would experience a species loss of 20 to 40% under the climate change. Overall, climate change and drought will affect the economy and agricultural production in the Western Cape.

1.2 Background of rooibos

This section covers the ecology and distribution of rooibos, its cultivation and production, and also describes the soil conditions in which rooibos grows.

1.2.1 Ecology and distribution of rooibos

Rooibos is a shrub that belongs to the Fabaceae family (Dahlgren, 1968), and is also one of the 800 species in the *Aspalathus* genus, which is the second largest genus of vascular plant in the CCR in South Africa (Manning and Goldblatt, 2012). It is endemic to this region, whose major biome is the Fynbos biome, which has a particularly high species density. Van Heerden et al. (2003) identified seven ecotypes of rooibos that differ in morphology, flavonoids and tea type. These ecotypes are genetically different and also differ in terms of their fire survival strategies, their vegetative and reproductive morphology and their chemistry (Van der Bank et al., 1995; Malgas et al., 2010; Hawkins et al., 2011). Among the ecotypes, some are reseeders while others are resprouters (Van der Bank et al., 1995, Van der Bank et al., 1999). The fynbos biome experiences fire from time to time, and fire is a trigger mechanism that activates growth for both types of life histories, i.e., seeders and sprouters (Brown et al., 1993). After fire incidents, the sprouters are able to regenerate thanks to soil-stored tubers called subterranean lignotubers, while reseeders grow back from the seeds stored in the soil (Van der Bank et al., 1999). In the fynbos biome, the seeders plant species dominate (Le Maitre and Midgley, 1992) in the early succession after fire, followed by the resprouters (Ojeda, 1998; Cowling et al., 2005; Ojeda et al., 2005).

Rooibos occurs naturally in the Cederberg Mountains of the Western Cape, as well as in the Northern Cape Province of South Africa (Morton, 1983; Joubert et al., 2008). Wild populations of rooibos have a narrow geographic range within the fynbos biome and are largely confined to the mountain ranges of the far southwestern part of the Northern Cape Province and the

Cederberg Mountains of the Western Cape (Lötter and Le Maitre, 2014). The 'Nortier' form of rooibos that is used for cultivation is a reseeder that produces large quantities of seeds (Morton, 1983). The cultivated areas of rooibos have now spread to the low-lying areas of the Western and Northern Cape due its commercial and medicinal importance (Lötter and le Maitre, 2014; Fig. 1.1.).

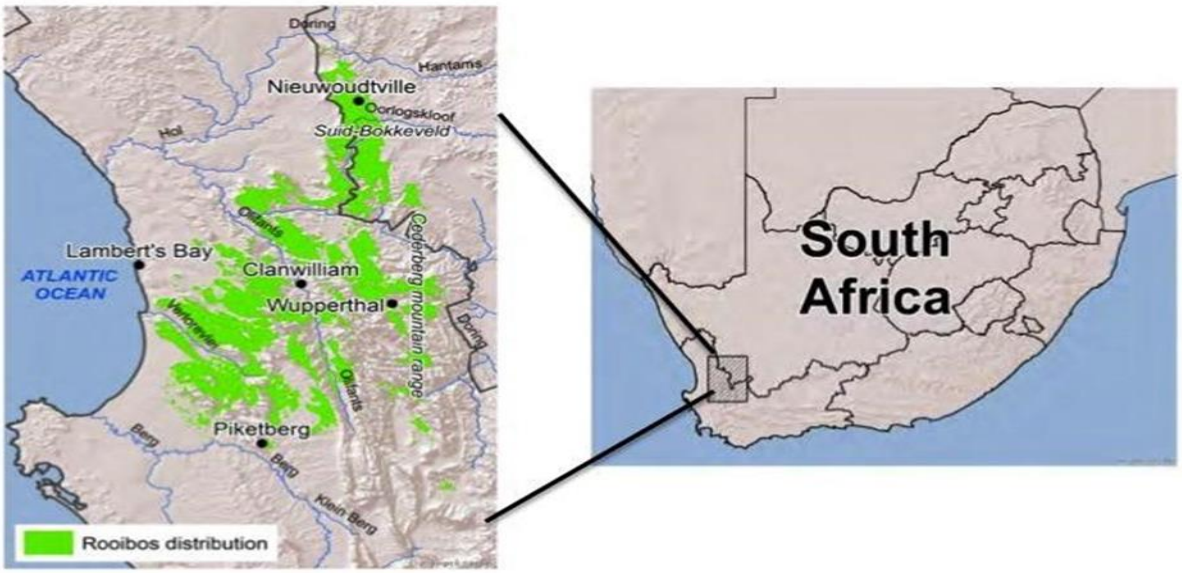


Fig. 1.1: Map showing the distribution of rooibos tea production in the northwestern part of the Western Cape (Lötter, 2015).

1.2.2 Cultivation and production of rooibos

The 'Nortier' form of rooibos, a reseeder, is commonly planted commercially due to its growth form and plentiful seed production (Morton, 1983). The hard-shelled seeds that are dispersed by ants are collected and scarified by acid or smoke-treated to break the seed dormancy (Morton, 1983). The scarified seeds are then planted in well-prepared seed beds in a nursery between February and March. The seedlings are watered, and allowed to grow to a height of 10 to 20 cm, before they are transplanted to the field by June, after the start of the winter rains. They are planted in rows, 1 m apart, and the spacing between the plants in each row may vary between farmers (Chimphango et al., 2016). Rooibos is grown without either fertilisation or

irrigation, and the plant has a lifespan of 6 to 7 years (Morton, 1983). The shrub is harvested annually from the second year during summer, and the maximum growth phase starts from the third year (Cheney and Scholtz, 1963). Rooibos is currently cultivated on about 95,000 ha by approximately 580 farmers, contributing about 99.5 % of its total production in the country (SARC, 2016).

1.2.3 Soil conditions in which rooibos grows best

Rooibos is adapted to the coarse, nutrient poor, acidic, well-drained, deep sandy soil of the Fynbos biome of the Western and Northern Cape, South Africa (Maistry et al., 2013; Muofhe and Dakora, 2000). The infertile soil in the fynbos biome has low levels of nitrogen (N), phosphorus (P) and calcium (Ca) and organic matter (Muofhe and Dakora, 2000). Rooibos can survive in low acidity, ranging from a pH of 3 to 5.5, and it obtains most of its nitrogen through symbiotic relationship with rhizobia bacteria (Hassen et al., 2012). It is reported that this association fixes atmospheric nitrogen (N) of c. 105-128 kg N ha-1 (Muofhe and Dakora, 1999). Also, rooibos roots have cluster roots (Hawkins et al., 2011; Maistry et al., 2013) and are colonised by mycorrhiza (Lambers et al., 2006), both of which are specialised mechanisms that assist phosphorus and nutrient acquisition.

1.3 Climate change projections and drought characteristics over the Western Cape

The Western Cape Province in South Africa has been identified as being particularly threatened by climate change (Intergovernmental Panel on Climate Change [IPCC], 2014). This region falls under the Mediterranean climate, which is projected to experience a reduction in winter rainfall and an increase in summer temperatures (Engelbrecht et al., 2008, IPCC, 2014; Naik and Abiodun 2020). The increase in temperature will increase the evaporative demand for moisture (Condon et al., 2020). This implies that the soil moisture, which has already been

reduced by the decrease in rainfall, will also increasingly be lost to the atmosphere through evapotranspiration.

Historical analysis from previous studies shows a significant increase in the temperature and in changes in the rainfall amount throughout the Western Cape. According to Midgley et al. (2005), an analysis of the air temperature from 1967 to 2000 shows a significant warming increase in the maximum temperature by 1°C from December to February (summer) and by 1 to 2°C from May to October. With regard to the minimum temperature, this has increased by 0.5 to 1.5°C in all the months, except June (Midgley et al., 2005). In addition, a historical analysis of rainfall by Hewitson et al. (2005) shows little or no change in rainfall over the mountainous areas, though a decrease in winter rainfall in the lowland areas of the Western Cape. Furthermore, droughts have become more intense in recent years (Ncube and Shikwambana, 2016). According to Botai et al. (2017), the Western Cape Province has experienced approximately 4% absolute changes in drought intensity over the last three decades.

Recently, the Western Cape region received below average rainfall for three consecutive years, i.e., from 2015 to 2017, which reduced water levels in the dams to such an extent that the City of Cape Town's water supply almost ran out in March 2018 (Otto et al., 2018; Wolski, 2018). In studying the characteristics of the drought, Botai et al. (2017) used the Standard Precipitation Index (SPI) accumulated over 3, 6 and 12 months, and showed that the 2015-2017 hydrological drought was a manifestation of past drought years. Furthermore, a recent study by Naik and Abiodun (2020) that investigated the drought characteristics over the Western Cape using the Standard Precipitation Evapotranspiration Index (SPEI) indicated that drought events will increase in the Western Cape, but that the drying patterns will not be homogenous across the entire region.

1.4 Soil moisture, evapotranspiration and crop growth relationship

Soil moisture, which is the amount of water held in the spaces between the soil particles that is available to plant roots, is particularly crucial in a semi-arid region for plant growth. This is because soil moisture is part of the Soil Plant Atmosphere Continuum (SPAC), it therefore plays a crucial role in the interphase that controls the exchange of water and heat energy between the land surface and the atmosphere (Zhu and Shao, 2008; Duniway et al., 2010). Soil moisture through the process of evapotranspiration provides part of the water used for cloud formation, and this is important for precipitation over land (Ek and Holtslag, 2004). Furthermore, through run-off and infiltration soil moisture controls the availability of water for plants and this is very crucial to plant growth (Hupet and Vanclooster, 2002; Fu at al., 2003).

Some of the factors that can affect the amount of moisture held in the soil include the soil properties (Famiglietti et al, 1998; Cantón et al., 2004), the type of crops and vegetation cover (Coenders-Gerrits et al., 2013; Liang et al., 2014), topography (Nyberg, 1996; Wilson et al., 2004), soil depth (Hopp and McDonnell, 2009), precipitation (Rosenbaum et al., 2012) and other meteorological conditions, such as solar radiation, temperature, wind speed and relative humidity (Lakshmi et al., 2003).

Evapotranspiration is the process through which moisture is lost to the atmosphere from soil, plants and other surfaces. It consists of evaporation from water bodies and from the soil, as well as transpiration from plants, in which water is conducted from the roots to the stomata. In order for evapotranspiration to occur, energy is needed; therefore, climate conditions, such as solar radiation, temperature, wind speed and relative humidity, determine the potential evapotranspiration. Furthermore, evapotranspiration plays a major role in determining the potential yield of crops (Bhatt and Hossain, 2019). Therefore, assessing evapotranspiration

rates is important for establishing the sustainability and survival of rooibos under changing climate conditions.

Factors that determine the potential evapotranspiration rate and how it translates into actual evapotranspiration include availability of soil moisture, soil type and type of crop and vegetation. According to Famiglietti et al. (1998), the type of soil texture and structure, and the amount of organic matter and nutrients in the soil all play a key role in determining the infiltration and retention of moisture in the soil. Soil texture is a major influence on the ability of the soil to retain moisture, as finely bonded soil particles will retain more moisture than loose soil particles (Brady et al., 2008). In the Western Cape, the main type of soil is sandy: although this allows deep penetration of moisture, its water holding capacity is low (Van Schalkwyk, 2018). Also, plant height, canopy, root depth and physiology can all determine the amount of water that will be loss through transpiration (Allen et al., 1998; Allen et al., 2011). For instance, a crop like pineapple, which closes its stomata during the day, will have less loss of moisture (Allen et al., 1998; Allen et al., 2011). Stomatal response to the environment, number of stomata present on the leaf and leaf area index differ from plant to plant (Allen et al., 1998; Allen et al., 2011). Therefore, understanding the relationship between soil moisture, evapotranspiration and rooibos growth is essential for improving the survival of rooibos in a changing climate, and for the development of soil moisture conservation strategies in the Western Cape which will presumably be of benefit for other agricultural crops.

According to Bhatt and Hossain (2019), assessing the relationship between soil moisture and evapotranspiration is important for determining adaptive strategies under changing climates in arid regions. López-Urrea et al. (2020) found a linear relationship between crop transpiration and ground cover values for canola in the United States of America (USA), by analysing evapotranspiration in canola fields for two years. This relationship was to be used to determine soil water requirements of canola for proper water management. Similarly, Zhou et al. (2020)

analysed the connection between hydrological cycles and crop yields for soybean and corn production under rainfed condition in the USA with the use of observations and model simulations from 2003 to 2014. This study found that both water demand from the atmosphere and soil water storage play an important role in quantifying the loss of yield under drought conditions. With regard to rooibos, however, little is known about the relationship between soil moisture, evapotranspiration and rooibos growth under either adequate conditions or drought conditions. Consequently, understanding the relationship between soil moisture and rooibos growth is essential for determining adaptation strategies for sustainable rooibos production in response to the changing climate.

1.5 Mitigation and adaptation strategies for drought in the Western Cape

Mitigation and adaptation are two major strategies for managing the negative impact of climate change. Mitigation is defined as "*anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases*", while adaptation is the "*adjustment in natural or human systems in response to actual or expected climate and its effects*" (IPCC, 2014). Furthermore, mitigation is any activity that can reduce or prevent the causes of climate change, while adaptation focuses on strategies that help local communities to deal with or adjust to the impact of climate change. According to Klein et al. (2005), mitigation and adaptation can be integrated to reduce the impact or magnitude of climate change and to aid in improving conservation, managing resources and tackling desertification.

Several adaptation strategies have been suggested globally in dryland cropping system and some have already been implemented in reducing the impact of droughts in the Western Cape (Ncube and Shikwambana, 2016). These include the early detection and monitoring of drought, the removal of invasive alien plants, the rehabilitation of wetlands, the creation of improved storage capacities and the management of water resources, coupled with the use of drought

resilient seed varieties, zero tillage, multi-cropping systems, crop rotation, mulching, root zone irrigation, rainwater harvesting and water storage (Department of Water and Sanitation [DWS] and Department of Environmental Affairs [DEA] Update, 2018; Ncube and Shikwambana, 2016). However, some of the recommended adaptation strategies still need to be tested experimentally to assess their effectiveness.

Agriculture uses about 43% available water for irrigation in the Western Cape (WWF Agricultural Water File, 2018; Zwane, 2019). This is due to commercial agriculture being very dependent on irrigation, because of the dry summers experienced in the Western Cape, when the temperature is mostly suitable for plant growth. As already shown by the years of drought and the increase in summer temperatures as a result of climate change, it is certain that warming temperatures will increase the evaporative demand for moisture (Condon et al., 2020). Similarly, research done by Chowdhury et al. (2016) and Ye et al. (2015) show that crop water requirements will increase in response to climate change as a result of increases in summer temperatures. This means that the amount of water used for irrigation to ensure a particular level of yield will also increase.

Combining drip irrigation with mulching, in response to water shortages and high evaporation rates, is a technique used in the semiarid regions of China (Liu et al., 2017; Qin et al., 2016; Tian et al., 2017). Drip irrigation is a type of low-volume irrigation system that helps to reduce water loss, as water flowing through pipes drips slowly into the root zone of nearby plants (Cerny et al., 2002). Also, mulching is the use of organic material, such as plant and animal waste, tree bark and sawdust, or inorganic material, such as plastic sheeting and landscape fabric, to cover soil surfaces (Jacks et al., 1955; Mulumba and Lal, 2008). One of the main benefits of mulching is the conservation of soil moisture and the regulation of soil temperature, which could be useful in limiting the loss of water from the soil surface (Mulumba and Lal,

2008), especially in sandy soil, where large fluctuations of soil temperature and moisture often occur.

1.6 Crop models

Crop models, which were developed initially to enable farmers better to predict harvests, are now important tools for agronomic and physiological research (Jones et al., 2003). Crop models are computer programs or sets of mathematical equations that have been developed to imitate the growth and development of a particular crop (Asseng et al., 2014). Over the years, the physiology and growth of plants and their interactions with their environment have been studied extensively, and equations have been developed to predict the growth of a plant and its components, such as leaf, stem and root biomass and grain yield. One of the major uses of such crop models in research is testing the impact and performance of a crop under different climatic scenarios (Bacsi et al., 1991; Subash and Mohan, 2012). Most crop models have soil water balance modules that can help to determine water uptake and evapotranspiration and to calculate how much water is in the soil profile (Boote, 2019). Due to climate variability and climate change, most research in crop science now focuses on how crops will cope under different climate scenarios, and what can be done to help increase crop production (Chloupek et al. 2004; Sultana et al., 2009; Li et al., 2017). Different water management levels, such as irrigation and mulching, are now simulated by crop models to see their potential impact on crop production (Andrade et al., 2005; Sarkar and Kar, 2006). In addition, crop models are useful tools for predicting yield; they can also be combined with economic models, to see the impacts of a crop on the economy of a country or region (Chen and Miranda, 2008; Piewthongngam et al., 2009). Hence crop models are useful in research, policy formation and decision making (Boote et al., 1996; Jones et al., 2003; Piewthongngam et al., 2009; Zamora et al., 2009).

There are different types of crop models however, the two widely used group of models are the statistical and dynamic system simulation models (Jones et al., 2017). Statistical models are empirical and regression models that were developed from historical data sets on system response example include the effect of fertilizer on crop yields (Oteng-Darko et al., 2013; Jones et al., 2017). While statistical model can be useful especially with good set of historical data however, it does not give information on the mechanism that gives the response (Jones et al., 2017). Also, statistical model performs poorly in estimating future climate impacts because they can not represent unobserved changes that are beyond the range of historical data (Oteng-Darko et al., 2013; Jones et al., 2017). The dynamic simulation models have functions that describes changes that occur in a system (Oteng-Darko et al., 2013; Jones et al., 2017). The dynamic simulation models may comprise of mechanistic and functional models (Jones et al., 2017). The mechanistic models are process based models that mimics important physical, chemical, and biological processes and they describe why and how a particular change or response occur (Oteng-Darko et al., 2013; Jones et al., 2017). Examples of dynamic simulation model includes EPIC (Williams et al., 1983, 1989), CRPSYST (Stöckle et al., 2003), DSSAT (Jones et al., 2003; Boote, 2019) and APSIM (Keating et al., 2003). However, some of the dynamic simulating models are complex and they will need more descriptive parameters (Jones et al., 2017).

Among the current group of dynamic simulation crop models, Decision Support System for Agrotechnology Transfer Cropping System Model (DSSAT-CSM) was chosen for this study because of the following reasons. Firstly, it can be easily adapted for new crop without changing its source code (Boote, 2019). There are files that are understandable and can be accessed in windows without changing the source code (Boote, 2019). Secondly, DSSAT-CSM, which is used globally, has been tested and validated in Southern Africa (Ngwira et al., 2014; Nyagumbo et al., 2016; Zinyengere et al., 2015; Nyagumbo et al., 2017). For instance,

Zinyengere et al. (2015) tested the usefulness of crop models under data limited dryland conditions of Southern Africa; based on this research, the performance of DSSAT-CSM was deemed satisfactory under these conditions. Also, DSSAT-CSM has been used by several researchers in Southern Africa (Ngwira et al., 2014; Nyagumbo et al., 2016; Nyagumbo et al., 2017). Ngwira et al. (2014) used DSSAT-CSM to project the weather effect of climate change on maize yields in Malawi, within a conservation agriculture and conventional tillage system; this study found DSSAT-CM to be useful in making decisions about conservation agriculture practices.

DSSAT-CSM is a process-based model that is being improved regularly to become more precise in simulating the growth and development of plants based on information about the weather, crop or cultivar traits and soil (Jones et al., 2003). DSSAT-CSM provides an integrated modelling platform that combines different models, tools and utilities. The DSSAT-CSM combines the CERES model for maize (Jones et al., 2003), the CANEGRO model for sugar cane (Singels et al., 2008), the CROPGRO model for grains, legumes and forages (Rymph, 2004), SUBSTOR for root and tuber crops and ALOHA for pineapples (Zhang et al., 1995). In addition, the DSSAT-CSM model has incorporated a subroutine to calculate the soil water balance on a daily basis (Boote, 2019). The soil water balance in the model is calculated by adding rainfall and irrigation amounts, and subtracting runoff, drainage, soil evaporation and plant transpiration daily (Boote, 2019). Presently, there is no crop model designed specifically for rooibos, and therefore adapting the CROPGRO model in DSSAT-CSM for rooibos will be useful for research and yield prediction with regard to rooibos.

1.7 Sustainability of rooibos production

In recent years, due to the health benefits of rooibos, there has been a growing demand for rooibos products. To meet this growing demand, production has to be increased. Since rooibos

does not grow outside the CCR, either the farms need to be expanded or the areas already under cultivation need to be managed better in order to meet the growing demand for rooibos. Expansion of rooibos farms is not the best way forward, however, because this may lead to the loss of other plants that are endemic to the CFR (Richardson et al., 1996), and expansion is furthermore restricted by environmental protection laws. Since soil moisture is potentially one of the main limitations to rooibos production in the region, it is thus important to study the processes that could lead to increased water loss and to look at the practices that could help to increase and conserve moisture in the soil.

