Water use and yield of selected indigenous fruit tree species in South Africa

Report to the
Water Research Commission

Prepared by:
Zanele Ntshidi[1], Sebinasi Dzikiti[5], Nompumelelo T. Mobe[1], Nontuthuko R. Ntuli[2], Rosemary Du Preez[4], Noluthando N. Nkosi[2], Lindokuhle N. Buthelezi[2], Lumko Ncapai[3], Leopold Wilkens[5], Mark B. Gush[6], Theodorus H.C. Mostert[2]

[1] Council for Scientific and Industrial Research, Smart Places Cluster
[2] Department of Botany, University of Zululand
[3] Transnet National Port Authority, Richards Bay
[4] ARC Institute for Tropical and Subtropical Crops, Nelspruit
[5] Stellenbosch University, Department of Horticultural Science
[6] Royal Horticultural Society, Wisley, Woking Surrey, United Kingdom

WRC Report No. 2720/1/22
ISBN 978-0-6392-0465-9

August 2022

Obtainable from
Water Research Commission
Private Bag X03
Gezina, 0031
orders@wrc.org.za or download from www.wrc.org.za

The publication of this report emanates from a project entitled *Water use of Indigenous Fruit Tree crops* (WRC Project No. K5/2720//4)

EXECUTIVE SUMMARY

BACKGROUND

Indigenous fruit tree (IFT) species are trees that grow in the wild, bear edible fruit, and they have their origin in South Africa. More than 20 types of IFTs have been identified in South Africa and these grow under a range of bio-climatic conditions across the country. So far, no detailed studies have determined the water use by indigenous fruit tree species in South Africa. Two previous projects funded by the Water Research Commission (WRC K5/1462 & WRC K5/1876) quantified the water use and water productivity of indigenous forests (Dye et al., 2008; Gush et al., 2015; Gush and Dye, 2015). These studies focused only on trees for timber production. Therefore, an important information gap currently exists on the water requirements and water productivity of IFTs in South Africa. This information is essential for maintaining the country's biological diversity, meeting environmental flow requirements for sensitive riparian species, as stipulated in Section 36 of the country's Water Act (1998), and supporting efforts to identify alternative crops through IFT domestication and agroforestry programmes.

With close to 40% of South Africa's population living in communal areas where poverty, unemployment, and food insecurity are high, IFTs are an important source of food, nutrition, and household incomes. They also provide medicine, building poles, firewood and fibre. Other products include jams, dried products, skin care products, beverages, etc. Elsewhere in Southern Africa, indigenous fruit are estimated to contribute as much as 42% of the natural food basket that rural households rely on (Akinnifesi et al., 2008). Despite their importance, these species are being lost to agricultural and urban expansion, and over exploitation through harvesting. Better management practices are required for the sustainable development of IFTs to create income-earning opportunities, prevent soil erosion, and to protect catchment water sources.

The Water Research Commission therefore initiated and funded this five-year project to close these important information gaps. The goal was to provide critical information relating to the ecophysiology of various IFT species that have the potential for domestication and commercialisation. To ensure that data were collected on priority species, the project commenced with a stakeholder engagement involving participants from various sectors, e.g. NGOs, universities, nurseries, etc. The aim of this engagement was to identify at most five IFT species that have a high domestication and commercialization potential out of the more than 20 species found in South Africa. Clearly, it was not possible to cover all the species in view of the limited time and resources. Next, detailed data were collected on the priority species over a period of at least two years per species. This is because indigenous fruit trees have severe alternate bearing tendencies, therefore, representative data could not be gathered in just one season of study. Focus was on trees growing in their natural habitats in the wild, but plants growing in indigenous tree experimental orchards were also used where these could not be found. Another stakeholder engagement was planned at the end of the project to share findings from the research with key stakeholders and to develop guidelines that could be used especially in domestication and commercialisation programmes. However, this could not be done due to restrictions resulting from the Covid 19 pandemic.

RATIONALE

Climate change is exacerbating water scarcity and causing frequent droughts in parts of South Africa (DAFF, 2013) and elsewhere. This means that the production of conventional crops using conventional agricultural practices will encounter greater problems in future given that only ~15% of land in South Africa is arable. Therefore, identifying and promoting alternative crops and cropping systems, e.g. through agroforestry (Everson et al., 2012) or domestication of IFTs (Nkosi et al., 2020) is an important strategy to adapt to climate change especially for resource poor rural households and emerging farmers. Utilisation of the so-called neglected underutilised crops such as IFT is important for the future sustainability of the country's agriculture (Mabhaudhi et al., 2019).

Indigenous fruit tree crops have several advantages over exotic ones. They are better adapted to the marginal and degraded soils often found in communal areas, they have a higher resistance to droughts, have low input and management requirements, the fruit is highly nutritious, and they are resistant to most pests and diseases common in exotic crops. The domestication of IFTs in South Africa has however, been relatively slow perhaps because of the commercial nature of the country's agricultural system.

Numerous pre and postharvest research needs must still be addressed in order to promote the cultivation of IFTs. For example, there is need to remove the many unknowns around the performance of IFTs in different agro-ecological zones and to establish the limits of the species' adaptability to climates and soils. From a commercial fruit production perspective, there is also a need for selections for traits such as larger fruit size with smaller stone and thinner skins, improved precocity, higher yields, less alternate bearing, and greater tolerance to droughts, pests and diseases. Detailed research is also required on the phenology of IFTs in different agro-ecological zones to better understand the timing of leafing, blossoming, fruit drop, and other seasonal features. Related to this is the need to identify male plants that produce pollen when superior females are blossoming for pollination and to increase fruit set.

The selection of indigenous fruit trees with superior qualities is being done by the ARC-Institute for Tropical and Subtropical Crops in Nelspruit. There are also NGOs who are involved in the domestication of indigenous fruit trees in South Africa. However, what is lacking is detailed eco-physiological and agronomic research to support these efforts and this study attempted to provide essential baseline information to support these activities. The research questions investigated in this study were:

- What are the seasonal and annual water use characteristics of key IFTs in South Africa?
- What are the main drivers of IFT water use in their natural habitats?
- What are the key ecophysiological processes that determine the yield of IFTs and how are these influenced by changes in growing conditions?
- What is the water use productivity (grams of fruit produced per m^3 of water transpired) of different IFTs and how does this vary between tree species and between growing regions?

AIMS AND OBJECTIVES

General aims

The overall aim was to quantify water use by selected indigenous fruit tree species, understand their response to environmental variables, and to make recommendations on species suited to specific areas for possible future growth and expansion of indigenous fruit crop production in South Africa.

Specific objectives

These were to:

1) Synthesise and compile available local and international knowledge on indigenous fruit tree species;
2) Shortlist indigenous fruit tree species with commercialisation potential, and to quantify their seasonal and annual water use, fruit and tree growth patterns under a range of bioclimatic conditions;
3) Establish how key physiological processes that determine tree growth and yield respond to environmental variables for IFTs growing in their natural habitats;

4) Develop or adapt appropriate models of water use by indigenous fruit tree crops in order to extrapolate the research results to other regions where IFTs grow, and;
5) Estimate the water productivity of different indigenous fruit tree crops in a range of bioclimatic conditions.