Some agricultural practices that can help to increase and improve soil moisture and increase yield are organic mulching, no tillage, fertiliser application and irrigation. Fertiliser applications have been used in dry land farming to increase yields of maize, wheat, sorghum and soil organic carbon (Liu et al., 2013a). However, research done on the use of fertilisers for rooibos showed that fertiliser in fact reduces biomass by more than 60% (Van Schalkwyk, 2018).

Zheng et al. (2020) reported that mulching increased plant transpiration and reduced soil evaporation of maize, and that maize yields increased in a study where maize under rainfed conditions was mulched. There is, therefore, a need to test the effect of mulching and irrigation on soil moisture and rooibos yield in the South African context.

1.8 Statement of problem

The drought in the Western Cape has been reported to have negative effects on rooibos yield (Archer et al., 2008). Rooibos has unique climate and soil requirements and attempts to plant it outside the Western and Northern Cape provinces have been unsuccessful (Wynberg, 2017). This means that the production of rooibos is limited to the Western and Northern Cape, and that the production of rooibos should therefore be well managed to meet the growing global

demand. Moreover, the growing season of rooibos peaks in the summer months, implying a greater reliance on soil moisture. Since evapotranspiration will pose a major challenge on increased water demand during the dry summer period, even more so under climate change, studying the relationship between rooibos growth and soil moisture will help us to understand the level of soil moisture that is needed for optimum growth and consequently to develop appropriate soil conservation strategies.

1.9 Study aim and objectives

The study thus set out to investigate the relationship between rooibos growth and soil moisture. The objectives of the study were: 1) to determine the effect of soil moisture on growth and evapotranspiration in rooibos under glasshouse conditions, 2) to adapt the CROPGRO model in DSSAT to simulate the shoot biomass yield of rooibos, using the rooibos CROPGRO model, 3) to investigate the effect of rooibos growth on soil moisture, and 4) to determine the effect of different levels of mulching and irrigation on rooibos yield and soil moisture.

1.10 Thesis overview

Chapter One introduced the topic of study and the literature review, focusing on climate change, drought and its implications for rooibos growth in the Western Cape. The chapter also presented the relevant descriptive information on rooibos and its cultivation. Furthermore, it identified adaptation strategies in response to droughts, and highlighted the importance of testing combined drip irrigation and mulching for crop production and soil moisture conservation. Chapter Two looks at the effect of soil moisture on growth and evapotranspiration in relation to rooibos grown in Clanwilliam and Citrusdal soil under glasshouse conditions. In that chapter, the effects of two drought treatments were tested on the biomass accumulation, evapotranspiration rate, chlorophyll fluorescence and gas exchange of rooibos. Chapter Three focused on the adaptation and application of the CROPGRO model in

DSSAT-CSM to test the relationship between rooibos growth and soil moisture, and thus the sustainable production of rooibos. The model was used to test the effect of rooibos cultivation on soil moisture by comparing the soil moisture in rooibos fields with the soil moisture of bare soil. The model was also used to test the effect of different levels of irrigation and mulching on soil moisture and shoot biomass. Lastly, Chapter Four contains the general discussion and synthesis of the findings of this study.

CHAPTER TWO

Effect of soil moisture on growth and evapotranspiration of rooibos grown in field soil under glasshouse conditions

2.1 Introduction

The Western and Northern Cape, where rooibos grows, have been experiencing drought regularly in recent times (Cowling et al., 1996; Archer et al., 2008; Malgas et al., 2010). For instance, the Western Cape received below average rainfall for three consecutive years from 2015 to 2017, reducing water levels in the dams so significantly that the City of Cape Town was left with almost no water supply in March 2018 (Otto et al., 2018; Wolski, 2018). Furthermore, several studies have projected that the Western Cape, which has a Mediterranean climate, is threatened by future climate change, such as a reduction in winter rainfall and an increase in temperature (Hewitson et al., 2005; Engelbrecht et al., 2009; Engelbrecht et al., 2011). This projected climate change will reduce soil moisture and enhance evapotranspiration, thereby altering soil water dynamics and the availability of water for root uptake to improve biomass yield. Soil moisture and evapotranspiration are important parameters in crop production and climate change processes, as they drive, among others, water availability for crop growth and global hydrological cycles (IPCC, 2013).

The decline in rooibos yields has been attributed to both climate variability (drought) and a decline in soil quality (Archer et al., 2008; Smith et al., 2018; MacAlister et al., 2020b). In Archer et al.'s (2008) study of the Suid Bokkeveld (Southern Bokkeveld) region from 2003 to 2007, an increased frequency of dry seasons, a late start of winter rainfall and increased heat stress in 2004/2005 were reported to decrease the yield of rooibos by 40% in the 2005 harvest. Although rooibos is grown in acidic and infertile sandy soil, studies by Smith et al. (2018) and MacAlister et al. (2020a) have shown a link between a reduction in soil elements, such as

differences in phosphorus, potassium and carbon, across various sites and a decline in rooibos growth and yield.

However, although drought has been seen to reduce yields (Archer et al., 2008), rooibos is still grown without irrigation. This may be due to the widespread scarcity of water in the region, coupled with the requirement for economic investment in irrigation systems that may in fact make rooibos production unprofitable. According to MacAlister et al. (2020b), rooibos has moreover developed drought tolerance mechanisms, such as the production of long roots, the maintenance of high relative water content, increased root to shoot ratios and production of polyphenols during drought. It was also reported that rooibos plants in the field maintain high levels of transpiration during the dry summer months (MacAlister et al., 2020a). Understanding the relationship between soil moisture and rooibos growth is essential for the determination of adaptation strategies for sustainable rooibos production in response to the changing climate. Therefore, the aim of this study was to determine the effect of soil moisture on biomass accumulation, evapotranspiration rate, chlorophyll fluorescence and gas exchange when growing rooibos under glasshouse conditions.

2.2 Material and methods

In the subsections below, we will start by looking at soil collection and plant growth conditions during the experiment, before describing the experimental treatments and plant cultures. Surface soil moisture content and evapotranspiration were measured, as were chlorophyll fluorescence and gas exchange. Once the plants were harvested, the biomass was measured, the root morphology was studied, and the chlorophyll and carotenoid concentrations were measured. The final subsection presents the statistical analysis.

2.2.1 Soil collection

Soil was collected from rooibos fields on Clanwilliam and Citrusdal farms in the Cedarberg Mountains of the Western Cape, South Africa, during September 2018. The site in Clanwilliam is located at 32.1976°S, 18.8967°E, and lies 312 m above sea level, while the site in Citrusdal is located at 32.58°S, 19.0118° and lies 588 m above sea level. These two sites are within the major rooibos producing areas of the region. The soil samples from these two sites were chosen because they differed in some nutrient elements, with Citrusdal soil showing significantly higher values of carbon (C), total and available phosphorus (P), potassium (K), calcium (Ca), boron (B), copper (Cu), manganese (Mn), sodium (Na) and zinc (Zn), while Clanwilliam soil was more acidic and had a higher Iron (Fe) content than Citrusdal soil (MacAlister et al., 2020a). The soil collected from the farms were from the first 20cm depth. The soil samples collected were air dried to ensure constant weight and passed through a 2 mm sieve to remove debris.

2.2.2 Plant growth conditions

The experiment was carried out in a well-ventilated glass house at the University of Cape Town (33.95°S, 18.46°E). The temperature during the experimental period from October 2018 to May 2019 ranged from 18°C to 42.5°C, with an average of 25°C and relative humidity ranged from 26.5% to 81% with an average 56%.The glasshouse is temperature regulated following the diurnal rhythm of day and night. However, it is cooled down when the ambient temperature is too high (>25°C and warmed-up in winter (<15°C).

Scarified seeds were planted in a nursery tray to raise seedlings for the experiment. Upon germination, the seedlings were watered every two days for 3 weeks. Prior to transplanting, pots that were 30 cm deep and 15 cm in diameter were filled with 12kg of soil from the rooibos farms. On the eve of transplanting, the soil in the pots was flooded with water to moisten it

thoroughly. The seedlings were transplanted into the deep pots and watered with 250ml of water daily for 16 weeks. The daily watering with 250ml had been determined in a preliminary experiment as adequate for effective rooibos growth and to reduce daily variations of soil moisture content in the pot. The seedlings grew very well, to an average height of 75cm, and were well branched, vigorous and healthy rooibos plants (see picture in Fig. 2.1 taken after 16 weeks of growth).

Fig. 2.1: Picture of rooibos plants growing in pots in the glasshouse, 16 weeks after planting.

2.2.3 Experimental treatments and plant culture

The experimental design was a completely randomized design where pots were randomly allocated on a tray and the tray was moved around the glasshouse once a week to avoid location effects. Prior to the commencement of the drought treatment, all 60 pots were measured to determine the amount of soil moisture in each of the pots. It was calculated that the pots were maintained at 40% field capacity (FC) for the 16-week growth period. The field capacity of the soil for each site was determined by recording the dry weight of the soil in three pots, flooding the pots with water, and then leaving them overnight for the excess water to drip off. The weight of the pot in the morning was recorded and denoted as wet weight and with the soil at 100%

FC. The amount of water to reach field capacity was obtained by subtracting the weight of the dry potted soil from the weight of the wet potted soil at 100% FC. The soil samples from the two sites were distributed among 60 pots each, and equally distributed to a control group and two drought treatments: moderate drought stress (MDS) and severe drought stress (SDS). The control group was watered to maintain the 40% FC of soil every day. The 40% FC was calculated by calculating the average soil moisture in the pots before starting the drought treatments. Maintaining the moisture at 40% daily involved maintaining soil moisture at 70% FC by watering every two days. The plants maintained at 40% received 1.750 litres of water weekly for a period of 20 weeks, followed by 2.8 litres of water per week once the plants became bigger. The daily watering schedule was followed in order to maintain a constant water treatment regimen. In the MDS treatment, plants were watered to 20% FC, which was half of the control group, while in the SDS treatment, watering was withheld during the period of the drought treatments.

The drought treatments started on 28 February 2019. The pots were weighed every day to measure the amount of soil moisture loss and the amount of moisture loss determined the amount of water that was added to the pot to maintain it at either 40 or 20%. The experiment was intended to last for six weeks, but the plants that received no water could only last for 10 days before signs of wilting developed. At this stage, all ten of the SDS plants were harvested, and four plants per site from the control group and from the 20% FC (MDS) treatment were harvested, and the biomass, root morphology and chlorophyll content were measured.

After the 10 days of drought treatment and data collection in the glasshouse, the control and 20% FC plants were kept in the glasshouse for another eight weeks before being transferred into a phytotron growth chamber to measure the gas exchange parameters. It was not possible to measure the gas exchange parameters in the glasshouse due to unstable weather conditions. Prior to the transfer, and for each of the two soil sites, two plants from the control group and

the MDS treatment group from each site were gathered together to represent the SDS treatment group in the phytotron. In the phytotron, constant climatic conditions were maintained, which allowed measurement of gas exchange parameters, including photosynthesis, transpiration, stomatal conductance, intracellular concentration of carbon dioxide (Ci) and vapour pressure deficit, which was calculated from the measured leaf temperature (Vpdl). The plants were moved into the phytotron on 24 April 2019. The photoperiod in the phytotron was set to 14hrs and the temperature was at 21ºC (night), 28ºC (day average) and maximum temperature of 33.5ºC. The experiment in the phytotron lasted for 14 days; however, the SDS treatment could not extend beyond five days. The SDS treatment plants were thus harvested at day 5 when the plants started to show signs of wilting, while the control and MDS treatment groups were maintained until the 14th day to avoid overgrowing of plants. It is noteworthy at this stage that the MDS treatment was maintained at 20% FC for 12 weeks, which is from the beginning of the treatment in the glasshouse to the end of the treatment in the phytotron.

2.2.4 Surface soil moisture content and evapotranspiration

The surface soil moisture content in each pot was measured daily during the drought experiments in both the glasshouse and the phytotron using a portable soil moisture probe (ML2X Moisture Meter, WET Sensor, Delta-T Devices, Cambridge, England), which measures the top 10 cm. The surface soil moisture was an important parameter to measure because evaporation occurs at the surface of the soil. Evapotranspiration (ET) was calculated daily by subtracting the weight of the pot before watering from the weight of the pot after watering the previous day. The amount of water calculated as evapotranspiration was the amount of water that was supplied on the day. This method was used to mimic the measurement of using a lysimeter in the field, where the weight of a soil column is measured, and the change in weight gives the amount of water loss (Lu et al., 2018). The weight of water loss was changed to volume using the calculation that the density of water of 1g is equal to 1ml of water. The

amount of water loss was further converted to mm by converting ml to litre. It is known that 1 mm of ET or rainfall = 1 litre per m^2 (Brouwer et al., 1985); therefore, to convert L to mm, the amount in litres was divided by the surface area of the pot. The pot used for the experiment had a radius of 7.5 cm or 0.075 m, which meant that the area of the pot was 0.018 m^2 (area of a circle = $\pi r^{\wedge 2}$). Hence, ET in mm = (ET in ml)/ (1000* 0.018) or ET in L/ 0.018.

2.2.5 Chlorophyll fluorescence

During the drought treatment, the quantum yield of the photosystem II (PSII) (F_q'/F_m') and the maximum photochemical efficiency of the PSII (F_v/F_m) were measured by the PAM 2100 portable fluorometer (Walz, Eiffeltrich, Germany) on a young fully expanded leaf. The quantum yield (F_q'/F_m') (where $F_q' = F_m' - F$) and the leaf temperature were measured during the day from 09h00, simultaneously with photosynthetic photon flux density (PPFD) values every two days in the glasshouse on five plants per treatment. Also, the maximum photochemical efficiency of the PSII (F_v/F_m) (where $F_v = F_m - F_o$) was taken at night, at least 1 hour after darkness, every two days in the glasshouse, also from five plants per treatment, and daily in the phytotron from four plants per treatment. The acronym F_o is the minimal fluorescence, F_m is the maximum fluorescence, F_v is the variable fluorescence, and F is the steady state value of fluorescence immediately prior to the flash of light (Maxwell and Johnson, 2000). Both F_v/F_m and F_q'/F_m' can be used as an indicator of drought stress (Maxwell and Johnson, 2000). Values lower than 0.83 for F_v/F_m in most plant species indicate that plants have been exposed to stress (Demmig and Björkman, 1987).

2.2.6 Gas exchange

The LICOR-6400XT Portable Photosynthesis System (LI-COR Biosciences, Lincoln, NE, USA) was used to measure gas exchange variables, which include maximum photosynthetic rate (P_{max}), stomatal conductance (g_s), transpiration (E), intracellular CO_2 (Ci), and vapour

pressure deficit calculated from measured leaf temperature (Vpdl) in the phytotron. These gas exchange parameters were measured at reference CO_2 concentration, maintained at 400 ppm, while the flow rate was 400 µmol s^{-1} and the light inside the chamber was set to 1500 µmol photons m^{-2} s^{-1} (MacAlister et al., 2020a) between 09h00 and 12h00. Fully grown young leaves (4 to 6 leaves) from each plant were used for measurements on four replicate plants, and the leaves used for each measurement were picked off the plant to measure the surface area with the STD4800 scanner and WinRHIZO version 2013a (Regent Instruments, Quebec, Canada), to ensure that all measurements can be expressed per leaf area.

A porometer (Decagon Devices Inc., Pullman, USA) was also used to measure the stomatal conductance and leaf temperature daily. Readings were done on young fully expanded leaves between 09h00 and 12h00.

2.2.7 Plant harvest and biomass

At harvest, the plant was divided into three organs: stem, leaves and roots. These were oven dried at 60°C for 72 hours and were measured for dry weight. The total biomass was obtained by adding up all the biomass from all the organs.

2.2.8 Root morphology

About 15% of the total root mass from the middle region of the roots (Vandamme et al., 2013) was collected for root morphological analysis, and stored in a 10% ethanol solution at 4°C until analysis. The roots were analysed by staining them with 2% (w/v) solution of gentian violet to enable better visualisation on the scanner. Total root length (cm), average diameter (mm) and total surface area (cm^2) were measured with a STD4800 scanner and WinRHIZO software version 2013a (Regent Instruments, Quebec, Canada), and converted to whole-root results by multiplying by their relevant conversion factors to 100% of the root.

2.2.9 Chlorophyll and carotenoid concentration

Four young fully grown leaves from each plant were collected from six replicate plants in the glass house and from four plants in the phytotron per treatment at harvest. These leaves were inserted into a vial covered with aluminium foil and containing 10 ml of 95% ethanol (Lichtenthaler, 1987). The vials were left to auto-extract for 24 hours in the dark. After the 24-hour period, the solution from the leaf extract was pipetted into a 96 well plate, and this plate was placed into a Thermo Helios Epsilon Plate reader (Thermo Scientific, USA). The light absorption of the solution was measured spectrophotometrically at specific wavelengths (664, 648 and 470 nm) and chlorophyll and carotenoids concentrations were calculated using equations by Lichtenthaler (1987) as follows:

$$Chla = (13.36 \times A664) - (5.19 \times A649) \quad (1)$$

$$Chlb = (27.43 \times A649) - (8.12 \times A664) \quad (2)$$

$$Chla+b = (5.24 \times A664) - (22.24 \times A649) \quad (3)$$

$$Cx+c = ((1000 \times A470) - (2.13 \times Chla) - (97.64 \times Chlb)) / 209 \quad (4)$$

The surface area of the leaves used for determining the chlorophyll and carotenoid concentration were determined using a STD4800 scanner and WinRHIZO version 2013a program. The surface area was used to express the chlorophyll and carotenoid concentration leaf area basis.

2.2.10 Statistical analysis

The data collected were analysed by running a two-way ANOVA using Statistica 13 (TIBCO Software Inc., CA, USA) to evaluate site and water stress treatment effect. A one-way ANOVA was used to test only for the drought treatment effect. Tukey's honest significant difference (HSD) post hoc test at 5% probability was used to separate significantly different means.

2.3 Results

This section presents the results on the effect of sites on rooibos growth and all other parameters and the effect of drought treatments on biomass, root morphology, gas exchange, chlorophyll fluorescence, chlorophyll and carotenoids concentration, soil moisture, evapotranspiration and stomatal conductance. Also, this section presents the relationship between soil moisture, temperature, stomatal conductance and evapotranspiration.

2.3.1 Site

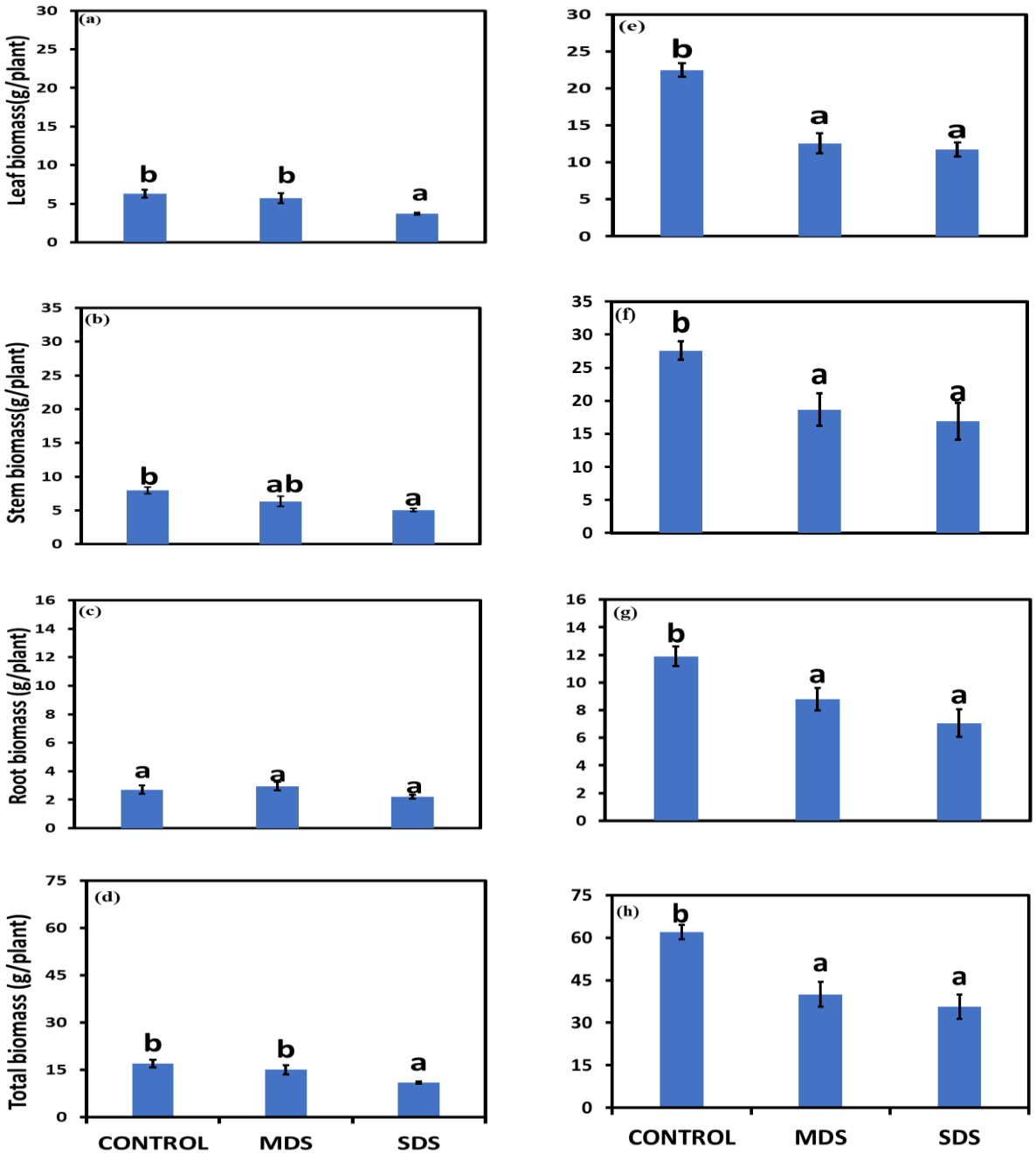
The two sites showed similar results for all parameters, including biomass, chlorophyll and carotenoids concentration, gas exchange parameters, chlorophyll fluorescence values, soil moisture and evapotranspiration. As a result, the data from the two sites were combined and assessed only for the effect of the drought treatments.

2.3.2 Biomass and root morphology

In the glasshouse measurements, the biomass of the MDS plants was similar to that of the control group for the leaf, stem and total biomass (Fig. 2.2a, b and d) at harvest. The SDS plants, however, had a reduced ($p < 0.001$) leaf biomass by about 40.7%, a reduced stem biomass by 37% and total reduced biomass by 35.7% relative to the control. The drought treatments did not show any effect on root biomass in the glasshouse measured plants (Fig. 2.2c and e). However, in the phytotron measured plants, the SDS treated plants and the MDS plants were similar, but had lower values ($p < 0.001$) than the control group in terms of the leaf, stem, root and total biomass (Fig. 2.2e, f, g and h). The biomass of the MDS plants after being maintained at 20% FC for 12 weeks was lower ($p < 0.001$) than that of the control group by

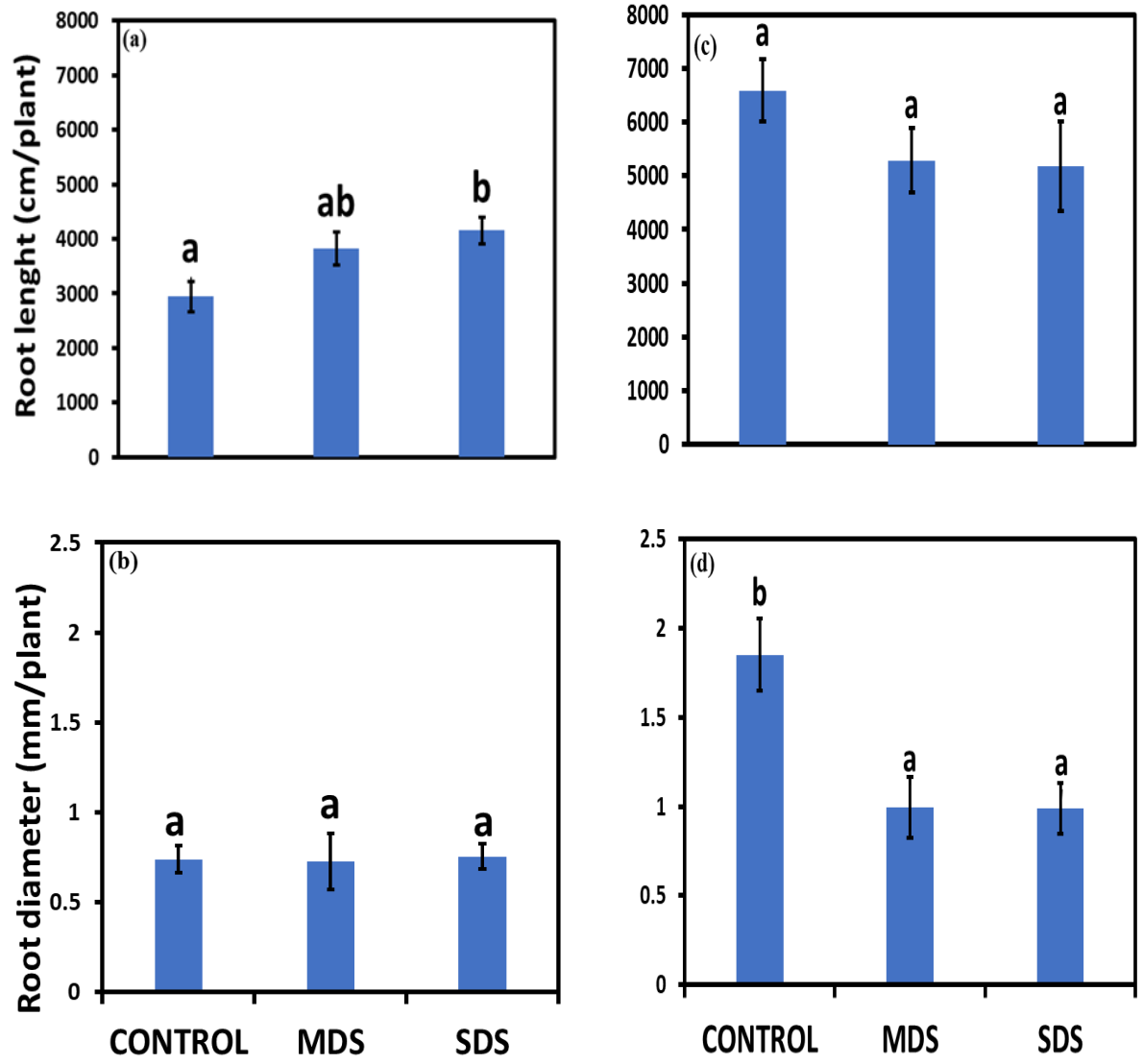
43% with regard to leaf biomass, 32.39% with regard to stem biomass and 35% for the total biomass (Fig. 2.2e, f and h).

Ten days of drought treatment in the glasshouse measurements showed an increase in root length in the two drought treatments: the SDS plants increased ($p < 0.001$) root length by 40% relative to the control (Fig. 2.3a); however, the root diameters of both treatments were similar to the control (Fig. 2.3b). In contrast to the glasshouse measurements, the root length was not altered by water treatments in the phytotron measurements (Fig. 2.3c), although the root diameter decreased ($p < 0.001$) in the two drought treatments (Fig. 2.3d) relative to the control.



Glasshouse measurements Phytotron measurements

Fig. 2.2: Effects of drought treatments on leaf biomass (a and e), stem biomass (b and f), root biomass (c and g), total biomass (d and h) from glasshouse and phytotron measurements. Vertical lines on bars denote standard error. Different letters indicate significant differences between treatments by Tukey's HSD post hoc test ($p < 0.001$). MDS stands for moderate drought stress and SDS stands for severe drought stress.



Glasshouse measurements Phytotron measurements

Fig. 2.3: Effects of drought treatments on root length (a and c), root diameter (b and d) from glasshouse and phytotron measurements. Vertical lines on bars denote standard error. Different letters indicate significant differences between treatments by Tukey's HSD post hoc test ($p < 0.001$). MDS stands for moderate drought stress and SDS stands for severe drought stress.

2.3.3 Gas exchange

Gas exchange measurements were conducted only in the phytotron. Photosynthesis, E and g_s of the MDS plants were lower ($p < 0.01$) than the control plants throughout the experimental period (Fig. 2.4a, b and c) by 46%, 56 and 63% respectively. Also, within two days of total

water withdrawal, SDS plants reduced P_{max} by 68%, E by 52% and g_s by 52% (Fig. 2.4a, b and c). After 2 days, gas exchange measurements could not be taken from SDS treated plants due to lack of sensitivity. The intracellular CO_2 (Ci) and the vapour pressure deficit calculated from measured leaf temperature (Vpdl) did not show any changes between treatment ($p > 0.05$) at each day, except for Vpdl on day 10 when the MDS was lower than the control group (Fig. 2.4d and e).

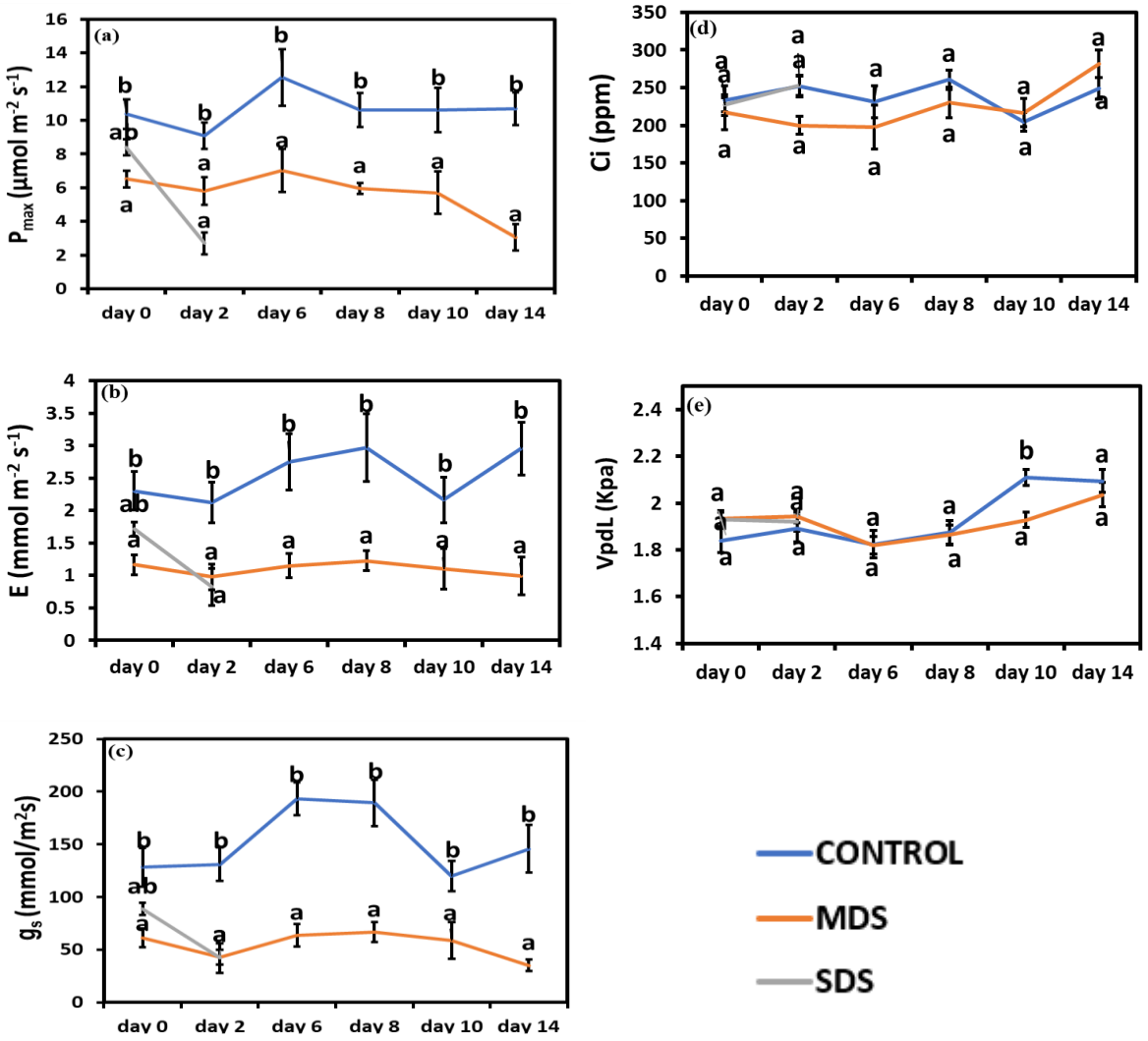
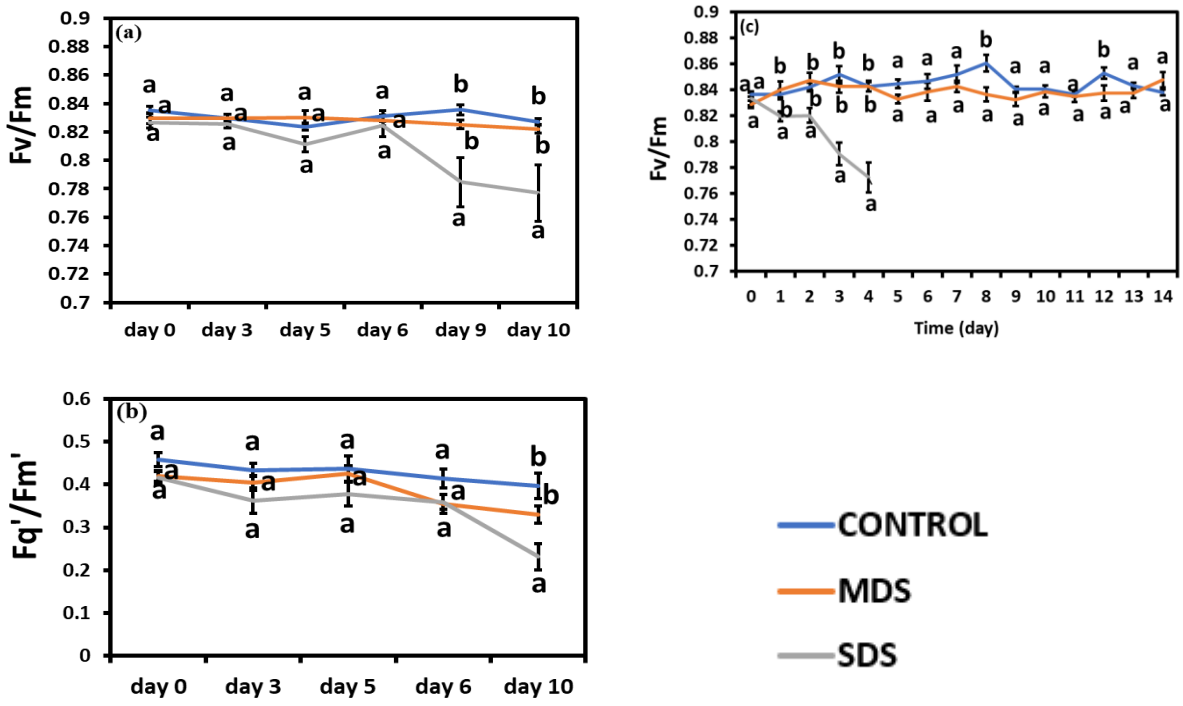


Fig. 2.4: Effect of drought on (a) maximum photosynthesis (P_{max}) (b) leaf transpiration (E) (c) stomatal conductance (g_s) (d) intracellular CO_2 (Ci) (e) vapour pressure deficit based on leaf temperature (Vpdl). Vertical lines on the line graph denote standard error. Different letters indicate significant differences between treatments at each day by Tukey's HSD post hoc test ($p < 0.01$). MDS stands for moderate drought stress and SDS stands for severe drought stress.

2.3.4 Chlorophyll fluorescence

All the drought treatments did not alter the quantum yield of the PSII (F_q'/F_m'), which is the operating efficiency of PSII, until the last day in the glasshouse measurements, when the SDS and MDS plants were similar but significantly lower ($p < 0.05$) than the control group in the glasshouse (Fig. 2.5b).

The F_v/F_m in the glasshouse was not affected by supplying water at 20% FC (MDS), while withdrawing watering (SDS) decreased ($p < 0.05$) F_v/F_m on days 9 and 10 (Fig. 2.5a), compared to the control plants. Similarly, the F_v/F_m in the phytotron was not affected by supplying water at 20% FC, but the values of the SDS plants reduced significantly ($p < 0.05$) from day 1 to day 4 (Fig. 2.5c). Thereafter, the SDS plants were insensitive to fluorometry measurements, and were therefore harvested. On the last day of the treatment in the phytotron measurement, after growing the plants under MDS condition for 12 weeks, the value of F_v/F_m for MDS plants was 0.845.



Glasshouse measurements Phytotron measurements

Fig. 2.5: Effect of drought on F_v/F_m from the glasshouse and phytotron measurements (a and c) and F_q'/F_m' (quantum yield of PSII) from the glasshouse measurements. The quantum yield of the PSII parameter was not assessed in the phytotron due to logistical reasons. Vertical lines on the line graph denote standard error. Different letters on bars indicate significant differences between treatments on each day by Tukey's HSD post hoc test ($p < 0.05$). MDS stands for moderate drought stress and SDS stands for severe drought stress.

2.3.5 Chlorophyll and carotenoids concentration

Only severe drought stress was significantly lower ($p < 0.05$) than the control for total chlorophyll content in both the glasshouse and phytotron measurements (Fig. 2.6 a and c). The carotenoid concentration did not show significant differences ($p > 0.05$) between treatments in the glasshouse measurements (Fig. 2.6b), while in the phytotron measurement, it decreased ($p < 0.05$) by 46% only in the SDS plants (Fig. 2.6d).

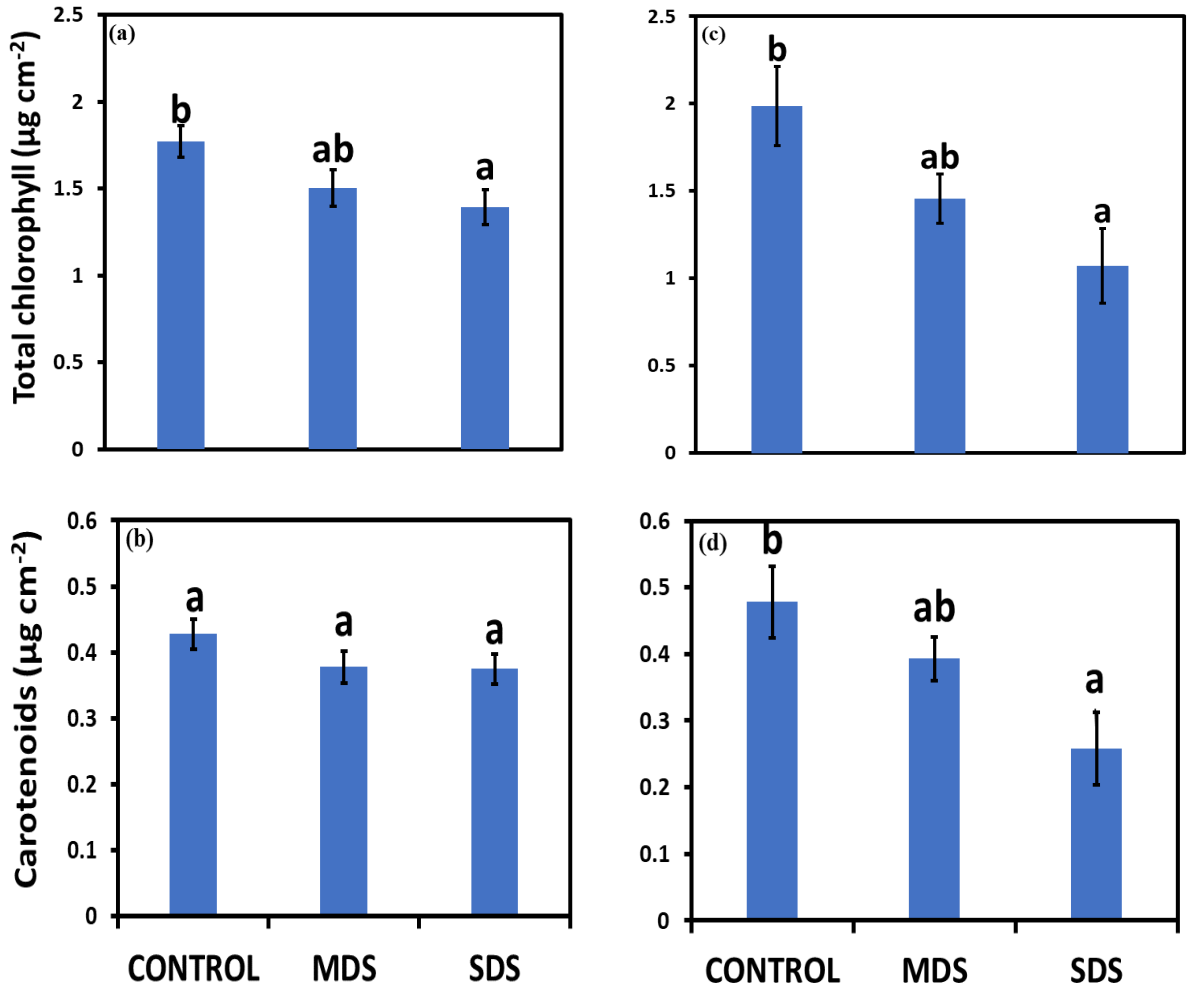


Fig. 2.6: Effect of drought on total chlorophyll (a and b) and carotenoids (c and d) from the measurements in the glasshouse and phytotron. Vertical lines on bars denote standard error. Different letters indicate significant differences between treatments by Tukey's HSD post hoc test ($p < 0.05$). MDS stands for moderate drought stress and SDS stands for severe drought stress.