METHODOLOGY

Workshop to identify species with domestication potential

To ensure that the most appropriate species were studied, the workshop was attended by mostly experts who work with indigenous tree species, community engagement projects, and by researchers. The 26 participants were drawn from organisations such as iSimangaliso Wetland Park, Ezemvelo KZN Wildlife, Agricultural Research Council, Siyazisiza Trust (NGO), Transnet, CSIR, University of Zululand and independent consultancies who work with indigenous trees.

The workshop aimed to trim the tree list and to identify a few priority species that have potential for domestication and commercialisation based on the experts' experience and on indigenous knowledge. Most species grow in the wild, although a few were found at experimental stations and in the backyard.

A decision was reached, in consultation with the WRC Reference Group, to prioritise species that are semi-managed and likely experience minimum water stress. Their transpiration would represent the maximum unstressed water use, which is a critical consideration in commercialisation programmes where the trees may need to be irrigated. However, the research team was encouraged to also study species suitable for subsistence type utilisation as many households depend on these.

The top ten species that were shortlisted by the workshop participants are shown in Table 1. The participants considered attributes such as: 1) range of uses, 2) abundance, 3) commercial value of the products, 4) ease of propagation, 5) drought and disease tolerance, 6) ease of harvesting, transportation, and storage.

The list of ten species was further trimmed resulting in the following species listed in order of priority:

- Sclerocarya birrea (Marula);
- Strychnos spinosa;
- Vangueria infausta;
- Dovyalis caffra, and;
- Syzygium cordatum

Table 1. Top ten IFT species identified by the participants grouped according to their perceptions of the value and disadvantages of each species.

Species	Pros	Cons
Strychnos spinosa / madagascariensis	Multi-uses, abundant, high commercial value, ease of propagation, drought tolerant, easily harvested, transported & stored.	Thorny
Syzygium cordatum	Multi-uses, high commercial value, there is an existing market for products, riparian stabilisation, firewood, coppices – manageable	Thirsty, fungus prone
Sclerocarya birrea	Multi-use as widely documented	

Species	Pros	Cons
Dovyalis caffra	Multi-use, high in Vitamin C, genetic selection underway (ARC) – amenable to domestication, living fences, jams, etc.	Fairly slow growing (~ 5 yrs to fruiting), thorny.
Ximenia caffra	Has good pulp to seed ratio, drought resistant, size is good for harvesting, aesthetically pleasing	Propagation difficult – need nurse species, thorny, beware of dark spots around fruit.
Vangueria infausta	Multi-use, good quality fruit, easily propagated, high value (alcoholic, dried fruit), drought and nutrient tolerant	Slow growing, hard seed difficult to eradicate.
Harpephyllum caffrum	Multi-use	Very large trees (can top). Has thick invasive roots – limitations for nurseries.
Englerophytum magalismontanum	Multi-use, established markets, high street value, palatable, jams / many products, easily propagated	Fairly slow growing.
Garcinia livingstonei	Multi-use, likeable, good fruit taste (unique), potential for weight-loss market (needs research), dried products, easily propagated	Sparsely distributed in the wild (however, potential for nursery or community planting).
Berchemia zeyheri	Multi-use, high value wood, potential for high value fruit products, common, grows easily, long season of fruiting	Slow growing.

DATA COLLECTION

Data were collected at three different sites in northern KwaZulu-Natal and in the Mpumalanga Province as summarised in Table 2. Species studied included Marula (Sclerocarya Birrea), Monkey orange (*Strychnos Spinosa*), Kei apple (*Dovyalis Caffra*) and Wild meddler (*Vangueria Infausta*).

Table 2. Summary of the study sites and species investigated during the period January 2018 to December 2021.

Species common name	Scientific name	Duration	Location & Province	Coordinates	Peak leaf area index	Soil texture
Marula	S. Birrea	January 2018 to March 2020	Bonamanzi, KwaZulu-Natal	Longitude: 32.2951 Latitude: 28.0567 Altitude: 68	1.2	Deep sandy
Monkey orange	S. Spinosa	January 2018 to March 2020	Bonamanzi, KwaZulu-Natal	Longitude: 32.2951 Latitude: 28.0567 Altitude: 68	1.4	Deep sandy
Marula	S. Birrea	October 2020 to	Hazyview, Mpumalanga	Longitude: 31.0838 Latitude: 25.1093 Altitude: 745	2.6	Clayey loam

Species common name	Scientific name	Duration	Location & Province	Coordinates	Peak leaf area index	Soil texture
		March 2022				
Kei apple	D. caffra	October 2020 to March 2022	Nelspruit, Mpumalanga	Longitude: 30.9716 Latitude: 25.4546 Altitude: 673	1.8	Deep sandy
Wild meddler	V. Infausta	October 2020 to March 2022	Bonamanzi, KwaZulu-Natal	Longitude: 32.2951 Latitude: 28.0567 Altitude: 68	1.7	Deep sandy
Kei apple	D. caffra	October 2020 to March 2022	Bonamanzi, KwaZulu-Natal	Longitude: 32.2951 Latitude: 28.0567 Altitude: 68	1.6	Deep sandy

A quantitative approach was used in this study to collect data on the ecophysiology of different IFT species to understand how the trees responded to environmental changes. Soil – plant – atmosphere interaction data were measured using:

1) automatic weather stations,
2) infrared gas analyser to monitor leaf gas exchange processes like leaf transpiration, photosynthesis, and stomatal conductance,
3) sap flow monitoring techniques to quantify whole tree transpiration rates, and;
4) time domain reflectometer probes to monitor the soil water content in the root zone and beyond

Most of these data collection methods are automated. Therefore, some measurements were collected at hourly intervals throughout the entire study. Phenological events were observed and documented while fruit growth rates were also measured in some cases. Quantitative relationships between tree water use and yield of the IFT species were determined. In this report, water use is taken to mean tree transpiration, as evapotranspiration data was not collected.

RESULTS AND DISCUSSION

As expected, the phenology of trees differed greatly between sites and with tree species. These data were collected only for the KwaZulu-Natal sites due to the proximity of the research team to the study sites. The dates which key phenological events occurred for Marula, Monkey orange, Kei apple, and Wild meddler were noted. Phenological calendars indicating when key events occurred, and their duration were developed (see Appendix A, B, C, and D). Growth curves for some fruit species were also developed.

Transpiration rates derived from the heat ratio sap flow method and leaf gas exchange measurements revealed the complex water relations of the different IFT species as detailed in Dzikiti et al (2022). The drivers of water use and leaf gas exchange varied considerably for co – occurring species, which was not expected. For example, data from KwaZulu-Natal showed that transpiration by Marula trees was strongly driven by rainfall, which influenced the available soil water content. However, a transpiration of a Monkey orange tree growing less than 20 m away was influenced by climatic factors (available energy) rather than by the available soil moisture. Comparison of data on the root system of these two species showed significant differences in the root density, distribution and depth with Monkey orange having a more extensive root system with numerous feeder roots. The significance of these results is that no two IFT species should be treated the same even if they originate from the same environment, as their physiology may be different. Therefore, they may require different management practices, e.g. with respect to irrigation, fertigation, etc. for optimal performance of the trees.

The daily and seasonal water use rates of the IFTs were highly related to the phenology of the trees, especially the duration and quantity of leaves in the canopy. For example, at the KwaZulu-Natal study site, canopy size of the Marula and Monkey orange trees were almost similar with the leaf area index at peak canopy cover of 1.2 and 1.4, respectively. However, Marula had a rather long dormancy period lasting about four months compared with less than one month for Monkey orange in winter. The annual total transpiration for a typical Monkey orange tree (6 061 ℓ/tree) was almost three times that of a Marula tree of similar size, which was only about 2 160 ℓ/tree. Physiological differences in the properties of the transpiration stream also played a part in the observed water use differences. For example, transpiration per unit leaf area was almost double for Monkey orange at about 2.3 ℓ/m^2/d compared with only about 1.4 ℓ/m^2/d for a typical clear day in summer when the trees were not short of water. The corresponding peak daily transpiration was about 36 ℓ for a Monkey orange tree compared to around 19 ℓ/d for Marula.

On average, the yield of Monkey orange trees at KwaZulu-Natal was about 15.2 kg of fruit calculated as an average from 10 trees over two years. This was much higher than the 4.3 kg/tree for the Marula trees. The water productivity (or transpiration ratio), defined as the fruit yield per unit volume of water transpired, was about 2.0 kg of fruit per cubic meter of water transpired by Marula compared to 2.5 kg of fruit per cubic meter of water consumed by Monkey orange. These values are not different possibly because the low yield of Marula is compensated by its low annual water use.

The tree water use rates were also strongly influenced by canopy size and the available soil water. Water consumption by a giant Marula tree growing on clayey soils in Hazyview, Mpumalanga, exceeded 100 ℓ/tree/d. These data suggest that indigenous fruit tree species can use large quantities of water where they can access it. However, the yield can also be large. For instance, this specific Marula tree produced 82 kg of fruit during the 2019 – 2020 growing season, which is almost double the yield of a high performing apple tree.

The soil – plant – atmosphere interaction data collected for the different IFTs were used to develop tree specific transpiration models using the combination Penman – Monteith approach. It is our hope and expectation that this model can be used to estimate the water requirements of specific indigenous fruit tree species in IFT commercialisation and agro-forestry activities. The model largely uses readily available data as inputs, which enhances its chances of utilisation out there.

NEW KNOWLEDGE AND INNOVATION

South Africa is endowed with numerous indigenous plant species many of which are neglected and underutilised. Yet many households still go hungry every day especially in poor rural households. There is need for research and information to support the cultivation of indigenous fruit trees to improve food and nutritional security of the population. This study provides critical baseline information on how indigenous fruit tree species interact with the environment. This information can be used to develop management plans, e.g. for irrigation and other farm operations. Commercialisation of IFTs like Marula whose products are marketed in over 100 countries globally is fast becoming a reality. For example, there is currently an open multimillion-Rand tender by the Industrial Development Corporation (IDC) to develop Marula orchards in the northern parts of the country. Such initiatives are the critical first steps towards the commercialisation of high value indigenous fruit tree species and the data generated in this study will be useful in such endeavours. Besides the detailed eco-physiological information generated about these potential crops, water use models parameterised for individual tree species have been developed and tested. These models can be useful tools for formulating irrigation guidelines for potential future tree crops like Marula. This information has been published in two international peer reviewed journals as detailed in the outputs section of this report. Much research on the potential utility of Marula as an alternative tree crop has mainly been done outside Africa in countries like Israel, China and the Czech Republic (Nerd and Mizrahi. 2000; Li et al., 2015). This study is the first of its kind in the native range for Marula.

CAPACITY BUILDING

Both institutional and individual capacity building were done. Institutional capacity was done through training of staff in the Department of Botany at the University of Zululand. The following people were trained: Dr Nontuthuko Ntuli (lecturer), Mr Prince Sokhela, and Ms Zoliswa Mbhele who are technicians. Training covered include basic data logging principles, uploading and downloading routines for data and programmes, setting up automatic weather stations, installing and troubleshooting heat pulse velocity sap flow systems. Four MSc students were trained on the project. One has completed her study while the other three are expected to graduate by the end of 2022.

CONCLUSIONS

This study has generated useful baseline data on the ecophysiology of high priority indigenous fruit tree species that include *S. birrea, S. Spinosa, D. caffra and V. infausta*. These species grow in large parts of the country and local experts reckon that they have a high potential for domestication and possibly commercialisation. There are currently efforts to plant the first commercial Marula orchards in South Africa and the data on its water use, and yield dynamics generated in this project will be essential for supporting such initiatives. However, the severe alternate bearing tendencies for the indigenous trees meant that more than one year's data were required per site in order to get credible data on the relationships between water use and yield. This had the effect of reducing the number of species that was assessed in this study. Our data shows that the physiology of the trees varied greatly between species. For this reason, a tree-species specific model for water use developed parameterised for each species. We hope this model will be useful for various agroforestry and indigenous plant commercialisation efforts.

RECOMMENDATIONS FOR FUTURE RESEARCH

Several gaps remain if domestication and commercialisation of indigenous fruit trees can gain momentum in the country and elsewhere on the African continent.

1) This study covered only four species. Even for these few species, numerous questions remain;
2) There is need for further research to understand how these species respond to different growing conditions. This study did not do an exhaustive comparison of the performance of the species in different climatic and soil conditions;
3) There is still need to select genotypes that give fruit with the best quality and yield;
4) Commercially viable means to propagate these genotypes should also be established;
5) Some species may require pollinators to perform optimally. The ratio between the fruit bearing trees and pollinators and the respective distances need to be investigated.
6) There are also further research needs postharvest, e.g. there is need to develop postharvest handling practices for indigenous fruit.
7) There is also need to improve the range of commercially viable products that can be developed from indigenous fruit.