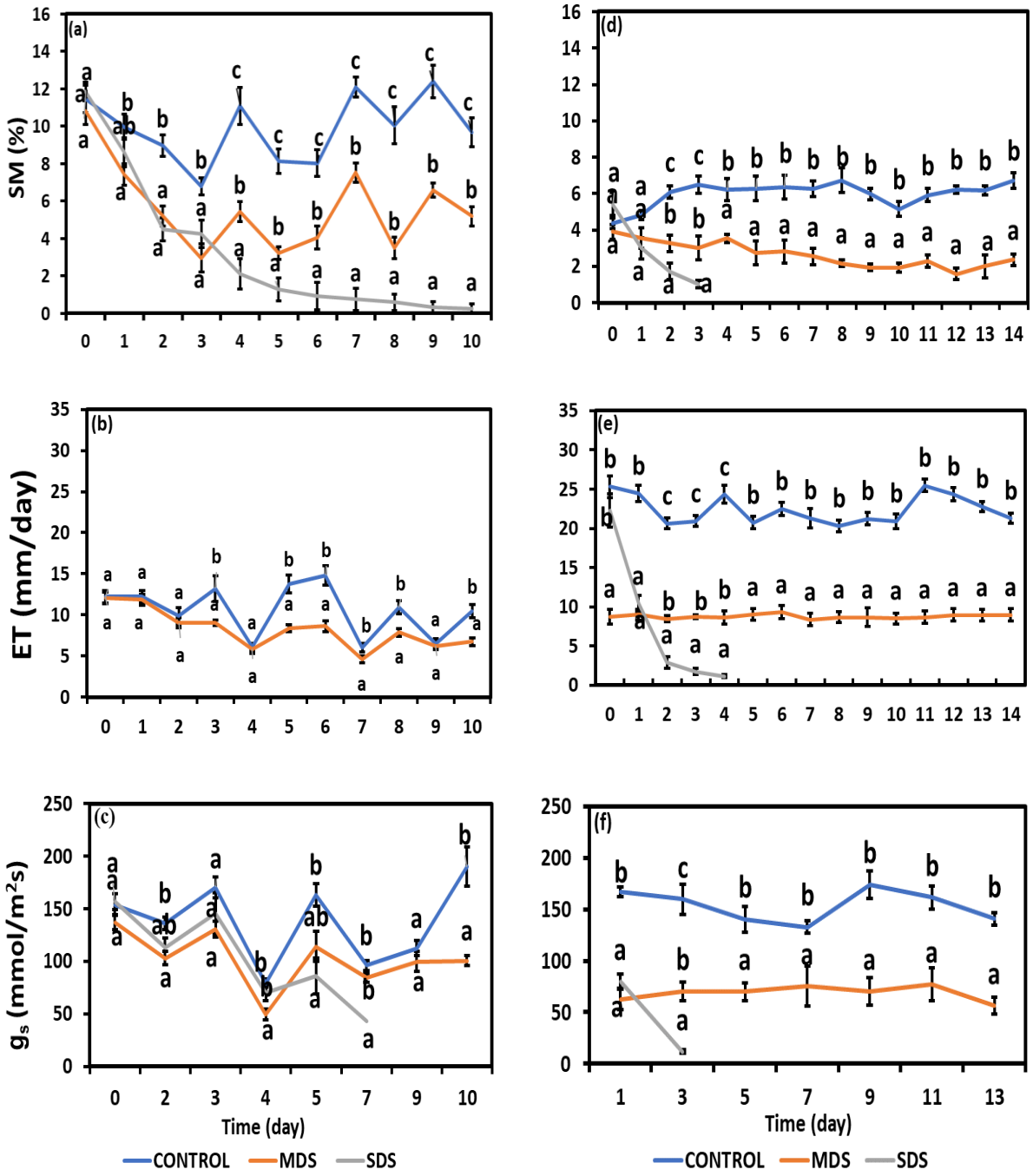
2.3.6 Soil moisture, evapotranspiration and stomatal conductance

In Fig. 2.7, soil moisture content, evapotranspiration and stomatal conductance showed similar trends in the glasshouse and phytotron measurements. With regard to the three parameters, both drought treatments were significantly lower ($p < 0.001$) than the control group, with the SDS plants being the lowest. Soil moisture in the top 10 cm decreased ($p < 0.001$) from 12% to 2% in the SDS plants in day 4 in the glasshouse and in day 3 from 5% to 1% in the phytotron

(Fig. 2.7a and d). The MDS treated plants maintained a lower rate of evapotranspiration and stomatal conductance in the phytotron measurements, while in the glasshouse, the response varied with days (Fig. 2.7b, c, e and f). The stomatal conductance for the SDS plants closed after the 5th day in the glasshouse measurements, when the water content in the pot was at 6.1% FC, while in the phytotron measurements, the stomatal conductance closed on day 3 when the water content in the pot was at 6.28% FC.

2.3.7 Correlation graphs

Fig. 2.8 shows relationships between soil moisture, temperature, stomatal conductance and evapotranspiration, when assessed within the drought treatment or control groups. MDS plants did not have any significant correlation with temperature for stomatal conductance and evapotranspiration, while in the case of the control plants, ambient temperature had a positive correlation with stomatal conductance ($r = 0.58$, $p < 0.01$) and evapotranspiration ($r = 0.91$, $p < 0.0001$) (Fig. 2.8a and b). Also, with regard to soil moisture, MDS plants had no correlation with stomatal conductance and evapotranspiration in MDS plants, while in the control plants, soil moisture had a negative correlation with stomatal conductance ($r = -0.6$, $p < 0.01$) and evapotranspiration ($r= -0.9$, $p < 0.0001$) (Fig. 2.8d and e). Furthermore, soil moisture and ambient temperature showed negative correlations in both MDS plants ($r = -0.65$, $p < 0.001$) and the control plants ($r = -0.9$, $p < 0.0001$) (Fig. 2.8c).



Glasshouse measurements Phytotron measurements

Fig. 2.7: Effects of drought treatments on soil moisture (SM) (a and d), Evapotranspiration (ET) (b and e) and stomatal conductance (g_s) (c and f). Stomatal conductance was measured by means of the porometer. Vertical lines on the line graph denote standard error. Different letters indicate significant differences between treatments at each day by Tukey's HSD post hoc test ($p < 0.001$).

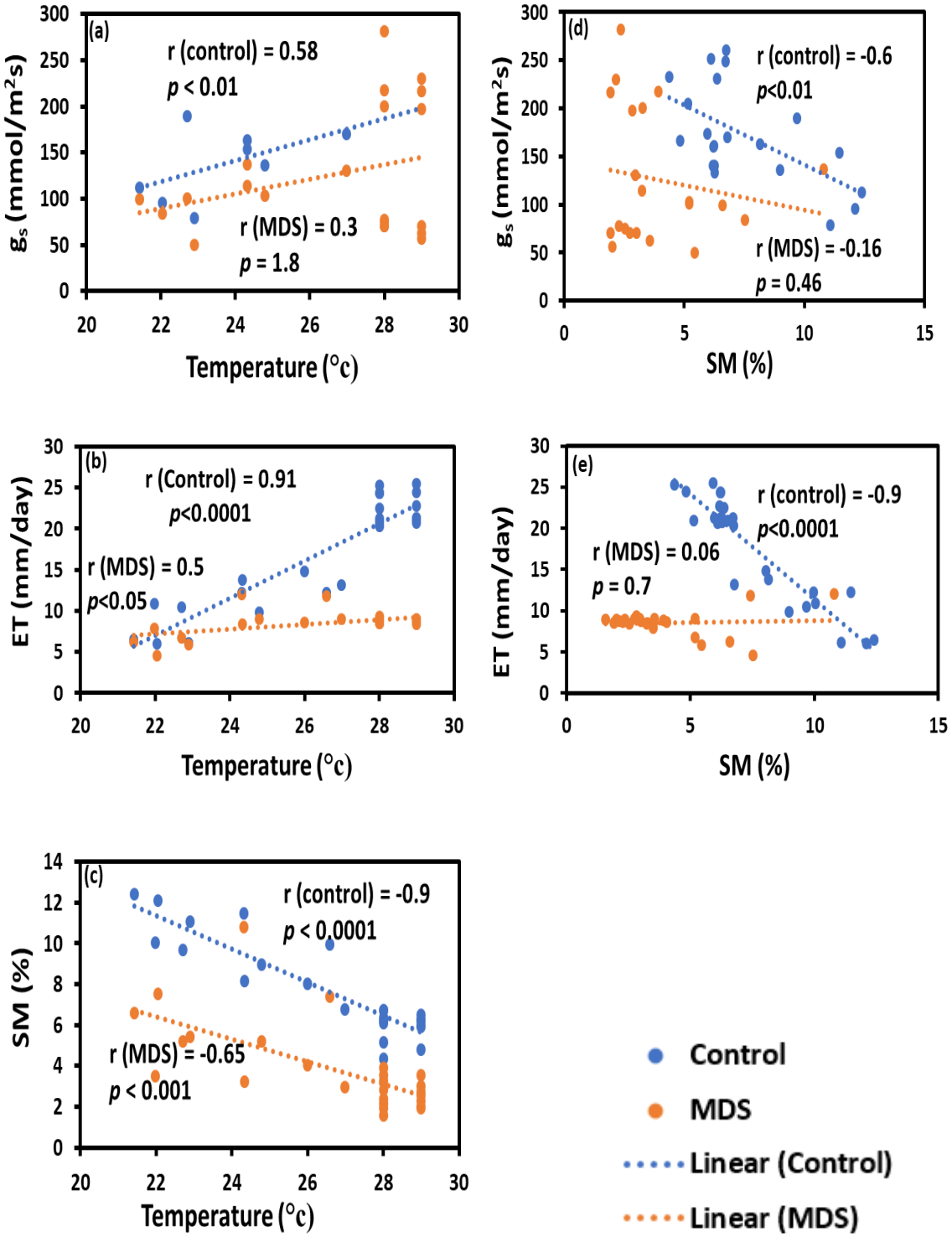


Fig. 2.8: Correlation showing relationship between average day temperature and (a) stomatal conductance (g_s), (b) evapotranspiration and (c) soil moisture, and relationship between soil moisture and (d) stomatal conductance (g_s) (e) evapotranspiration at adequate water supply (control) and moderate drought stress (MDS).

2.4 Discussion

One important way in which rooibos copes with drought is through adjusting its root morphological features, such as root length and root diameter (Fig. 2.4) (Lotter et al., 2014; MacAlister et al., 2020b). In the current study, the SDS plants showed the longest root length in the glasshouse measurements. Although the differences in root length were not seen in the phytotron measurements, probably because of the potting effect, the SDS plants were found to have thinner roots. Both longer roots and thinner roots allow plants to increase the volume of soil explored per unit biomass, which increases water absorption and nutrient uptake (Eissenstat, 1992; MacAlister et al., 2018; MacAlister et al., 2020b). The results evidently showed that thinner roots and increased root length help rooibos to cope with drought, and thus contribute to rooibos growth and survival during periods of drought.

The results of this study clearly showed that a 50% decrease in water supply to rooibos plants reduced the biomass yield by about 40%; this agrees with previous reports (Lotter et al., 2014; MacAlister et al., 2020b). The results also showed that by completely withdrawing water from the SDS plants, rooibos could not last more than 10 days. This, therefore, confirms result from Stassen (1987) and MacAlister et al. (2020a) that rooibos plants in the field survive the hot and dry summer months by taking up moisture from deep soil layers and actively transpiring during the day. It is conceivable that rooibos has a long tap root that can go more than 2 m downwards (Morton, 1983), and that it thus grows well in deep soils that have high water storage for growth and survival during summer and drought periods (Stassen, 1987). However, the delay in the water stress effect among the MDS plants supports the view that rooibos plants are drought tolerant plants (Lotter et al., 2014; MacAlister et al., 2020b) because a long period of time under daily 20% FC was required (i.e., at the end of the phytotron experiment) before the about 40% reduction in biomass yield was observed.

The reduction in biomass under continual water stress can be attributed to a reduction in maximum photosynthesis. Reduction in photosynthesis may be as a result of either stomata limitation or metabolic impairment (Cornic and Massacci, 1996; Flexas and Medrano, 2002). However, in the case of rooibos, the reduction in photosynthesis is predominantly a non-stomatal limitation, because the intracellular CO_2 (Ci) remained relatively constant during the experiment for both moderate and severe drought stress. Generally, Ci initially decreases and then increases during drought as stomata close, which then indicates stomatal limitation to photosynthesis (Flexas and Medrano, 2002); for rooibos, however, while stomata opening is reduced during drought, Ci remained relatively constant. This observation agrees with the results obtained by MacAlister et al. (2020b), who found that the values of Ci/Ca and PWUE (photosynthetic water use efficiency) remained unchanged for rooibos under water stress. This implies that water stress did not affect the supply of CO_2 to the cells, but that other physiological processes may be responsible for the reduction in maximum photosynthesis. This may be as a result of variable mesophyll conductance, which influences the diffusion of CO_2 from substomatal cavities to the sites of carboxylation (Flexas and Medrano, 2002; Flexas et al., 2008), and decreases in ATP synthesis and ribulose 1,5 biphosphate (RuBP) regeneration (Tezara et al., 1999) are limiting the photosynthetic process. Therefore, it can be concluded that drought induced a reduction in stomatal conductance (g_s), transpiration (E) and maximum photosynthesis (P_{max}), which eventually reduced biomass after a period.

For rooibos, under moderate drought stress, the parameters that measure the efficiency of the PSII were not affected. Both F_v/F_m and yield (F_q'/F_m') can be used as an indicator of drought stress (Maxwell and Johnson, 2000): when F_v/F_m value is lower than 0.83, it indicates that plants are exposed to environmental stress, such as drought (Demmig and Björkman, 1987). The F_v/F_m ratio, which marks the maximal photochemical efficiency of the PSII on dark adapted leaves, and the quantum yield (F_q'/F_m'), which is the operating efficiency obtained on

light exposed leaves, were not affected by the MDS treatment. Furthermore, the SDS did not affect F_v/F_m until the 9th and 10th days when the values decreased. This suggests that the light harvesting system used for rooibos is not sensitive to drought stress. Similar study on *Acacia confusa* and *Leucaena leucocephala* by Liang et al. (1997) showed that drought affects the stomata more than the light harvesting system in some crops, the light harvesting system was not affected until when the whole root zone was dry. Similarly, in this rooibos study both F_v/F_m and yield (F_q'/F_m') were not sensitive to water stress until there was complete drying of the root zone in the SDS plants. Subrahmanyam et al. (2006) attributed the no sensitivity to chlorophyll fluorescence in two cultivars of wheat to maintenance of leaf water potential during drought stress. This explanation may also apply in this study because, the relative water content (RWC) of rooibos leaves, as observed by MacAlister et al. (2020b), was high and maintained until the last day under the SDS treatment. In addition, the lack of effect of the drought stress treatment on the chlorophyll and carotenoids supports the notion that the light harvesting systems of the plants are not sensitive to drought stress conditions.

Soil moisture availability and the type of surface determine the amount of potential evapotranspiration that will translate into actual evapotranspiration. Potential evapotranspiration is the maximum evapotranspiration that can occur in a place at a particular time, and it is dependent on the atmospheric conditions, such as temperature, solar radiation, relative humidity and wind speed (Pruitt, 1973; Xiang et al., 2020). This study clearly shows that evapotranspiration was reduced as soil moisture decreased. The process of reduction in evapotranspiration as soil moisture is reduced can be explained in the reduction in stomatal conductance in the drought treatments. Drought induces a reduction in stomata conductance, which reduces the plant transpiration, and this can be seen in the reduction of stomatal conductance under the moderate drought conditions. Furthermore, the SDS plants gradually reduced their stomatal conductance until the stomata closed when the soil was close to its

wilting point. When the soil has reached its wilting point, the reduction in soil moisture and evapotranspiration ceases because the plant can no longer obtain water from the soil.

Evapotranspiration is beneficial when water is not a limiting factor because ET is directly proportional to biomass. As seen in the control where water is not limiting, as ET increases more biomass was produced in the control and much difference could be seen in biomass accumulation between glasshouse and phytotron measurements (Fig 2.2 and Fig 2.7b and e). However, ET is one of the major processes that reduce soil moisture. Under an adequate supply of moisture, as seen among the control plants, soil moisture decreased as evaporation increased (Fig. 2.8e). Therefore, factors that can reduce evapotranspiration are very important to soil moisture conservation because high ET will likely lead to water stress under water limited condition. Two important factors to be considered in reducing evapotranspiration are the effect of temperature and the increase in surface area (Hanson, 1991). Warming, or an increase in temperature, increases the evaporative demand for moisture (Rind et al., 1990; Condon et al., 2020), because with the increase in temperature, the capacity of air to contain water (i.e., the saturated mixing ratio) increases, as the relative humidity drops, thereby absorbing more moisture from the plants, soil or water surfaces. It is worth noting than an increase in evaporative demand will lead to an increase in evapotranspiration, when soil moisture is available. This study shows that, given adequate soil moisture or access to soil moisture, rooibos will evaporate more moisture as the temperature increases. This can be seen in the strong positive relationship between temperature and stomatal conductance ($r = 0.65$) and evapotranspiration ($r = 0.91$). This implies that, as temperature increases, evapotranspiration will increase, when there is a sufficient supply of moisture. Furthermore, evapotranspiration increased in the control plants during the phytotron measurement (14 mm to 22 mm), which was associated with an increase in the surface area of the plants (i.e., bigger shrubs of rooibos).

An increase in the surface area also increases evapotranspiration (Al-Kaisi et al., 1989; El Nadi, 1974; Hanson, 1991).

Another important observation was that rooibos plants were able to regulate the rate of evapotranspiration relative to the amount of moisture in the soil. The MDS plants transpired a lower amount of moisture and maintained it throughout their time in the phytotron, despite increases in the average day-time temperature from 26 to 28.5ºC. This is evident in the relationship between evapotranspiration, stomatal conductance with temperature and soil moisture, as the MDS plants show no correlation. This therefore means that the amount of soil moisture greatly influences evapotranspiration in rooibos.

One major limitation of glasshouse experiments is that the pot restricts the growth of the roots however, the glasshouse trials still have its own advantage over field experiments. In field experiments, a lot of factors cannot be controlled and harvest of roots for deep rooted plant like rooibos is difficult because some parts of the roots are lost during harvest. Although the glasshouse trial restricts root growth however, differences can still be seen in between treatments when deep and bigger pots are used. This experiment used bigger and deeper pots that contains 12 kg of soil and this reduced early impacts of pots on the root growth. The potting effect was only seen after 6 months of growth in the phytotron measurements.

In conclusion, although rooibos shows drought tolerant traits, its survival during the dry summer months in the field is most likely as a result of access to soil moisture. In this study, we found that the root grows longer during periods of drought, as the plant searches for moisture, and that access to adequate soil moisture will help to improve yields. This implies that, in order for rooibos to produce high yields, an adequate supply of moisture is needed. Also, an increase in temperature will lead to an increase in evaporative demand; however, the

amount of moisture available in the soil will determine the amount of water that will be lost through evapotranspiration in rooibos.

CHAPTER THREE

Relationship between *Aspalathus linearis* (Burm. F.) R. Dahlgren (rooibos) growth and soil moisture using the DSSAT-CSM crop model

3.1 Introduction

Rooibos, a medicinal caffeine-free herbal tea plant, plays an important role in the South African economy, but it can only grow in the winter-rainfall region of the country. There is a concern that the ongoing climate change, which is associated with an increase in temperature, a reduction in rainfall, and increased drought severity globally and over the winter-rainfall area in the Western Cape (Abiodun et al., 2018; Engelbrecht, 2005; Engelbrecht et al., 2008; Hewitson and Crane, 2006), will affect rooibos cultivation. This concern has motivated many studies to investigate the effects of temperature and drought on rooibos production (MacAlister et al., 2020a; MacAlister et al., 2020b; Lotter et al., 2014). However, carrying out research in the field comes with numerous difficulties, and it is also labour intensive and very expensive (Boote et al., 1996). Some studies have shown that crop modelling can be a good supplementary or alternative approach to field experiments (Asseng et al., 2014; Jones et al., 2000; Matthews et al., 2013).