ACKNOWLEDGEMENTS & REFERENCE GROUP

We acknowledge support from the Water Research Commission for initiating and funding this study through project number WRC K5/2720//4. Financial contribution from the Council for Scientific and Industrial Research (CSIR), through the Parliamentary Grant (P1DHS01) is also gratefully acknowledged. Many thanks go to Bonamanzi Game Reserve in northern KwaZulu-Natal for allowing us to use their facilities. Their assistance is truly appreciated. We also thank Mr Prince Sokhela and Ms Zoliswa Mbhele from the Department of Botany at the University of Zululand for the technical support during the course of the project. We are grateful to the staff of ARC Nelspruit for always assisting with data collection. Last, but not least, we extend our gratitude to members of the reference group for their guidance and constructive discussions during the course of the project. These include the following:

Dr Luxon Nhamo : Water Research Commission (Chairperson)
Prof Sylvester Mpandeli : Water Research Commission
Dr Samkelisiwe Hlophe-Ginindza : Water Research Commission
Dr P Dye : Retired CSIR Fellow
Prof C Everson : South African Environmental Observation Network (SAEON)
Dr E February : University of Cape Town
Dr N Taylor : University of Pretoria
Mr DB Versfeld : Dirk Versfeld CC
Prof P Chirwa : University of Pretoria

LIST OF ABBREVIATIONS AND SYMBOLS

ROMAN SYMBOLS

A	Branch leaf area	cm^2
A_{st}	Stem cross sectional area	cm^2
C_p	Specific heat at constant pressure	J kg^{-1} K^{-1}
d	Zero plane displacement height	m
e_a	Actual vapour pressure of the air	kPa
e_s	Saturation vapour pressure of the air	kPa
e_0	Actual vapour pressure of the air	hPa
ET_o	Reference evapotranspiration	mm d^{-1}
ET	Actual evapotranspiration	mm d^{-1}
fRs	Stress factor for solar radiation	-
fT	Stress factor for temperature	-
fVPD	Stress factor for vapour pressure deficit	-
$f\theta$	Stress factor for soil moisture	-
g_s	Stomatal conductance	m s^{-1}
g_{max}	Maximum surface conductance	m s^{-1}
h	Tree height	m
H	Sensible heat flux	W m^{-2}
k_{d1}	Parameter for VPD stress factor	kPa^{-1}
k_t	Ratio of the measured solar irradiance to the extra-terrestrial radiation	W m^{-2}
k	Extinction coefficient	-
L	Total leaf area	-
LAI	Leaf area index	-
MAE	Mean absolute error	-
Mw	Molar mass of water vapour	g
Ma	Molar mass of air	g
NSE	Nash-Sutcliffe Efficiency	-
Pa	Atmospheric pressure	kPa
R^2	Coefficient of determination	-
r_a	Average stomatal resistance	s m^{-1}
r_b	Aerodynamic resistance	s m^{-1}
RH	Average relative humidity	%
RH_{max}	Maximum relative humidity	%
RH_{min}	Minimum relative humidity	%
R_n	Net all wave radiation	W m^{-2}
Rn_{tree}	Net radiation absorbed by the tree canopy	W m^{-2}
R_s	Downward solar irradiance	W m^{-2}
R_{ns}	Net shortwave radiation	W m^{-2}
R_{nl}	Net longwave radiation	W m^{-2}
$\bar{r_s}$	Stomatal resistance	s m^{-1}
R_{so}	Clear sky shortwave radiation	W m^{-2}
SF	Stem sap flow	g/h
SWC	Soil water content	cm^3 cm^{-3}
SWC_{max}	Soil water content at saturation	cm^3 cm^{-3}
SWC_{min}	Soil water content at the wilting point	cm^3 cm^{-3}

RMSE	Root means square of error	-
T	Average air temperature	K
Ta	Air temperature	°C
T_c	Hourly average transpiration	g h^{-1}
T_h	Upper temperature	°C
T_L	Lower temperature	°C
T_{max}	Maximum air temperature	°C
T_{min}	Minimum air temperature	°C
U_z	Wind speed at 2.0 m	m s^{-1}
VPD	Vapour pressure deficit of the air	kPa
θ_{FC}	Volumetric soil water content at field capacity	cm^3 cm^{-3}
θ_{WP}	Volumetric soil water content at permanent wilting point	cm^3 cm^{-3}
x	Thermocouple gauge spacing	cm
z	Height of measurement of wind speed	m
z_h	Height of measurement of relative humidity	m
Z_o	Roughness length	-
z_{oh}	Roughness length for heat and humidity	m
z_{om}	Roughness length for momentum transfer	m

GREEK SYMBOLS

α	surface albedo	-
σ	Stefan-Boltzmann constant	-
Δ	slope of saturation vapour pressure vs temperature curve	kPa K^{-1}
ρ	density of air	kg m^{-3}
ε_a	emissivity of the atmosphere	-
ε_s	emissivity of the surface	-
γ	psychrometric constant	kPa K^{-1}
λ	latent heat of vaporisation	Jkg

This page is deliberately left blank

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Indigenous fruit tree (IFT) species are trees that grow in the wild, bear edible fruit, and they have their origin in South Africa. More than 20 types of IFTs have been identified in South Africa and these grow under a range of bio-climatic conditions across the country. So far, no detailed studies have determined the water use by indigenous fruit tree species in South Africa. Two previous projects funded by the Water Research Commission (WRC K5/1462 & WRC K5/1876) quantified the water use and water productivity of indigenous forests (Dye et al., 2008; Gush et al., 2015; Gush and Dye, 2015). These studies focused only on trees for timber production. Therefore, an important information gap currently exists on the water requirements and water productivity of IFTs in South Africa. This information is essential for maintaining the country's biological diversity, meeting environmental flow requirements for sensitive riparian species, as stipulated in Section 36 of the country's Water Act (1998), and to support efforts to identify alternative crops through IFT domestication and agroforestry programmes.

With close to 40% of South Africa's population living in communal areas where poverty, unemployment, and food in-security are high, IFTs are an important source of food, nutrition, and household incomes. They also provide medicine, building poles, firewood and fibre. Other products include jams, dried products, skin care products, beverages, etc. Elsewhere in Southern Africa, indigenous fruit are estimated to contribute as much as 42% of the natural food basket that rural households rely on (Akinnifesi et al., 2008). Despite their importance, these species are being lost to agricultural and urban expansion, and over exploitation through harvesting. Better management practices are required for the sustainable development of IFTs to create income-earning opportunities, prevent soil erosion, and to protect catchment water sources.

The Water Research Commission therefore initiated and funded this five-year project to close these important information gaps. The goal was to provide critical information relating to the ecophysiology of various IFT species that have the potential for domestication and commercialisation. To ensure that data were collected on priority species, the project commenced with a stakeholder engagement involving participants various sectors, e.g. NGOs, universities, nurseries, etc. The aim of this engagement was to identify at most five IFT species that have a high domestication and commercialisation potential out of the more than 20 species found in South Africa. Clearly, it was not possible to cover all the species in view of the limited time and resources. Next, detailed data were collected on the priority species over a period of at least two years per species. This is because indigenous fruit trees have severe alternate bearing tendencies, so representative data could not be gathered in just one season of study. Focus was on trees growing in their natural habitats in the wild, but plants growing in indigenous tree experimental orchards were also used where these could be found. Another stakeholder engagement was planned at the end of the project to share findings from the research with key stakeholders and to develop guidelines that could be used especially in domestication and commercialisation programmes. However, this could not be done due to restrictions resulting from the Covid 19 pandemic.

1.2 RATIONALE

Climate change is exacerbating water scarcity and causing frequent droughts in parts of South Africa (DAFF, 2013) and elsewhere. This means that the production of conventional crops using conventional agricultural practices will encounter greater problems in future given that only ~15% of land in South Africa is arable. Therefore, identifying and promoting alternative crops and cropping systems, e.g. through agroforestry (Everson et al., 2012) or domestication of IFTs (Nkosi et al., 2020) is an important strategy to adapt to climate change especially for resource poor rural households and emerging farmers. Utilisation of the so-called neglected underutilised crops such as IFT is important for the future sustainability of the country's agriculture (Mabhaudhi et al., 2019).

Indigenous fruit tree crops have several advantages over exotic ones. They are better adapted to the marginal and degraded soils often found in communal areas, they have a higher resistance to droughts, have low input and management requirements, the fruit is highly nutritious, and they are resistant to most pests and diseases common in exotic crops. The domestication of IFTs in South Africa has however, been relatively slow perhaps because of the commercial nature of the country's agricultural system.

Numerous pre and postharvest research needs must still be addressed in order to promote the cultivation of IFTs. For example, there is need to remove the many unknowns around the performance of IFTs in different agro-ecological zones and to establish the limits of the species' adaptability to climates and soils. From a commercial fruit production perspective, there is also a need for selections for traits such as larger fruit size with smaller stone and thinner skins, improved precocity, higher yields, less alternate bearing, and greater tolerance to droughts, pests and diseases. Detailed research is also required on the phenology of IFTs in different agro-ecological zones to better understand the timing of leafing, blossoming, fruit drop, and other seasonal features. Related to this is the need to identify male plants that produce pollen when superior females are blossoming for pollination and to increase fruit set.

The selection of indigenous fruit trees with superior qualities is being done by the ARC Institute for Tropical and Subtropical Crops in Nelspruit. There are also NGOs who are involved in the domestication of indigenous fruit trees in South Africa. However, what is lacking is detailed eco-physiological and agronomic research to support these efforts and this study attempted to provide essential baseline information to support these activities. The research questions investigated in this study were:

- What are the seasonal and annual water use characteristics of key IFTs in South Africa?
- What are the main drivers of IFT water use in their natural habitats?
- What are the key ecophysiological processes that determine the yield of IFTs and how are these influenced by changes in growing conditions?
- What is the water use productivity (grams of fruit produced per m^3 of water transpired) of different IFTs and how does this vary between tree species and between growing regions?

1.3 AIMS AND OBJECTIVES

1.3.1 General aim

The overall aim was to quantify water use by selected indigenous fruit tree species, understand their response to environmental variables, and to make recommendations on species suited to specific areas for possible future growth and expansion of indigenous fruit crop production in South Africa.

1.3.2 Specific objectives

These were to:

1) Synthesise and compile available local and international knowledge on indigenous fruit tree species;
2) Shortlist indigenous fruit tree species with commercialisation potential, and to quantify their seasonal and annual water use, fruit and tree growth patterns under a range of bioclimatic conditions;
3) Establish how key physiological processes that determine tree growth and yield respond to environmental variables for IFTs growing in their natural habitats;

Develop or adapt appropriate models of water use by indigenous fruit tree crops in order to extrapolate the research results to other regions where IFTs grow, and; estimate the water productivity of different indigenous fruit tree crops in a range of bioclimatic conditions.

1.4 STUDY APPROACH WORKSHOP TO IDENTIFY SPECIES WITH DOMESTICATION POTENTIAL

To ensure that the most appropriate species were studied, the workshop was attended by mostly experts who work with indigenous tree species, community engagement projects, and by researchers. The 26 participants were drawn from organisations such as iSimangaliso Nature Reserve, Ezemvelo KwaZulu-Natal Wildlife, Agricultural Research Council, Siyazisiza Trust (NGO), Transnet, CSIR, University of Zululand and independent consultancies who work with indigenous trees. The workshop aimed to trim the tree list and to identify a few priority species that have potential for domestication and commercialisation based on the experts' experience and on indigenous knowledge. Most species grow in the wild, although a few were found at experimental stations and in the backyard. A decision was reached, in consultation with the WRC Reference Group, to prioritise species that are semi-managed that likely experience minimum water stress. Their transpiration would represent the maximum unstressed water use, which is a critical consideration in commercialisation programmes where the trees may need to be irrigated. However, the research team was encouraged to also study species suitable for subsistence type utilisation as many households depend on these.

The top ten species that were shortlisted by the workshop participants are shown in Table 1. The participants considered attributes such as: 1) range of uses, 2) abundance, 3) commercial value of the products, 4) ease of propagation, 5) drought and disease tolerance, 6) ease of harvesting, transportation and storage.

The list of ten species was further trimmed resulting in the following species listed in order of priority:

- Sclerocarya birrea (Marula);
- Strychnos spinosa;
- Vangueria infausta;
- Dovyalis caffra, and;
- Syzygium cordatum.

1.4.1 Data collection

Data were collected at three different sites in northern KwaZulu-Natal and in the Mpumalanga Province as summarised in Table 2. Species studied included Marula (Sclerocarya Birrea), Monkey orange (*Strychnos Spinosa*), Kei apple (*Dovyalis Caffra*) and Wild meddler (*Vangueria Infausta*).

A quantitative approach was used in this study to collect data on the ecophysiology of different IFT species to understand how the trees responded to environmental changes. Soil – plant – atmosphere interaction data were measured using: 1) automatic weather stations, 2) infrared gas analyser to monitor leaf gas exchange processes like leaf transpiration, photosynthesis, and stomatal conductance, 3) sap flow monitoring techniques to quantify whole tree transpiration rates, and; 4) time domain reflectometer probes to monitor the soil water content in the root zone and beyond. Most of these data collection methods are automated. Therefore, some measurements were collected at hourly intervals throughout the entire study. Phenological events were observed and documented while fruit growth rates were also measured in some cases. Quantitative relationships between tree water use and yield of the IFT species were determined. In this report, water use is taken to mean tree transpiration, as evapotranspiration data were not collected.

1.5 EXTENT TO WHICH CONTRACT OBJECTIVES HAVE BEEN MET

The contract objectives have largely been met, and in some instances, exceeded. Priority species were identified in a workshop that had experts from the field. These species were monitored, and the data collected used to write papers and calibrate the big leaf modified model. Two peer-reviewed articles were published in international journals and, the plan was to publish one. One of the papers was led by a M.Sc. student. Four M.Sc. students were registered through this project and are in various stages of their theses write-ups, while one graduated in 2020. Lastly, a conference paper has been published by the 6th International Congress on Water, Waste And Energy Management, registered with ISBN.