The CROPGRO model in DSSAT-CSM is an all-encompassing model built for legumes, it includes the SOYGRO model for soybeans, the PNUTGRO model for peanuts and the BEANGRO model for dry beans (Boote et al., 1998). These original models have all been combined in the CROPGRO model from many independent models to have one source code written in the FORTRAN programming language (Boote et al., 1998; Jones et al., 2003). The CROPGRO model is a mechanistic model that can simulate soil water and nitrogen balances, residue dynamics, soil organic matter, pest and disease damage (Boote et al., 1998; Jones et al., 2003; Rymph, 2004). The CROPGRO model calculates canopy photosynthesis daily and

hourly by using leaf-level photosynthesis and calculating light interception by the hedgerow (Boote et al., 1998). Also, the CROPGRO in DSSAT-CSM has evolved to be the major crop model available for legumes and its been adapted to for annual legumes which includes pigeon pea (Alderman et al., 2015), tomatoes (Boote et al., 2012; Scholberg et al., 1997), safflower (Singh et al., 2015) chickpea (Hoogenboom et al., 1997), velvet bean (Hartkamp et al., 2002), faba bean (Boote at al., 2002) and perennial forage model (Rymph; 2004).

There is a need to study the relationship between soil moisture and higher evaporative demand, since rooibos grows during the summer, when it is hot and dry. Also, more research is needed on what best practices can be done to increase and conserve soil moisture. This will increase the production of rooibos, especially under the changing climate. Due to the appropriateness and relevance of the CROPGRO in simulating the growth of legume and satisfactory performance of DSSAT-CSM in Southern Africa in conservation agriculture (Ngwira et al., 2014; Nyagumbo et al., 2016; Nyagumbo et al., 2017), it was deemed suitable to adapt CROPGRO model in DSSAT-CSM for rooibos because it is a legume growing in Southern Africa under dry land conditions. The model will be useful to determine the effect of water management practices, such as mulching and irrigation, on soil moisture, growth and evapotranspiration in rooibos. Therefore, the aim of this chapter is to adapt the CROPGRO model for rooibos, and to use it to determine the effect of rooibos growth on soil moisture, and the effect of mulching and irrigation on rooibos growth and soil moisture.

3.2 Methodology

This section discusses the adaptation of the CROPGRO model in DSSAT-CSM for rooibos, and the model setup for the sensitivity experiment under the model application.

3.2.1 Adaptation of CROPGRO MODEL

In the current study, the CROPGRO model in DSSAT-CSM 4.7.0.0 was adapted by changing 20 parameters in the cultivar, ecotype and species file in the model. Several studies on crops such as pigeon pea (Alderman et al., 2015), tomatoes (Boote et al., 2012; Scholberg et al., 1997), safflower (Singh et al., 2015) chickpea (Hoogenboom et al., 1997), velvet bean (Hartkamp et al., 2002), faba bean (Boote at al., 2002) have adapted the model by changing the parameters in this file, without changing the source code. Information from the pigeon pea study was used as a starting point for setting the parameters for rooibos, because pigeon pea is a long season shrub.

Some of the parameters changed in the model file were obtained from the glasshouse study (Chapter 2) and the literature. The list of all the parameters changed and the source from which they were obtained are presented in Appendix A.1, A.2 and A.3. Furthermore, observational data were used for inverse modelling, where parameters were changed to examine their effects on the simulated parameter, and the line of best fit with the sets of parameter values fitting into the observational data line was used. The method of inverse modelling was used in adapting CSM-CROPGRO model in pigeon peas (Alderman et al., 2015). Therefore, to adapt CROPGRO for rooibos, the already known parameters were set, and then the other parameters in the cultivar and ecotype were changed manually to see how these affect the model, before choosing the best set of parameters. In the species file, the parameters affecting leaf and vegetative growth and plant phenology were changed. With regard to the parameters that are not found in rooibos, and that did not show any effects on the output results in the simulation when they were changed to another value, these were not changed from the pigeon pea parameters in the model.

The model simulations were calibrated and evaluated using the glasshouse experiment data (reported in Chapter 2), and two field observational data (from MacAlister et al., 2020a and Van Schalkwyk, 2018). The study by MacAlister et al. (2020a) assessed the effect of temperature on plant growth over a two-year period at four rooibos producing areas along a temperature and rainfall gradient. The locations studied were Aurora (32.685200S, 18.438050E, alt. 93 m), Citrusdal (32.638367S, 18.958433E, alt. 588 m), Clanwilliam (32.161417S,18.777350E, alt. 312 m) and Uitsig (31.920800S, 19.071833E, alt. 344 m). A study by Van Schalkwyk (2018) determined the soil water balance and the effect of fertiliser on rooibos plant growth in the field in 2016. This field experiment measured the evapotranspiration and soil water content of rooibos weekly under unfertilised and fertilised condition for eight months, a period that covered both winter and summer months; the biomass was harvested at 8, 11 and 14 months after planting (Van Schalkwyk, 2018). The biomass from the deep unfertilised soil was uses in evaluating the model.

The biomass data from MacAlister et al., 2020a and Van Schalkwyk, 2018 observational studies were translated on a per hectare basis for use by the model. According to Stassen (1987), 8000 to 10000 rooibos seedlings were planted on a hectare. For the current study, the amount of 10000 plants per hectare was thus used in the translation of the observational data. This was supported by the report that rooibos in the field is planted 1 m apart (Chimphango et al., 2016). Therefore, the model is built to have one rooibos plant per one square meter, which works out to 10000 plants in a hectare.

3.2.1.1 Model experimental set-up

The simulation was set up by building an experimental file (XBUILD). This experimental file incorporates other components, like the weather, the soil, and management practices, such as the application of fertiliser, pesticide and irrigation. However, the experiment was set up

without irrigation and fertiliser, because rooibos is grown as a rainfed crop and without fertilisation.

The model uses daily weather data. The weather used in the model was built using the WeatherMan component of the model, and the daily weather data used were obtained from the Agricultural Research Council's Institute for Soil, Climate and Water (ARCISCW, Pretoria, South Africa). DSSAT-CSM uses daily weather data with minimum of maximum temperature, minimum temperature, rainfall and solar radiation data. All the model simulations started during the rainy season and there was one month model spin-up before the planting date, to adjust the soil condition to the climate data before the planting.

3.2.1.2 Soil file (SBUILD)

The soil profile for rooibos was developed by changing some variables in the default deep sandy soil to the type of soil variables found in rooibos producing areas. The soil data was obtained from reports by Van Schalkwyk (2018) and MacAlister et al. (2020a), where chemical and physical analysis of soil was obtained across several rooibos producing sites. Rooibos grows in deep sandy soil that is acidic and poor in nutrients (Tables 3.1 and 3.2).

Table 3.1: Soil profile characteristics of a deep default sandy soil, as used in the DSSAT model. The letters are abbreviations used in the model. SLB: depth to base of soil layer, SSKS: Saturation hydraulic conductivity, SLOC: soil organic carbon, SLCL: Clay, SLSI: Silt, SLNI: Total nitrogen, SLHW: pH in water, SCEC: Cation exchange capacity.

SLB	SSKS	SLOC	SLCL	SLSI	SLNI	SLHW	SCEC
Cm	cm h^{-1}	%	%	%	%		cmol kg^{-1}
5	-99	0.7	10	30	0.07	6.5	-99
15	-99	0.7	10	30	0.07	6.5	-99
30	-99	0.66	10	30	0.07	6.5	-99
45	-99	0.58	10	30	0.06	6.5	-99
60	-99	0.58	10	30	0.06	6.5	-99
90	-99	0.43	10	30	0.04	6.5	-99
120	-99	0.26	10	30	0.03	6.5	-99
150	-99	0.12	10	30	0.01	6.5	-99
180	-99	0.04	10	30	0	6.5	-99
210	-99	0.01	10	30	0	6.5	-99

Table 3.2: Soil profile characteristics developed for rooibos. See Table 3.1 for details of the abbreviations.

SLB	SSKS	SLOC	SLCL	SLSI	SLNI	SLHW	SCEC
Cm	cm h^{-1}	%	%	%	%		cmol kg^{-1}
5	21	0.19	0.9	3.6	0.01	5.5	0.6
15	21	0.19	0.8	3.6	0.01	5.5	0.6
30	21	0.19	0.9	3.6	0.01	5.5	0.6
45	21	0.18	1.0	3.6	0.01	5.2	0.6
60	21	0.18	1.1	3.6	0.01	5.2	0.6
90	21	0.1	2.2	3.6	0.01	5.2	0.6
120	21	0.1	1.2	3.6	0.01	5.2	0.6
150	21	0.1	0.8	3.6	0.01	5.2	0.6
180	21	0.1	0.8	3.6	0.01	5.2	0.6
210	21	0.1	0.8	3.6	0.01	5.2	0.6

3.2.1.3 Estimation of parameters

1. Time between emergence and flowering

The time between emergence and flowering (EM-FL) for rooibos was calculated to be 355 days, as explained below. The EM-FL value of rooibos is higher because rooibos starts flowering from the end of August to February, which is during the spring and summer period, from its second year of growth onwards (Van Rooyen et al., 1999). The days taken from seed emergence at the nursery, which is usually around February, after which they are transplanted into the field around June, to flowering in their second year during August is 477 days. Since the EM-FL is to be counted during photothermal days, which are the days on which the plants are actively growing, the months of June and July were subtracted, because rooibos experiences a period of dormancy or "rest period" during winter months (Malgas and Oettle, 2007).This therefore reduced the EM-FL value to 355 days. The EM-FL value made the simulation to be perennial.

2. Phenology parameters and photosynthesis

The phenology was set by changing four sets of parameters that control the early reproductive and vegetative stages (Table 3.3). These parameters are base temperature (minimum temperature) (TB), first optimum temperature (Topt1), second optimum temperature (Topt2) and maximum temperature (T_{max}) for reproductive and vegetative growth of rooibos. The base temperature for the reproductive stage was set at 10ºC because rooibos flowers during spring and summer. Also, the base temperature of the vegetative growth was set to 10°C rooibos experiences a period of dormancy or "rest period" during winter months (Malgas and Oettle, 2007)." Therefore, the average temperature of winter temperature of 10 degree Celsius was used. Vigorous growth usually occurs during the spring and summer months, when the maximum temperature is between 20 and 30°C. This therefore sets the first optimum

temperature at 25°C, and the second optimum at 30°C for both vegetative and reproductive growth. According to the fieldwork done by MacAlister et al. (2020a), rooibos closes its stomata at temperatures above 40ºC, which therefore sets the maximum temperature.

Table 3.3: A comparison between rooibos and pigeon pea for phenology parameters in species file.

Growth stage		**Tb**	**Topt1**	**Topt2**	**Tmax**
Vegetative development	Pigeon pea	10	25	35	45
	Rooibos	10	25	30	40
Early reproductive development	Pigeon pea	10	25	24	45
	Rooibos	10	25	30	40

3. Leaf parameters

The leaf parameters were revised to reflect those of rooibos. Rooibos has a small needle leaf. The specific leaf area under standard conditions (SLAVR) of rooibos was set to 40, and the maximum size of three leaflets (SIZLF) to 4. These values were obtained from the glasshouse experiment. The SLAVR and SIZLF of rooibos are very small when compared to other plants. For instance, pigeon pea has a SLAVR value of 320 and a SLAVR value of 40 (Table 3.4).

The maximum leaf photosynthesis rate (LFMAX) parameter for rooibos was estimated as 0.6. This was obtained from the glasshouse experiment, where the LFMAX rate was 14 µmol $m^{-2}s^{-1}$. In the model, 1.76 is equal to 40 µmol $m^{-2}s^{-1}$. This therefore makes the value for rooibos 0.6.

Table 3.4: Specific leaf area (SLA) as defined in the species file of the CROPGRO model for pigeon pea and rooibos. Values were obtained by measuring the leaf area and weight during the glasshouse study.

Variable	CROPGRO parameter	Pigeon pea values	Rooibos values
Specific leaf area of leaves at plant emergence	FINREF	225	25
Specific leaf area of the reference cultivar at early vegetative phase	SLAREF/ SLAVR	320	40
Maximum size of full leaf (three leaflets)	SIZREF/ SIZLF	171.4	4
Upper limit of specific leaf area	SLAMAX	669	60
Lower limit of specific leaf area	SLAMIN	245	15

3.2.1.4 Statistical evaluation metrics

The model was evaluated using three types of statistical measures, which included coefficient of determination (R^2), Willmott Agreement Index (d) and Relative root mean square error (RRMSE). The model used these three statistical measures because no single measure can determine model performance, and each of the statistical measures has its own strengths and limitations (Kobayashi and Salam, 2000; Legates and McCabe, 1999).

Coefficient of determination (R^2) describes the proportion of the variance in measured data explained by the model (Moriasi et al., 2007). R^2 ranges from 0 to 1 with higher values indicating low variance. According to Santhi et al. (2001) and Van Liew et al. (2003), values higher than 0.5 for a model are considered acceptable. Although R^2 is generally accepted and widely used for model evaluation, however, R^2 statistics tend to be oversensitive to outliers and insensitive to additive and proportional differences between observation and simulated data (Legates and McCabe, 1999).

The Willmott Agreement Index (d) is a measurement of agreement between general trends in simulated and observed data (Willmott et al, 1985): d can detect additive and proportional differences between observed and simulated data; however, d is oversensitive to outliers due

to the squared differences (Legates and McCabe, 1999). The index varies between 0 and 1, and a value of 1 indicates perfect agreement: in the case of $d < 0.7$, the model is considered to have poor agreement; $0.7 \leq d < 0.8$ shows moderate agreement; $0.8 \leq d < 0.9$ indicates good agreement; and $d \geq 0.9$ is an "excellent" agreement between observed and simulated data (Liu et al., 2013b).

Relative root mean square error (RRMSE) describes how far the prediction errors are from the regression line. When RRMSE equals zero, it indicates a perfect agreement and no error; RRMSE ≤ 1.5 indicates good agreement; 1.5–3.0 indicates moderate agreement; and ≥ 3.0 indicates poor agreement (Liu et al., 2013b).

The equations for the three statistics include:

$$R^2 = \left\{ \frac{\sum_{i=1}^{n}(O_i-\bar{O})\,(P_i-\bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i-\bar{P})^2}} \right\} \qquad 0 \leq R^2 \leq 1 \qquad [1]$$

$$d = 1 - \left\{ \frac{\sum_{i=1}^{n}(P_i-O_i)^2}{\sum_{i=1}^{n}[(P_i-\bar{O})+(O_i-\bar{O})]^2} \right\} \qquad 0 \leq d \leq 1 \qquad [2]$$

$$RRMSE = \frac{\sqrt{\sum_{i=1}^{n}(P_i-O_i)^2/n}}{\bar{O}} \qquad [3]$$

where n is the number of observations, P_i is the predicted value for the ith measurement, O_i is the observed value for the ith measurement, and $\bar{O}$ is the overall mean of observed values.

The three statistical values may not give the same rating; therefore, when the ratings are different, we considered all three values in our assessment. Also, the three statistical measures were not used for observational data less than 5.

3.2.2 Model setup for sensitivity experiment under model application

The sensitivity experiments were set up according to the objectives of the study. The objectives of the study were to determine the effects of rooibos growth on soil moisture, and to determine the effects of mulching and irrigation on rooibos growth and soil moisture. Table 3.4 gives information about the experiments and indicates the numbers and names of the simulations performed for each experiment. Fig. 3.1 illustrates the rainfall and temperature data used to simulate the experiments. Other weather variables used in obtaining the results, but not presented in the figure, are relative humidity, solar radiation and wind speed.

To set up the irrigation treatment, the drip type of irrigation was chosen, because it is mostly recommended for shrubs and small trees, and because it has been used across several types of fruit trees in the region. It is a low volume type of irrigation system, which helps to reduce water loss because water from pipes drips slowly to the root zone (Cerny et al., 2002). Irrigation was done once a week during the summer period, from December to March. Such an irrigation schedule of once a week was chosen because watering shrubs and trees too often in facts limits root growth (Cerny et al., 2002). Furthermore, 25.4 mm of water as recommended was used to encourage the deep root system of shrubs (Cerny et al., 2002), and thereafter the subsequent irrigation level was lowered, to reflect the scarcity of water in the region.

The mulching material used was wheat straw at three levels (8000 kg/ha, 4000 kg/ha and 2000 kg/ha). Wheat residue was chosen, because farmers in the area plant wheat after the cultivation of rooibos for 1 to 2 years, before planting rooibos again; moreover, wheat straw is used as mulch among grape vines in the Western Cape (Myburgh, 2013). The mulching level of 8000 kg/ha was recommended in the work done by Myburgh (2013), and the lower levels were used to see the effect of mulching when the amount of mulching material was inadequate.

The combined effects of both treatments (irrigation and mulching) were thus tested in the model.

Table 3.5 A brief description of the sensitivity experiments. The names of the simulations used in each experiment are in bold.

Experiments	Purpose	Number of simulations with model set-ups
Soil moisture and rooibos	To see the effect of rooibos growth on soil moisture under rainfed condition	Two simulations, namely, **bare soil** and **rooibos** field (growing in deep soil under rainfed conditions). The cumulative evapotranspiration and soil moisture are presented in Figs. 3.6 and 3.7. Soil moisture from 10 soil layers, with each layer being 20 cm deep, was compared. Soil moisture layer 1 (**SML1**) is 0 to 20 cm deep, Soil moisture layer 2 (**SML2**) is 20 to 40 cm deep, Soil moisture layer 3 (**SML3**) is 40 to 60 cm deep, Soil moisture layer 4 (**SML4**) is 60 to 80 cm deep, Soil moisture layer 5 (**SML5**) is 80 to 100 cm deep, Soil moisture layer 6 (**SML6**) is 100 to 120 cm deep, Soil moisture layer 7 (**SML7**) is 120 to 140 cm deep, Soil moisture layer 8 (**SML8**) is 140 to 160 cm deep, Soil moisture layer 9 (**SML9**) is 160 to 180 cm deep, Soil moisture layer 10 (**SML10**) is 180 to 200 cm deep.
Soil depth	To see the effect of soil depth on shoot biomass of rooibos under rainfed conditions	Two simulations with different soil depth (shallow soil: 0.9m; deep soil: 2.1m; hereafter **SS** and **DS**)
Mulching	To see the effect of mulching on shoot biomass of rooibos in deep and shallow soil	Mulch material: Wheat residue. Three simulations with different amounts of mulch (MUL = 2000, 4000 and 8000 kg; hereafter, **ML2, ML4** and **ML8**, respectively) for shallow and deep soil each.
Irrigation	To see the effect of irrigation on shoot biomass of rooibos in deep and shallow soil	Irrigation frequency: Once a week Irrigation period: December to March Type of irrigation: Drip irrigation Two simulations with different amounts of irrigation water (IR = 12.5mm and 25.4mm; hereafter **IR12** and **IR25** respectively) for shallow and deep soil each.
Combined Irrigation and mulching practise	To see the effect of combining different levels of mulching and irrigation on shoot biomass, and checking which of the combinations give the highest yields	Six simulations of different combination of mulching and irrigation water: IR = 12.5mm and MUL = 8000 kg/ha (i.e. **IR12ML8**) IR = 12.5mm and MUL = 4000 kg/ha (i.e **IR12ML4**) IR = 12.5mm and MUL = 2000 kg/ha (i.e **IR12ML2**) IR = 25.4mm and MUL = 8000 kg/ha (i.e. **IR25ML8**) IR = 25.4mm and MUL = 4000 kg/ha (i.e. **IR25ML4**) IR = 25.4mm and MUL = 2000 kg/ha (i.e. **IR25ML2**)
Agricultural practises and soil moisture	To see the effect of irrigation and mulching both individually and combined in growing rooibos on soil moisture	A comparison of average extractable soil moisture of **ML8**, **ML4**, **ML2**, **IR12**, **IR25**, **IR12ML8**, **IR12ML4**, **IR12ML2**, **IR25ML8**, **IR25ML4**, **IR25ML2** was presented in Fig. 3.11.