CHAPTER 2: KNOWLEDGE REVIEW

2.1 INTRODUCTION AND BACKGROUND

Up to 40% of South Africa's population lives in rural areas. These are mostly poor former "Homelands" where poverty, unemployment, and illiteracy are high. Poverty levels are estimated to exceed 70% in some areas, while many households are headed by women and children. As much as 43% of households in provinces, such as rural KwaZulu-Natal are headed by women and children (Stats SA., 2015). These population groups are most vulnerable to food shortages and to rises in food prices given the increasing reliance on food purchases by both urban and rural households reaching up to 90% of the food supplies in some instances (Baiphethi and Jacobs, 2009).

Even though South Africa is a food secure country at the national level, producing enough staple foods and having the capacity to import food if needed, many rural households are in fact not food secure (du Toit, 2011; Altman et al., 2009). According to the General Household Survey by Statistics South Africa (2011), about 25.5% of South African households, mostly in rural areas, have inadequate or severely inadequate food access. This is because yield of staple crops like maize, which is mostly grown under subsistence farming, is generally low and declining as fewer families engage in subsistence farming. Other contributory factors to the low yields include infertile and degraded soils, limited use of technology, and chemical fertilisers, which are beyond the reach of most households. On the other hand, large proportions of the produce from commercial farms are geared towards the export market or processed into commercial products.

Exacerbating food insecurity in rural South Africa is climate change, which is projected to cause frequent droughts and raise air temperatures in parts of the country (Schulze, 2005). This means that the production of conventional crops using conventional agricultural practices will encounter greater problems in future, hence worsening food insecurity. Therefore, identifying and promoting alternative crops and cropping systems, for example, through agroforestry and reverting to and increasing the production of indigenous crops is an important strategy to adapt to climate change especially for the resource poor rural households and emerging farmers (Everson et al., 2012; DAFF, 2011).

This review focuses primarily on indigenous crops. These are defined as crops that have their origin in South Africa and they fall into three categories namely grains, vegetables, and fruit. These crops grow under a wide range of bioclimatic conditions in the country although their production and consumption has been declining over the decades, as farmers preferred the high yielding and high value exotic crops (DAFF, 2011). According to the Department of Agriculture, Forestry, and Fisheries (DAFF, 2011), key challenges that have constrained the development of indigenous crops in South Africa include the fact that:

- The sector is currently fragmented;
- Most of the crops are found and harvested in the wild;
- Production and consumption of indigenous products has declined, and;
- There is little information owing to limited research.

Despite South Africa being endowed with close to 20 edible indigenous fruit tree species (IFTs), this sector, except for Marula (Sclerocarya birrea), is poorly developed. Elsewhere on the African continent, IFTs are estimated to contribute as much as 42% of the natural food basket of rural households (Akinnifesi et al., 2008). IFTs are also an important source of income through the sale of fresh fruit, dried and processed fruit products. This provides poor households with money to buy food and to meet basic nutritional requirements. The IFTs are better adapted to the marginal and degraded soils often found in rural areas. They have a higher resistance to droughts, have low input and management requirements, the fruit is highly nutritious, and they are resistant to most pests and diseases common in exotic crops. Therefore, acknowledging the potential of IFTs in the country will alleviate poverty and improve the quality of life of South Africans.

2.2 RURAL CROP PRODUCTION TRENDS

Both the area planted and crop production in rural South Africa have experienced substantial changes since the early 1900s (Fig. 2.1). The period between the 1930s and 1970s saw a steep decline in rural food production, where maize is the dominant crop planted accounting for over 70% of the cultivated area. According to Liebenberg (2013), yields from the former "Homelands" have stabilised at only about 6% of the country's total crop production. Yet close to 20 million South Africans live in rural areas with high rates of poverty, unemployment, and food insecurity. In addition to food shortages, malnutrition levels are also high with up to 26.5% of children under five years old and those aged between four and six being undernourished in 2012 (Van Der Byl., 2012).

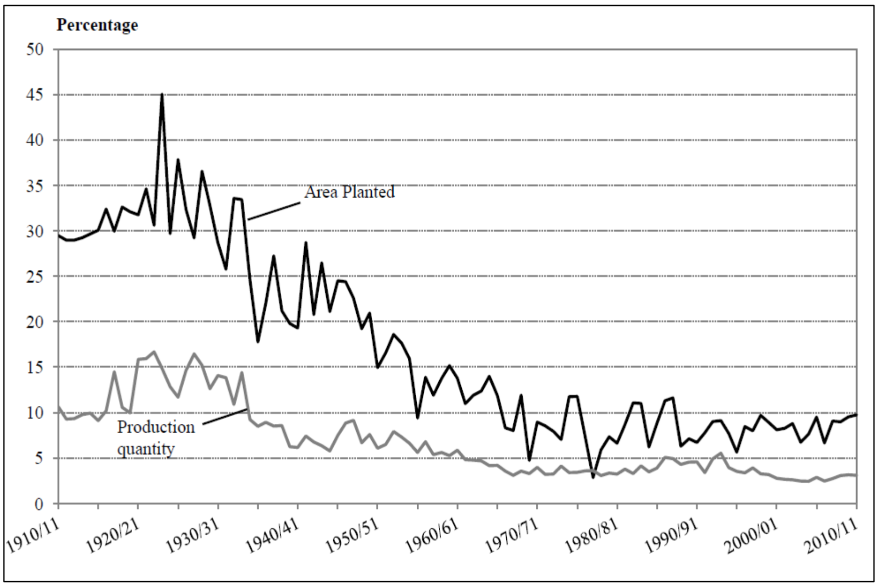


Fig. 2. 1. Share of area planted and crop production trends in rural South Africa (after Liebenberg, 2013)

Nationally the production of staple maize hovers around 8.0 million tonnes per year. This is enough to meet the country's needs with surplus to export (Mqadi, 2005; Liebenberg, 2013). However, rural maize production has declined over the years as most communities have reduced their participation in subsistence farming (National Income Dynamics Study, 2013). Factors that have contributed to this include;

1) the migration of workforce to urban areas especially after 1994
2) loss of personnel in the working age groups due to diseases mainly HIV/AIDS
3) increasing reliance on the government's social grant system
4) unreliable rainfall regimes due to climate change
5) soil degradation
6) poor soil fertility
7) rising input costs (Mqadi, 2005), among others

At the same time rural unemployment rose from about 44% in 2009 to about 47.6% in 2013 according to a Stats SA (2013). All these factors increase the vulnerability of many rural households to hunger, malnutrition, and poverty.

Elsewhere in Sub-Saharan Africa, food production, including staple cereals, has generally increased over the years as shown in Fig. 2. 2. However, the rate of increase in food production has been substantially slower than the rate of population growth (Chauvin et al., 2012). As a result, food insecurity has persisted and, in most cases, increased compounded by political instability in some countries. For sustainable rural development it is essential to increase crop production to ensure food and nutrition security and to increase income generating opportunities while protecting the environment (NDP, 2030).

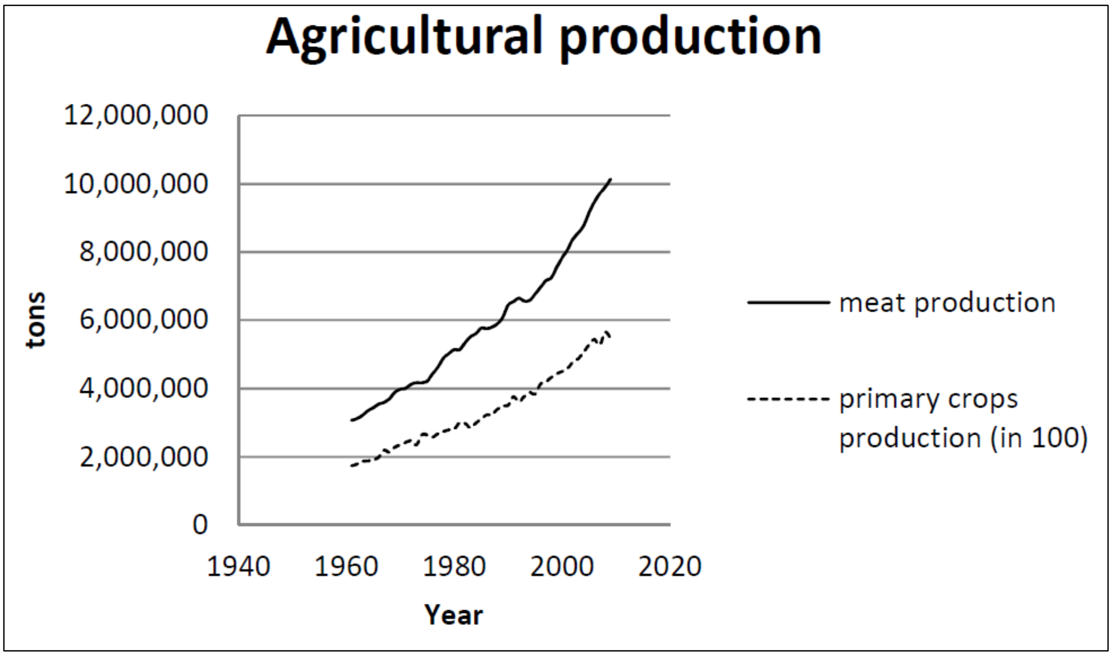


Fig. 2. 2. Food production trends in Sub-Saharan Africa (after Chauvin et al., 2012)

2.3 ROLE OF INDIGENOUS TREE CROPS IN FOOD AND NUTRITION SECURITY

As the growing conditions become increasingly unsuitable for most staple crops, it is important to increase production from indigenous plants. Indigenous plants are sources of non-timber forest products that provide energy, shelter, food, and medicine (Rankoana, 2016). For centuries, rural communities have traditionally relied on these plants, although their use has declined due to preference for exotic high value crop species. Studies reveal that most fresh fruits are important sources of carbohydrates and thus have high calorific values. The highest (88.2%) and lowest (35.2%) levels were obtained for *Parinari curatellifolia* and *Azanza garckeana*, respectively (Akinnifesi et al., 2008). Meeting the nutritional requirements is also essential for healthy communities.

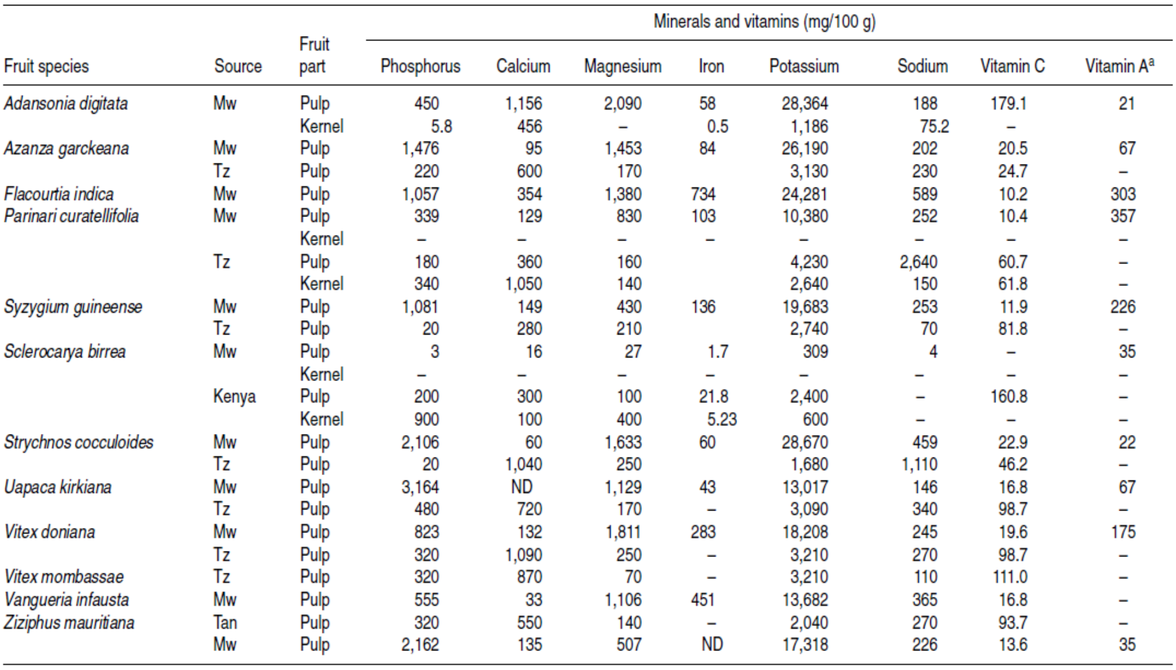
A study by Kucich and Wicht (2016) on the rural household dietary diversity in two districts of the Eastern Cape Province showed that sugar, tea, coffee, grains, and potatoes were among the food groups most frequently consumed. Only about 5% and 3% of households, respectively, reported consuming vegetables and fruits. According to the World Health Organization (WHO), an adult, on average, should consume at least 600 g of fruit and vegetables per day to achieve optimal health benefits (WHO, 2004). In situations where households do not grow their own food, meeting this requirement is difficult given the rising costs of fruit and vegetables purchased from supermarkets. Cheaper alternatives such as different types of indigenous fruit growing in the wild, in agroforestry systems or in home gardens are therefore critical to overcome the twin hurdles of affordability and accessibility.

A survey by Rose et al (2002) found that South African adults consume about 115 g of vegetables and 91 g of fruit per day, on average. The combined fruit and vegetable intake of rural adults only reaches about 141 g per day. Another South African study showed that children aged between 1-5 years consumed 52 g of vegetables and 48 g of fruit per day on average, which is one third of the recommended amount (Kucich and Wicht, 2016). Maynard et al (2003) and Hertog et al (1996) in separate studies showed that increased consumption of fruit in childhood has the added advantage of limiting the incidence of cancer in adulthood. So clearly, there is a need to increase the consumption of fruit and vegetables, but affordability and access are currently major challenges.