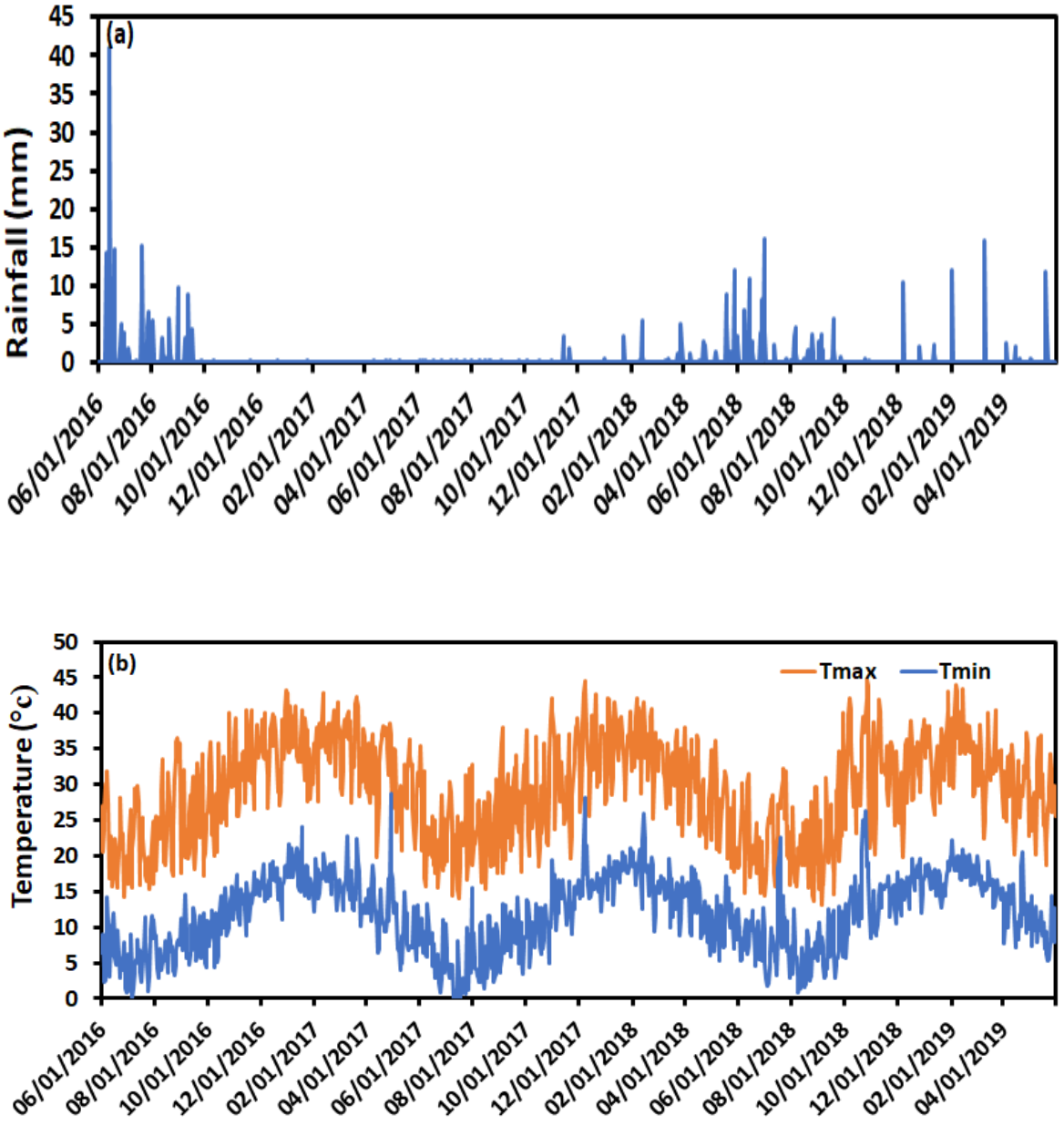


Fig. 3.1: Observational daily weather data in the Clanwilliam region used in simulating the result in the model (a) rainfall (b) maximum (T_{max}) and minimum (T_{min}) temperature.

3.3 Results

This section presents model evaluation using glasshouse and field observational data and model application. The model was applied to study the sensitivity of rooibos growth to soil moisture, soil depth, mulching and irrigation.

3.3.1 Model evaluation

3.3.1.1 Model evaluation using the glasshouse experiments

This section presents the capability of the model to simulate rooibos growth in the glasshouse experiment reported in the previous chapter, by using the observed weather data in the glasshouse experiment to run the simulation in the model, and then comparing the results of the model simulation with the observed results.

Fig. 3.2 compares the temporal variation of the simulated rooibos shoot biomass with the observation. The model simulation agrees with one observation point at 125 days after planting, but it underestimates the biomass of the harvest at 225 days after planting by 50% under glasshouse conditions.

Fig. 3.3 presents the simulated and observed relationships among three important agroclimatic variables (ET, Temp and SM). The simulation agrees with the observation on the positive correlation between air temperature and ET, except that the correlation is stronger in the observation (r=0.9) than in the model simulation (r = 0.5). The simulation also agrees with the observation on the negative correlation (r = 0.9) between ET and SM. Furthermore, both simulation and observation show a negative correlation between the air temperature and SM, but the observation (r = -0.8) is stronger than the model simulation (r = -0.43). However, the actual value of evapotranspiration in the glasshouse is larger than that of the model, and the actual value of soil moisture in the model is larger than that of the glasshouse study.

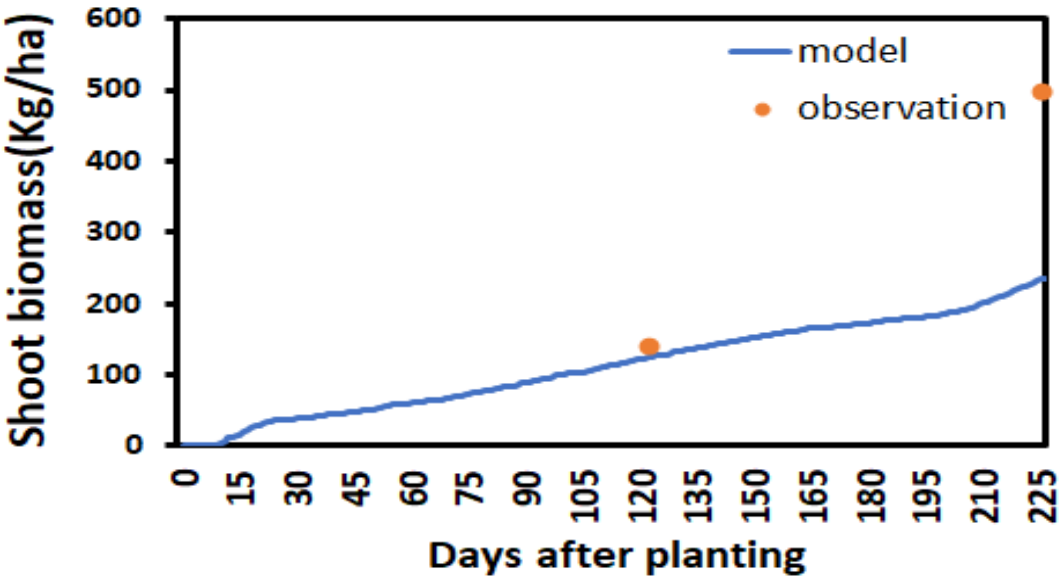


Fig. 3.2: A comparison between the model simulation in lines and the observed data in shapes (orange dot) from glasshouse measurement for dry shoot biomass.

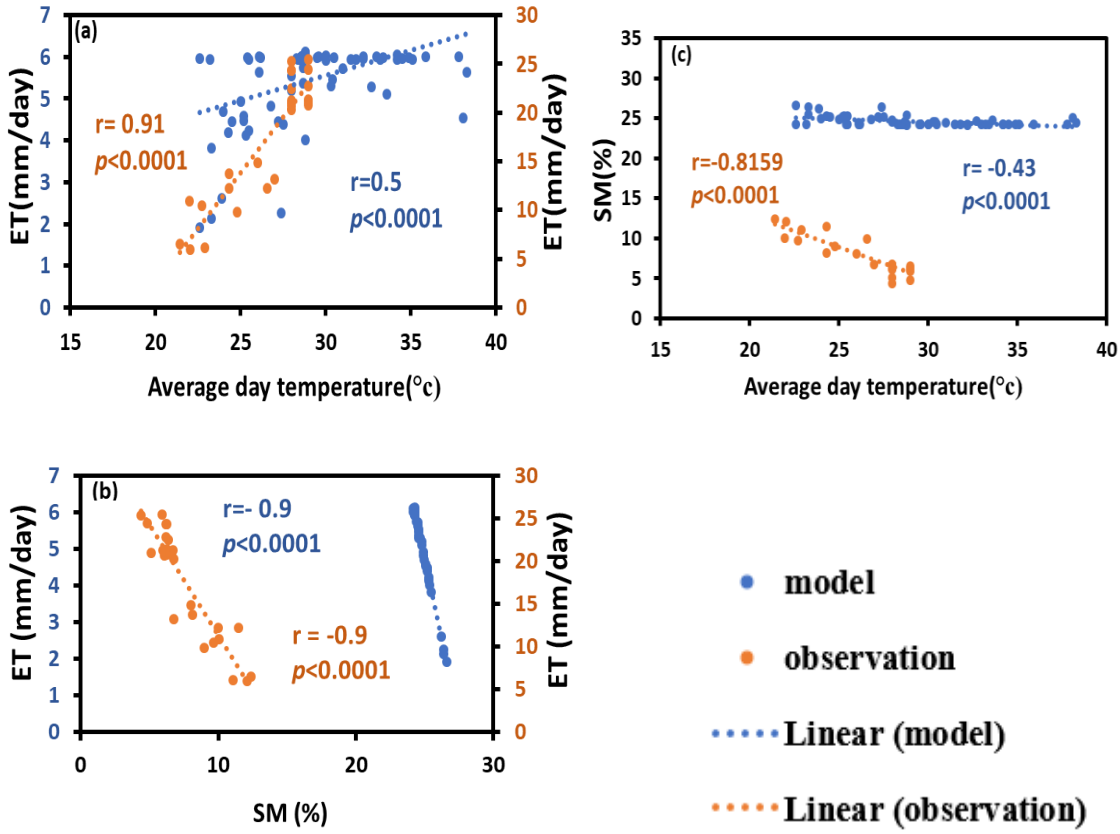


Fig. 3.3: The relationship between (a) temperature and evapotranspiration (ET), (b) soil moisture (SM) and evapotranspiration, and (c) average temperature and soil moisture. The letter r refers to the correlation value, and p is the probability value.

3.3.1.2 Model evaluation using field observation

The capacity of the model to simulate the shoot biomass of rooibos in field experiments was presented in this section by focusing on the part of rooibos that is used for production of tea. The weather and soil data from Clanwilliam were used in the model simulation and the observed shoot biomass from MacAlister et al. (2020) and Van Schalkwyk (2018) were compared with the simulation. The results of the comparison are presented in Figs. 3.4 and 3.5.

The model captured the slow growth curve for the first 399 days, after which the curve changes to a steeper curve, indicating rapid growth. It was also shown in earlier reports that rooibos grows rapidly after the first year (MacAlister et al., 2020a). The capturing of the steep growth curve is crucial for the correct simulation of the shoot biomass. The biomass produced by the model is in good agreement with the observational data, with a Willmott Agreement Index value of 0.94, RRMSE value of 0.29 and R^2 value of 0.83 (Fig. 3.4).

To further evaluate the model, the cumulative ET was compared with the observed data under field conditions. The model simulations agreed with the observational field data, with a d value of 0.56, RRMSE of 0.82 and R^2 value of 0.97 for cumulative ET (Fig. 3.5).

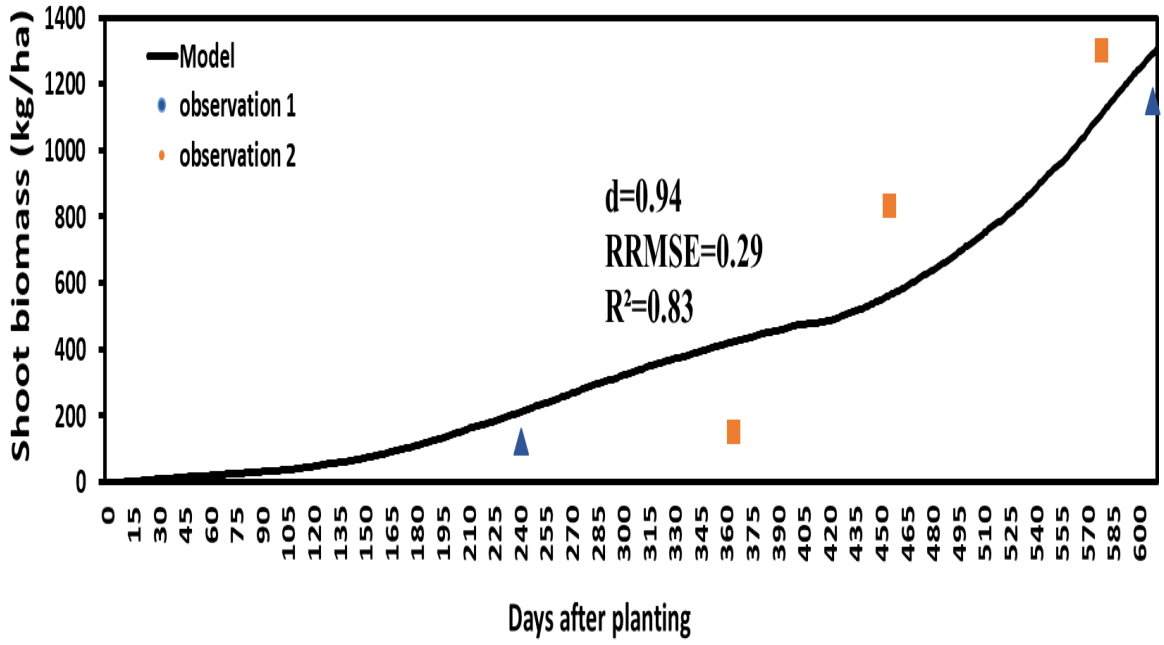


Fig. 3.4: A comparison between the model simulation (the solid line) and the observed data (triangle and rectangle) for dry shoot biomass. The triangle shape represents the observational data from MacAlister et al. (2020a), while the triangle shape represents the observational data from Van Schalkwyk (2018). d is 0.94, RRMSE is 0.29, and R^2 is 0.83.

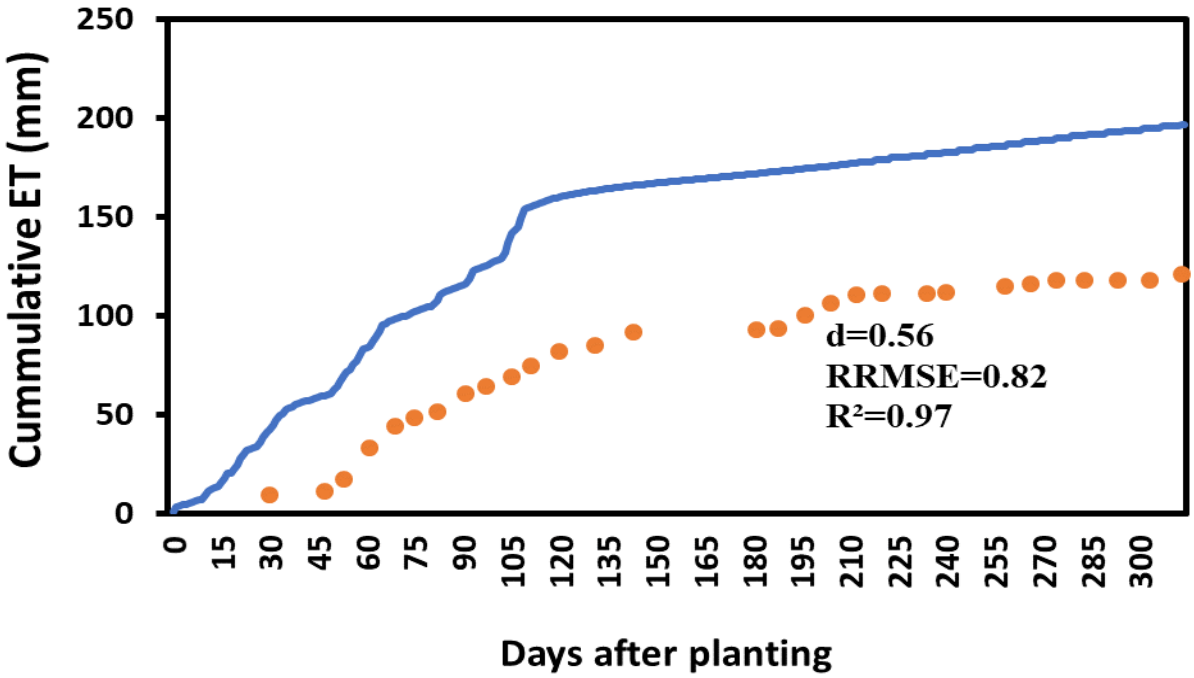


Fig. 3.5: A comparison of model simulation (complete line) and observational data (dotted line) from Van Schalkwyk (2018) for cumulative evapotranspiration. d is 0.56, RRMSE is 0.82, and R^2 is 0.97.

3.3.2 Model application

This section presents the results of the sensitivity experiments, in which the model was used to study the effect of rooibos growth on soil moisture, and the effect of mulching and irrigation on rooibos yields. The model simulations used are the ones evaluated with the field experiments, except that the periods of the simulation are longer, and the experiment is set up based on the objective of the study. Table 3.5 above briefly summarises the information about the experiments and indicates the numbers and names of the simulations performed for each experiment, and Fig. 3.1 gives the rainfall and temperature data used in the simulation experiments.

3.3.2.1 Effect of rooibos growth on soil moisture

The effect of rooibos growth (3-year-old shrubs) on soil moisture was explored by comparing bare soil cumulative evapotranspiration and extractable soil moisture (the maximum amount of moisture that can be extracted from the soil) in the soil over the same period of time within the rooibos field. In Fig. 3.6a, it can be seen that the rooibos field had overall higher cumulative evapotranspiration than bare soil. When studying the slope of the bare soil, a relatively slow and flat line can be seen from day 150 to day 720, which is the result of a drought that occurred in 2017. The Clanwilliam region received very little rainfall (only 12.36 mm) in 2017, as can be seen in the observational weather data in Fig. 3.1a. During this period, in the rooibos field, the slope was slow but not flat, and the rooibos field showed higher cumulative evapotranspiration than the bare soil. A comparison of the simulated cumulative evapotranspiration of the rooibos field with bare soil at different soil depths showed that evapotranspiration of the rooibos field from 2.1 m depth was 33% higher than that of the bare soil. Also, a comparison of the extractable soil moisture showed that the reduction in extractable soil moisture was greater in the rooibos fields than in the bare soil (Fig. 3.6b).

In Fig. 3.6c, the moisture for rooibos in the topsoil (SML1; 0 to 20cm depth) was similar to that in the bare soil, while in the other 9 layers (SML2 to SML10), the soil moisture in the rooibos field was lower than that of the bare soil. Among these 9 layers, SML5 (80 to 100cm depth) had the highest decrease of 25%, followed by SML4 (60 to 80cm depth) and SML3 (40-60cm depth), which showed a decrease of 20 and 19.4% respectively. The remaining soil layers, i.e., SML2 (20 to 40cm depth) and SML6 to SML10 (100 to 200cm depth), were similar in their decrease, which ranged from 11 to 14%.

To further study the effect of rooibos cultivation on soil moisture using the model, Fig. 3.7 compared monthly average soil moisture in four layers, namely, SML1, SML2, SML5 and SML10. For the topsoil SML1 (0 to 20 cm depth), the soil moisture content in rooibos was similar to that of the bare soil, although both the bare soil and the rooibos field showed fluctuations between the months, with the highest soil moisture occurring in June while the lowest occurring in November. The soil moisture in SML2, SML5 and SML10 in the rooibos field was lower than that of the bare soil, although the decrease varies from month to month, and the degree of variation between the months differs from layer to layer. The layer SML2 (20 to 40 cm depth) had the highest variation in decrease between the months, ranging from a 1% decrease in July to a 29.5% decrease in April. The next was SML5 (80 to 100 cm depth), which had a 14% decrease in June and a 32% decrease in April. SML10 had the lowest variation in decrease, ranging from 10% decrease (June and July) to 19% decrease (April).

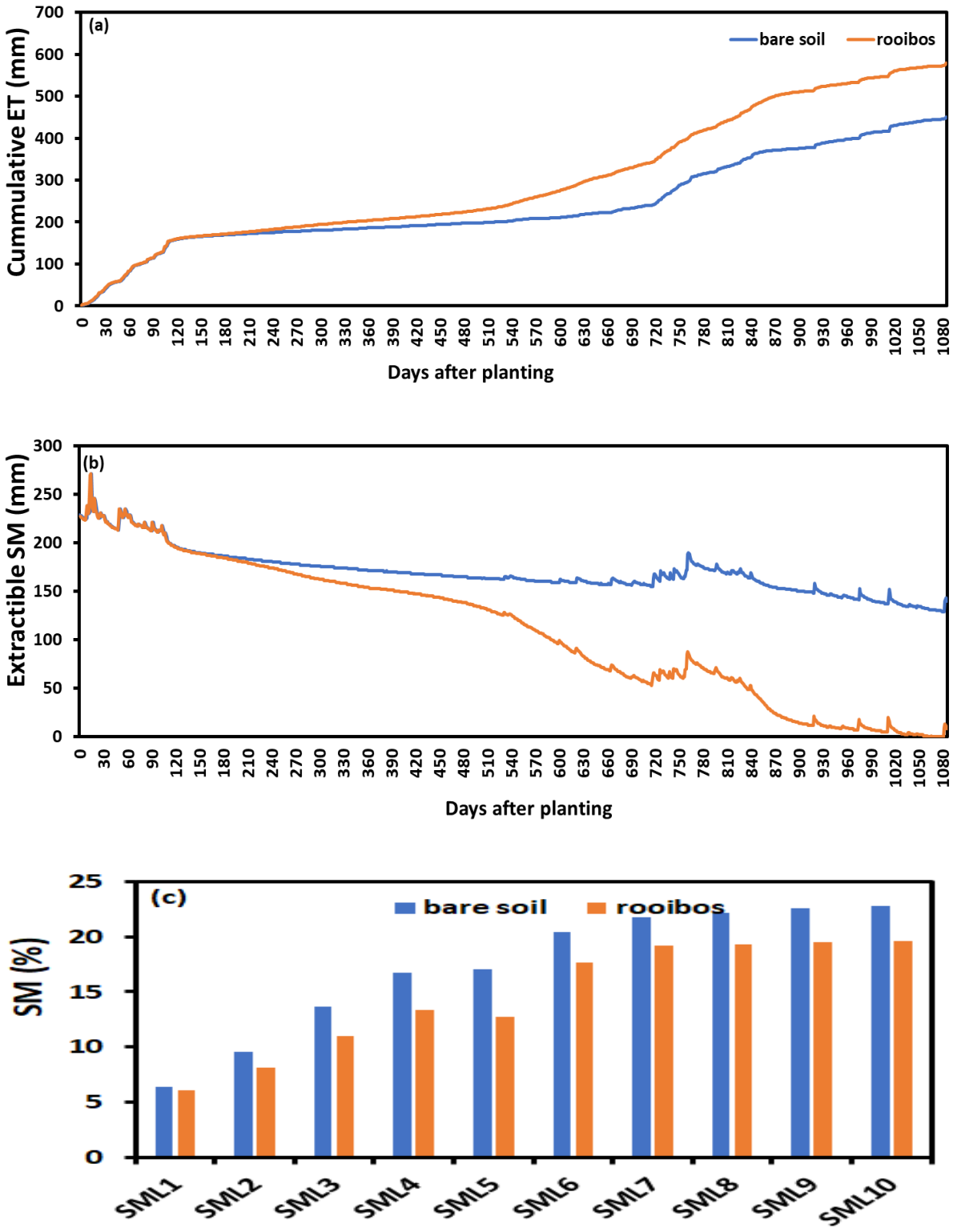


Fig. 3.6: A comparison of rooibos and bare soil simulations: (a) daily evapotranspiration, (b) total extractable soil moisture in the soil profile, (c) average of daily soil moisture for 3 years in each layer. SML represents the soil moisture layers, and each layer is 20 cm deep.

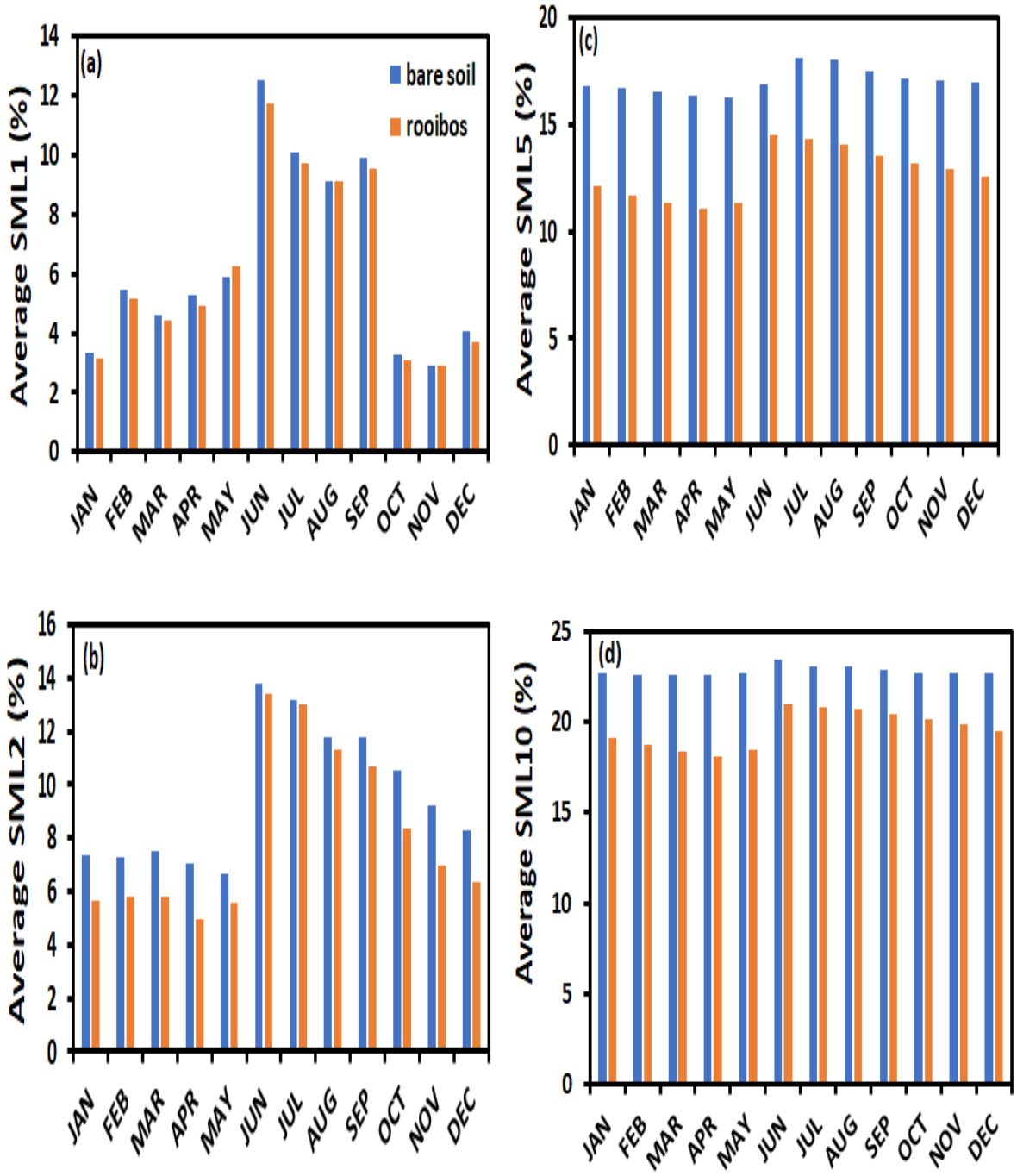


Fig. 3.7: A comparison of monthly average soil moisture for three years between bare soil and rooibos for (a) SML1, representing 0 to 20 cm depth, (b) SML2, representing 20 to 40 cm depth, (c) SML5, representing 80 to 100 cm depth, and (d) SML10, representing 180 to 200 cm depth.

3.3.2.2 Sensitivity of rooibos yield to shallow and deep soil

Fig. 3.8 shows that, within the first 300 days after planting, the difference between rooibos shoot biomass in both shallow and deep soil is not discernible. However, after 300 days, the difference gradually increased to about 200 kg/ha by 570 days, and increased rapidly afterwards, with biomass yields from deep soil higher than those of shallow soil. At the end of the simulation, the rooibos yield was about three times higher in deep soil than in shallow soil. Hence, while the rooibos shoot biomass increases gradually with time in shallow soil, it had an exponential increase in deep soil.

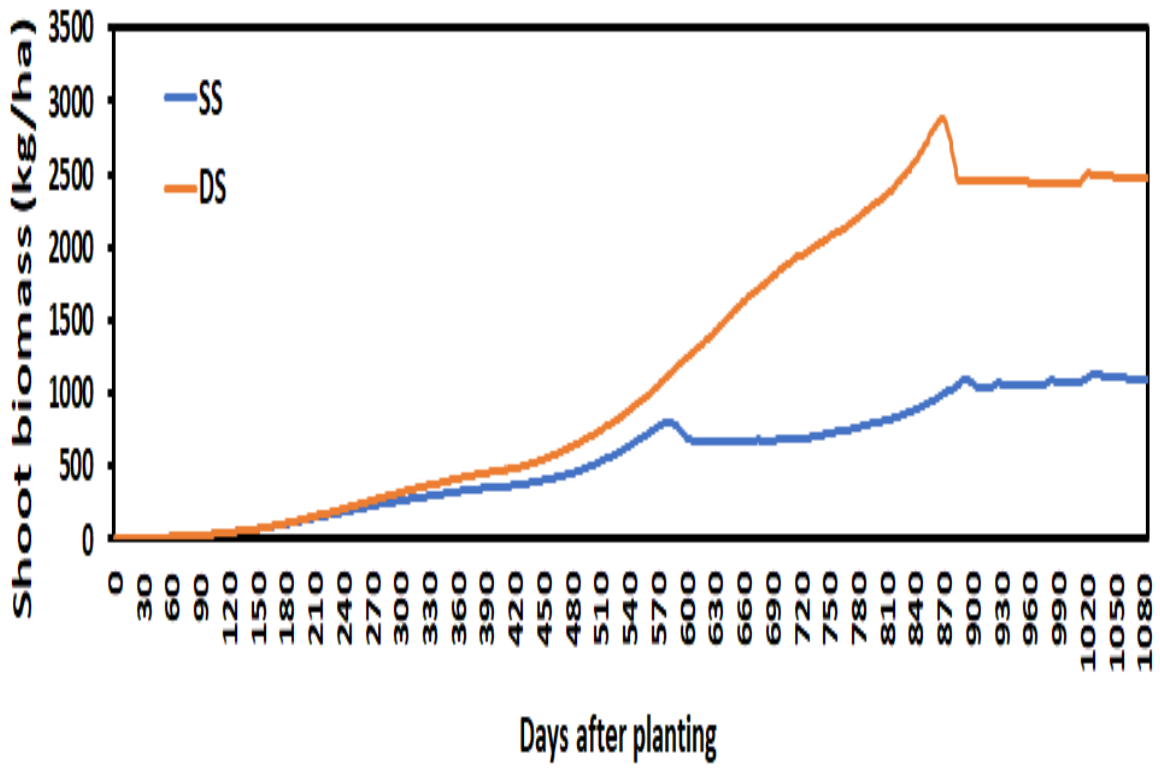


Fig. 3.8: A comparison of simulated dry rooibos biomass yield in shallow soil (SS) and deep soil (DS) under rainfed conditions.

3.3.2.3 Effect of mulching on rooibos yield

Fig. 3.9 shows that mulching increases the shoot biomass in both shallow and deep soil. However, in the deep soil, mulching starts to increase the shoot biomass after 850 days (about 2 years) of planting, while in shallow soil, the increase starts about 260 days earlier (i.e. 590 days after planting). Furthermore, in both shallow and deep soil, ML8 (i.e. 8000 kg/ha mulching) shows the highest biomass among the three treatments, while ML2 (2000 kg/ha mulching) shows the lowest. At the end of the simulation, ML8, ML4 and ML2 treatments increased shoot biomass by 135%, 111% and 67% respectively in shallow soil relative to the control, while in deep soil, it increased shoot biomass by 85%, 72% and 47% respectively.

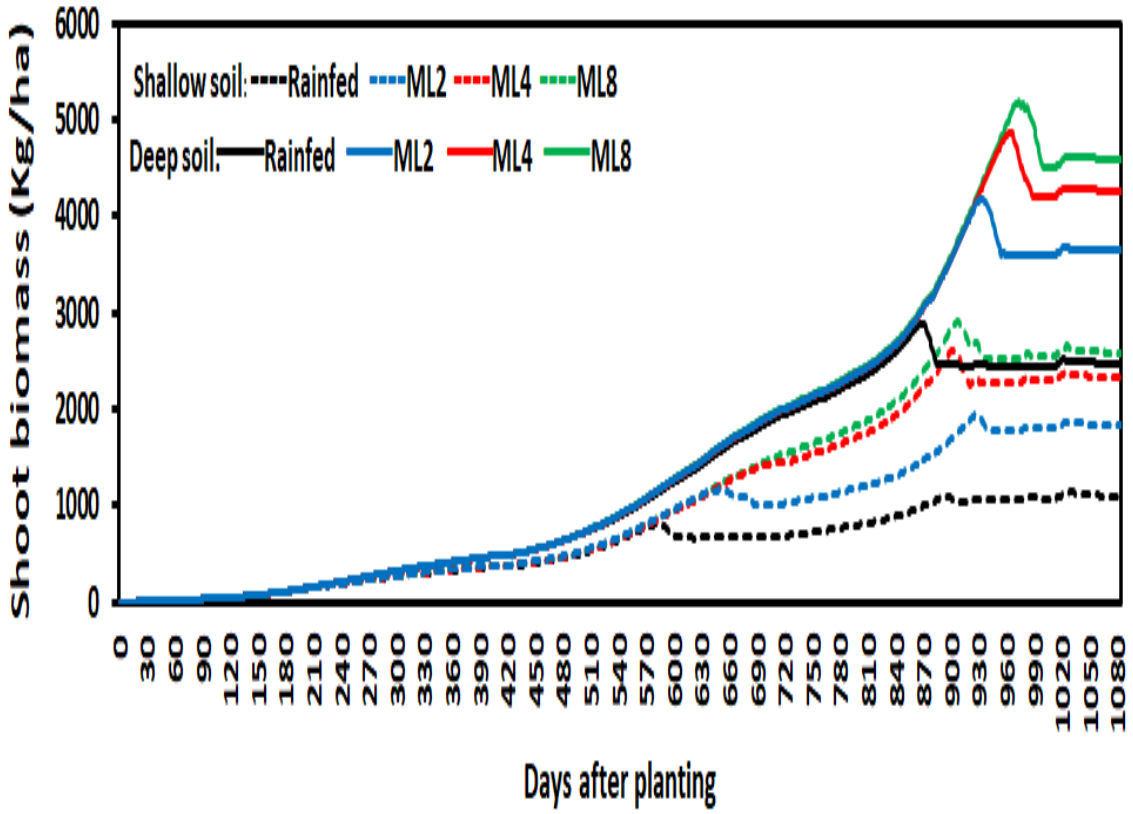


Fig. 3.9: A comparison between simulated shoot biomass under three different levels of mulching (8000 kg/ha, ML8; 4000 kg/ha, ML4; and 2000 kg/ha, ML2) for shallow and deep soil in the rainfed model.

3.3.2.4 Effect of irrigation on rooibos yield

In shallow soil, the shoot biomass of the irrigated rooibos starts becoming larger than that of rainfed rooibos at around 550 days after planting; but, in deep soil, the shoot biomass of the irrigated rooibos started to become larger than that of rainfed at around 870 days after planting (Fig. 3.10). Irrigating at 25.4 mm in deep soil resulted in the highest shoot biomass and irrigating at 25.4 mm in shallow soil resulted in the second highest biomass at the end of the simulation. By the end of the simulation, IR12 and IR25 increased rainfed shoot biomass by 180% and 390% respectively, while in deep soil IR12 and IR25 increased shoot biomass by 66% and 160% respectively.

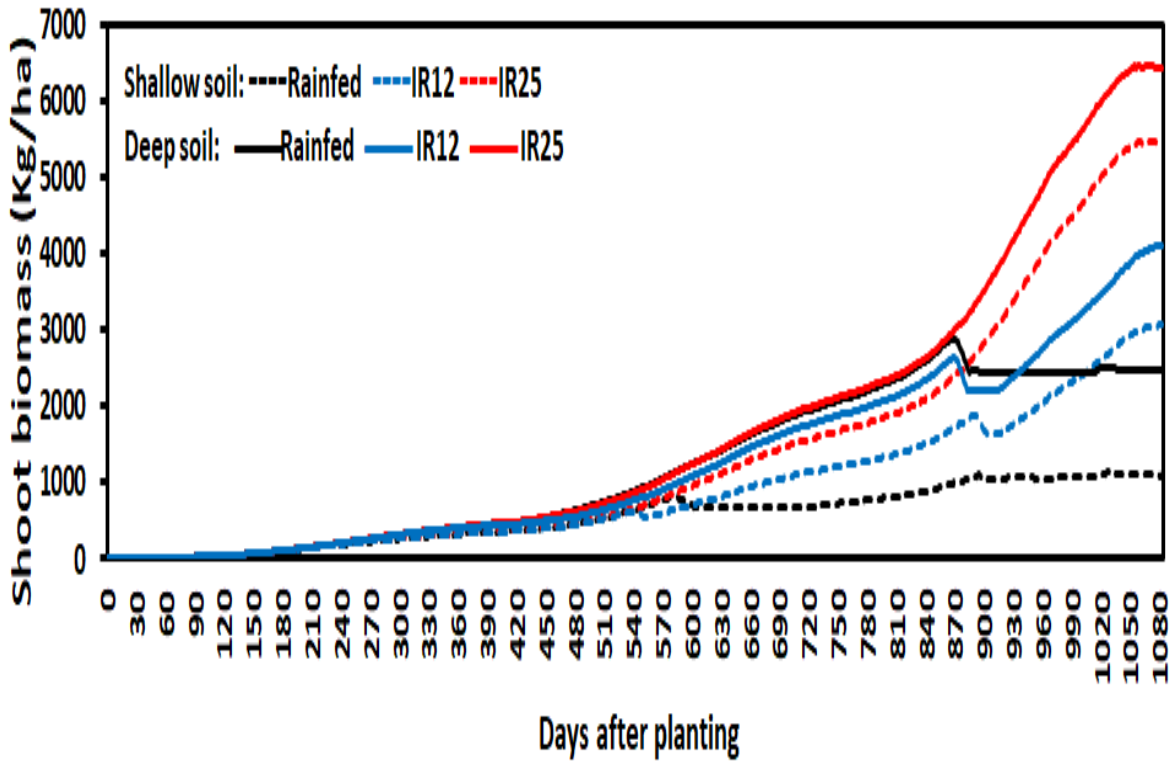


Fig. 3.10: A comparison of simulated shoot biomass for two different levels of irrigation (IR) applied once a week at 25.4mm (IR25) and 12.5mm (IR12) in deep soil and shallow soil.

3.3.2.5 Effect of combining mulching and irrigation on rooibos yield

Fig. 3.11 shows the results of combining different levels of mulching with irrigation and comparing these results with mulching and irrigation when these are applied alone. In both deep and shallow soil, the six combined treatments gave shoot biomass results that were higher than only irrigating at 12.5 mm and mulching at 8000 kg/ha. The biomass yield from the combined treatments were high, and similar to only irrigation at 25.4 mm, except for the yield from IR12ML2 treatment, which was lower in deep soil (Fig. 3.11a).

Relative to the control plants, all the treatments contributed a greater shoot biomass increase in shallow soil than they did in deep soil (Fig. 3.11b). For instance, the IR12ML4 treatment contributed 396% more biomass in shallow soil and 172% in deep soil under rainfed growth conditions.

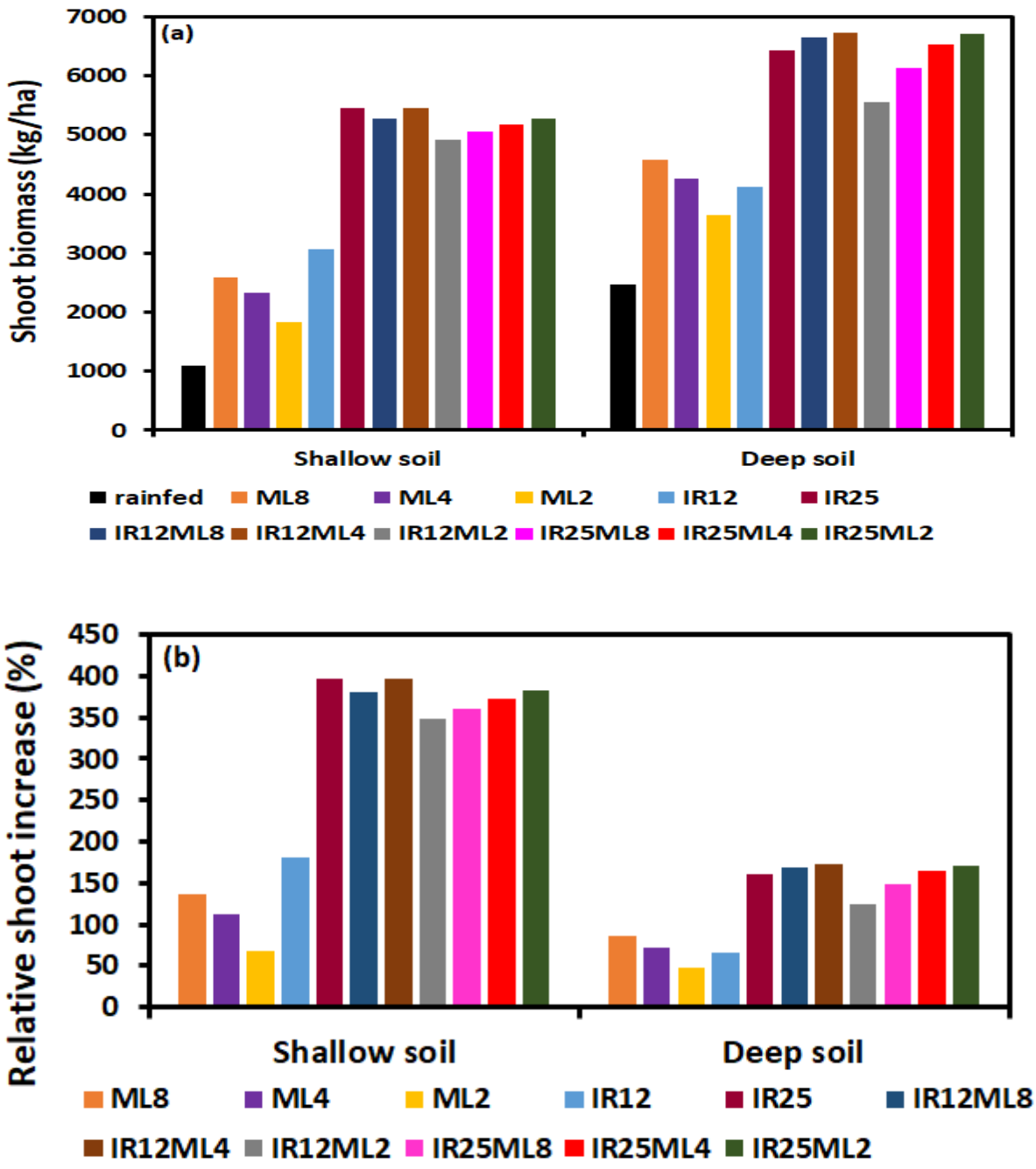


Fig. 3.11: A comparison of different levels of combined irrigation and mulching with irrigation and mulching alone in deep soil (DS) and shallow soil (SS) using simulated data: (a) Shoot biomass (b) Percentage increase of each of the treatments compared to rainfed growth conditions.

3.3.2.6 Effect of mulching and irrigation in rooibos on soil moisture

This section compares the effect on soil moisture of mulching and irrigation both separately and in combination. There was higher extractable soil moisture in deep soil relative to shallow

soil for all treatments. Mulching retained more extractable soil moisture than did the control rainfed plots, and mulching at ML8, ML4 and ML2 increased the rainfed soil moisture by 38%, 32% and 22% respectively in deep soil, and by 49%, 41%, 29% respectively in shallow soil (Fig. 3.12). For irrigation, irrigating at 12.5 mm reduced soil moisture by 14% in shallow soil and 43% in deep soil when compared to rainfed soil moisture (Fig. 3.12), while irrigating at 25.4 mm in deep soil was similar to the rainfed control, and irrigating at 25.4 mm in shallow soil was higher than the control rainfed by 13% (Fig. 3.12). Irrigation combined with mulching showed the highest extractable soil moisture relative to the rainfed control plots, except for IR12ML2, which was similar to the control in the deep soil and higher than the rainfed soil moisture by 33% in shallow soil (Fig. 3.12). The highest among all the combined treatments was irrigation combined with 8000 kg/ha; IR25ML8 and IR12ML8 increased the rainfed soil moisture by 197% and 190% respectively in shallow soil and 104% and 100% respectively in deep soil (Fig. 3.12). IR25ML4, IR25ML2 and IR12ML4 increased rainfed soil moisture by 178%, 163%, 146% respectively in shallow soil and 95%, 86%, 79% respectively in deep soil (Fig. 3.12).

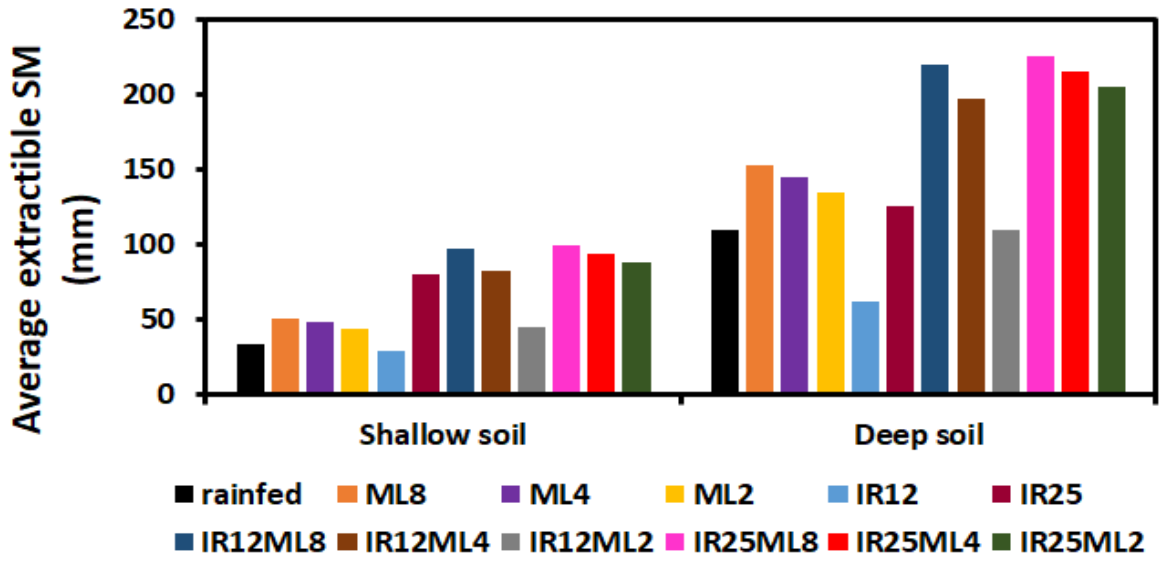


Fig. 3.12: A comparison of the effects on extractable soil moisture of different levels of irrigation and mulching both alone and in combination.

3.4 Discussion

This study presents the first crop model to be adapted specifically for rooibos. The rooibos crop model performed better in the field experiments than in the glasshouse experiment. The poor performance of the model under glasshouse conditions could be as result of the model being built to simulate field environment and not glasshouse conditions. Also, the discrepancy in biomass under glasshouse conditions may be as a result of the input of climactic data (Fig. 3.2). DSSAT-CSM uses the Priestley and Taylor equation derived in 1972 where solar radiation is required in calculating photosynthesis and evapotranspiration (Boote, 2019). The data for solar radiation for the glasshouse was not measured and was also not available from the literature. Consequently, solar radiation from the field data was used in the model and this might have reduced the effectiveness of the model under glasshouse conditions. Also, the discrepancy in the actual values of evapotranspiration and soil moisture loss could be as a result of the lack of windspeed data in the glasshouse. In addition, the amount of water given to the plants in the glasshouse experiments was 250 ml of water daily. This amount of water is similar to 13.4 mm rainfall daily using the surface area of the pot in which the rooibos shrubs were grown in the glasshouse. However, such an amount of daily rainfall would supply too much moisture under field conditions, therefore reducing the effectiveness of the model. Nonetheless, the model performed well under field conditions, partly because of the incorporation of suitable climatic and field physiological values (Fig 3.4). In the simulation of the pattern of growth of rooibos in the first year, slow growth was observed, and this did not change when irrigation was applied to the rooibos plants (Fig 3.4). This agrees with the results of Stassen (1987) and MacAlister et al. (2020a) that showed slow growth of rooibos during the first year. The model also performed well in simulating the dry shoot biomass of rooibos, with high Willmott Agreement Index (d=0.94) and coefficient of determination (R^2 =0.83), and a moderate RRMSE of 0.29 (Fig 3.4).

Although the R^2 value for cumulative evapotranspiration is 0.97, which means that there are small differences between the measured and simulated values, thus indicating that the model was good, the RRSME values however indicated that the model overestimated the ET (Fig. 3.5). This poor performance may be as a result of the inadequacy of the model, or of the quality of the observational data. The observational data used in evaluating the model employed a soil moisture probe to measure the soil water content (SWC) of the soil, and observational weather data from the nearest weather station to calculate evapotranspiration. However, this weather data may not be a true representation of the amount of rainfall received by the plot. Furthermore, the soil moisture data obtained may not be a true representative of the water taken-up by rooibos because the soil probe used for the observations did not go deeper than 80 cm whereas rooibos tap root can grow up to 2 to 3 m deep in the soil.

Overall, we recognize the limitation of the model and the need for more calibration to be done on the rooibos model. One major limitation of the model is the lack of enough observation and physiological data to calibrate the model. Also, the model over estimated evapotranspiration. However, this is a sensitivity study in which the consistent model bias will cancel out the over estimation for evapotranspiration. Both observation and model result showed similar patterns for evapotranspiration and this important for sensitivity test. Furthermore, the model performed well regarding the yield, and the growth pattern of rooibos in the field. However, further research is also needed to improve the rooibos model to include the yearly harvesting of rooibos and the extension of the simulation to 5-7 years. Although there is need for more calibration to be done on the model, however, this model is useful for sensitivity study.

The simulation experiment in this study showed that during the hot summer months, rooibos evaporates more moisture when compared to bare soil, because of its access to soil moisture (Fig. 3.6). This implies that the depletion of soil moisture occurs during the dry summer months, where the month of April had the most depleted soil moisture from 20 cm to 200 cm

depth (Fig. 3.7). Similar studies done on rubber tree plantation by Giambelluca et al. (2016) in north-eastern Thailand and central Cambodia found high rates of water use by the rubber tree during the dry season, and more than half of the water transpired by the rubber tree during the dry season came from a depth of 1.7 m below the surface. This implies that rooibos survives droughts and dry summers by accessing underground soil moisture under field conditions. Therefore, soil moisture storage is needed for sustainable rooibos cultivation in the area, a topic that requires further studies.

The reduced biomass in the simulation experiments in shallow soil (Fig. 3.8) and the reduction in biomass by 40% in MDS plants in the glasshouse study (Fig. 2.2) confirm that, to get high biomass from rooibos, an adequate supply of soil moisture is needed. Also, in the deep soil the reduction in biomass after 750 days of planting was because of very little rainfall during the time of simulation. This was supported by the high biomass obtained from irrigated rooibos in the simulation's experiments and the decline in biomass was not observed (Fig. 3.10). However, water resources for irrigation are scarce and pose a challenge in the Western Cape (Western Cape Government, 2014; Zwane, 2019). Therefore, the focus will need to be on practices that will help to reduce water loss from the soil. From this study, it can be seen that mulching will increase yield, and that a combination of mulching and irrigation would increase the yield even further (Fig. 3.11). For instance, supplying half the amount of the recommended amount of irrigation (12.5 mm), combined with half the amount of recommended mulching (4000 kg/ha), would be the best option, as this produced a similar amount of biomass as did irrigation only at 25.4 mm. Combining drip irrigation with mulching is a new technique used in semi-arid regions in China in response to water shortages and high evaporation rates (Qin et al., 2016; Liu et al., 2017; Tian et al., 2017). When mulching is combined with irrigation, mulching helps to regulate soil temperature, thereby reducing evapotranspiration and conserving moisture.

Another finding from this study is that an increase in biomass from irrigation and mulching cannot be seen in the first year of growth of rooibos. Similar studies done on switchgrass by Giannoulis et al. (2016) also showed that the application of irrigation did not increase biomass accumulation until the second year. This is because the first year is the period of establishment for these plants. Similarly, because rooibos is a perennial shrub, irrigation and mulching will not increase the biomass until the second year, as seen in the shallow soil, while in deep soil the increase is only seen at the end of the second year and into the third year. This implies that, when experimenting with mulching or irrigation in the field, the time duration should be more than one year.

Furthermore, irrigation and mulching contributed more to an increase in biomass when compared to the rainfed biomass in shallow soil than it did in deep soil. According to Van Schalkwyk (2018), shallow soils have the highest water use efficiency. This may be because shallow soil contains or stores less water than is inadequate for rooibos growth. As a result, shallow soil benefits more from irrigation or mulching

Overall, the rooibos crop model has clearly shown that an increased supply of soil moisture greatly enhances the production of biomass yield in rooibos in the field. Also, rooibos extracts moisture from deeper soil layers, which enables it to hydrate its leaves and to transpire during the summer period for growth and biomass production. Water loss through evapotranspiration is high in rooibos fields, and thus mulching of the plants would be beneficial for increased biomass production. However, it was also found that even better rooibos yields could be obtained when mulching was combined with drip irrigation.

CHAPTER FOUR

General Discussion and Synthesis

This research work combined glasshouse experiment and crop modelling using DSSAT-CSM to study the relationship between rooibos growth and soil moisture. The glasshouse experiment used soil from two different sites to test the effects of different levels of soil moisture on evapotranspiration and biomass accumulation. The crop modelling chapter (Chapter 3) tested the effect of rooibos growth on soil moisture and the effect of different agricultural practices on the production of rooibos and the maintenance of soil moisture using simulation experiments.

From the glasshouse experiment, this study found that rooibos growth tolerates moderate drought stress (MDS), leading to a reduction in biomass of about 40%. Also, it was found that the root of rooibos was sensitive to drying conditions, and that it increased rapidly in length in search of moisture within a few days of drought. In addition, the study confirmed that chlorophyll fluorescence parameters (F_v/F_m and F_q'/F_m') and chlorophyll concentration were not affected by MDS. Furthermore, the level of soil moisture in the soil determines the amount of potential evapotranspiration that will translate into evapotranspiration. As discussed in the Chapter 3, the CROPGRO model in DSSAT-CSM was adapted for rooibos, and it simulated rooibos growth over a three-year period. It was noted that the 3-year-old rooibos depleted moisture from soil layers as deep as 200 cm during the dry summer and especially during droughts to survive and continue growing. In addition, mulching was found to be very useful in conserving moisture under both irrigated and non-irrigated conditions. The combination of a medium amount of mulching material (4000 kg/ha) and a lower level of drip irrigation (12.5mm) produced an amount of biomass that was similar to the high amount obtained when only irrigating with water (25.4mm).

The results from the glasshouse study showed that the root of rooibos was very sensitive to drying conditions; within 10 days, the root length increased by 40% among the SDS plants, as they searched for moisture. Also, from MacAlister et al. (2020a), it was confirmed that rooibos increased its stomatal conductance and transpiration during the hot dry summer months, which was associated with leaf cooling as a heat stress tolerance mechanism. This implies that rooibos takes up moisture from deeper soil layers, which enables it to hydrate its leaves and to transpire during the summer period, and thus sustain both photosynthesis and biomass production.

The results from Chapters 2 and 3 highlight the significance of soil moisture for the sustainable production of rooibos. In order for rooibos to produce a sufficiently high amount of biomass to meet the rising demand, an adequate amount of soil moisture is needed. This is consistent with the notion that rooibos prefers deep sandy soil (Stassen, 1987; Van Schalkwyk, 2018) with more water storage capacity than shallow sandy soil. This study finds that there is potential for soil moisture to be depleted because of the high evaporative demand, as a result of high summer temperatures in the rooibos growing regions of the Western and Northern Cape. Furthermore, the projected climate change, which will lead to a reduction in soil moisture and increased evaporative demand, will adversely affect the production of rooibos. It is therefore important to study the soil moisture recharge systems in the rooibos production region.

Since evapotranspiration will be a major challenge under climate change conditions, there is a need to conserve soil moisture. This is particularly important, as soil moisture serves as an interphase in the exchange of water and energy, making it important for evapotranspiration processes (Zhu and Shao, 2008). Maintaining and conserving soil moisture will help to avoid degradation and excessive drying of the soil (Maybank et al., 1995). Mulching is needed to conserve the soil moisture from the winter rainfall (Mulumba and Lal, 2008) by reducing evapotranspiration. Therefore, this study recommends mulching for both rainfed and irrigated farms.

Although irrigation does increase rooibos yields, water resources for irrigation are scarce and pose a challenge in the Western Cape (Zwane, 2019). It is, therefore, highly unlikely that rooibos farms could be irrigated, given the limitations of water resources throughout the region and the high investment cost of irrigation systems. However, mulching is a possibility. There is a need for research to be done on the best type of mulching, that will allow more penetration of water and regulate soil temperature. Organic mulching may be the best type of mulching, but it may not be available in sufficiently large quantities for commercial farming. Plastic mulching or ground cloth mulching are possible alternatives. The plastic mulch poses environmental risk, however, because it is not easily biodegradable and thus has to be removed from the field after use and it causes microplastics to proliferate and leach into the soil (Moreno et al., 2014). Also, plastic mulch, especially the black plastic mulch, heats up the soil temperature; this may be good during cold winters, but poses a risk to plant roots during hot summers (Heißner et al., 2005). In addition, rainfall cannot infiltrate the plastic mulch directly, except when holes are made (Kader et al., 2017). Plastic mulch may be used for annual crops because these only last for few months (Scarascia-Mugnozza et al., 2011). Ground cloth mulching is currently gaining recognition in orchards, as it is highly efficient in conserving water, has a longer life span, restrains weed growth, improves air permeability, regulates soil temperature and allows infiltration of rainfall (Jinfeng et al., 2015). Therefore, there is a need for more research to be done on mulching material that could be used for rooibos production in the Western Cape. Further research is also needed to improve the rooibos model to include the yearly harvesting of rooibos and the extension of the simulation to 5-7 years, and in its agreement with observational data on evapotranspiration. Finally, the quality of rooibos tea was not examined in this study, and thus it would be valuable to research the effect of soil moisture on tea quality.

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APPENDICES

A.1: CROPGRO parameters changed in the Cultivar file

Variable	**CROPGRO PARAMETER**	**Pigeon pea value**	**Rooibos value**	**Source**
Time between plant emergence and flower appearance (photothermal days)	EM-FL	32.7	355	Estimation from Van Rooyen et al., 1999
Maximum leaf photosynthesis rate at 30°C, 350ppm CO_2 and high light	LFMAX	1.1	0.6	Glasshouse study
Specific leaf area of cultivar under standard growth conditions	SLAVR	320	40	Glasshouse study
Maximum size of full leaf (three leaflets)	SIZLF	171.4	4	Glasshouse study
Maximum weight per seed	WTPSD	0.19	0.1	Glasshouse study
Average seed per pod under standard growing conditions	SDPDV	3.89	1	Van Rooyen et al., 1999

A.2: CROPGRO parameters changed in the Ecotype file

Variable	**CROPGRO parameter**	**Pigeon pea values**	**Rooibos values**	**Source**
Time between planting and emergence	PL-EM	5.02	6	Inverse modelling
Rate of appearance of leaves on the main stem	TRIFL	0.8	1.5	Inverse modelling
Relative height of this ecotype	RHGHT	1	1.5	
Slope of relationship reducing progress toward flowering if TMIN for the day is less than OPTBI	SLOBI	0.028	0.05	Inverse modelling

A.3: CROPGRO parameters changed in the Species file

Variable	CROPGRO parameter	Pigeon pea value	Rooibos value	Source
Daily dry matter partitioning to leaf	XLEAF	0.0, 3.0, 6.5, 10.0, 20.0, 35.0, 45.0, 60.0	0.0, 1.5, 2.0, 3.0, 5.0, 7.0, 30.0, 50.0	Inverse modelling
Daily dry matter partitioning to leaf corresponding to the cumulative number of fully emerged leaves given in XLEAF(1-8)	YLEAF	0.47, 0.48, 0.53, 0.46, 0.35, 0.35, 0.25, 0.20	0.60,0.60,0.60,0.40, 0.25, 0.20, 0.20, 0.20	Inverse modelling
Daily dry matter partitioning to stem corresponding to the cumulative number of fully emerged leaves given in XLEAF(1-8)	YSTEM	0.15, 0.15, 0.18, 0.28, 0.44, 0.45, 0.55, 0.62	0.10, 0.10, 0.10, 0.10, 0.10, 0.10, 0.20, 0.25	
Specific leaf area of leaves at plant emergence	FINREF	225	25	Glasshouse study
Specific leaf area of the reference cultivar at early vegetative phase	SLAREF	320	40	Glasshouse study
Upper limit of specific leaf area	SLAMAX	669	60	Glasshouse study
Lower limit of specific leaf area	SLAMIN	245	15	Glasshouse study
Leaf area for three leaves	SIZREF	171.4	4	
Phenology parameter for vegetative development Base temperature (Tb), First optimum temperature (Topt1), Second optimum temperature (Topt2), Maximum temperature (Tmax)	Tb, Topt1, Topt2, Tmax	10, 28, 35, 45	10, 25, 30, 40	MacAlister et al., 2020
Phenology parameter for early reproductive development	Tb, Topt1, Topt2, Tmax	10, 20, 24, 45	10, 25, 30, 40	MacAlister et al., 2020

Base temperature (Tb), First optimum temperature (Topt1), Second optimum temperature (Topt2), Maximum temperature (Tmax)				