There has been a strong drive in recent years to plant indigenous fruit trees, which are adapted to the harsh South African climatic conditions, and they require fewer inputs. Moreover, these crops are already known by the communities. Therefore, their acceptance is a given with the added advantage of their higher nutrient content. For example, fruit such as Marula (*Sclerocarya birrea*) contain up to four times more minerals and Vitamin C than commercial oranges (Rampedi, 2010). This figure rises to almost ten times for baobab fruit (known as monkey bread – *Adansonia digitata*) and Tables 2.1 and 2.2 summarise the nutritional composition of various indigenous fruit tree crops found in selected Southern African countries.

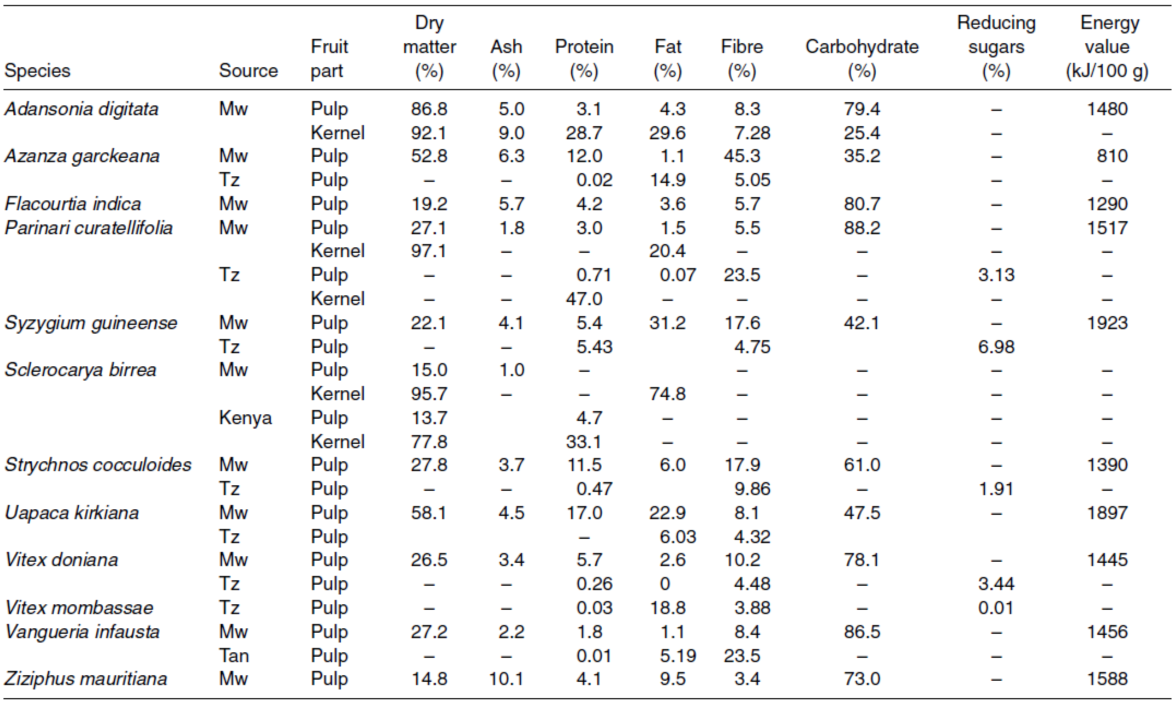
According to Akinnifesi et al (2008), the seed kernel of *A. digitata* is rich in protein (28.7%) and fat (29.5%). These values are like those of leguminous crops (Brand et al., 1985). *Sclerocarya birrea*, on the other hand has up to 28% protein and 57% oil levels. The seed kernels of *Adansonia digitata* and *Sclerocarya birrea* are also vital sources of trace elements such as iron, zinc, and copper. A detailed account of the nutritional composition of a wide range of indigenous fruit types is given in Saka (1996).

Table 2. 1 Mineral composition and vitamin content of selected edible fruits in Southern Africa, i.e. Malawi (Mw), Tanzania (Tz) and Kenya (source: Akinnifesi et al., 2008)



			Minerals and vitamins (mg/100 g)							
Fruit species	Source	Fruit part	Phosphorus	Calcium	Magnesium	Iron	Potassium	Sodium	Vitamin C	Vitamin A^a
Adansonia digitata	Mw	Pulp	450	1,156	2,090	58	28,364	188	179.1	21
		Kernel	5.8	456	–	0.5	1,186	75.2	–	
Azanza garckeana	Mw	Pulp	1,476	95	1,453	84	26,190	202	20.5	67
	Tz	Pulp	220	600	170		3,130	230	24.7	–
Flacourtia indica	Mw	Pulp	1,057	354	1,380	734	24,281	589	10.2	303
Parinari curatellifolia	Mw	Pulp	339	129	830	103	10,380	252	10.4	357
		Kernel	–	–	–	–	–	–	–	–
	Tz	Pulp	180	360	160		4,230	2,640	60.7	–
		Kernel	340	1,050	140		2,640	150	61.8	–
Syzygium guineense	Mw	Pulp	1,081	149	430	136	19,683	253	11.9	226
	Tz	Pulp	20	280	210		2,740	70	81.8	–
Sclerocarya birrea	Mw	Pulp	3	16	27	1.7	309	4	–	35
		Kernel	–	–	–	–	–	–	–	–
	Kenya	Pulp	200	300	100	21.8	2,400	–	160.8	–
		Kernel	900	100	400	5.23	600	–	–	–
Strychnos cocculoides	Mw	Pulp	2,106	60	1,633	60	28,670	459	22.9	22
	Tz	Pulp	20	1,040	250		1,680	1,110	46.2	–
Uapaca kirkiana	Mw	Pulp	3,164	ND	1,129	43	13,017	146	16.8	67
	Tz	Pulp	480	720	170	–	3,090	340	98.7	–
Vitex doniana	Mw	Pulp	823	132	1,811	283	18,208	245	19.6	175
	Tz	Pulp	320	1,090	250	–	3,210	270	98.7	–
Vitex mombassae	Tz	Pulp	320	870	70	–	3,210	110	111.0	–
Vangueria infausta	Mw	Pulp	555	33	1,106	451	13,682	365	16.8	–
Ziziphus mauritiana	Tan	Pulp	320	550	140	–	2,040	270	93.7	–
	Mw	Pulp	2,162	135	507	ND	17,318	226	13.6	35

Table 2. 2 Chemical composition of selected indigenous fruit trees based on studies from Malawi, Tanzania, and Kenya (source: Akinnifesi et al., 2008).



Species	Source	Fruit part	Dry matter (%)	Ash (%)	Protein (%)	Fat (%)	Fibre (%)	Carbohydrate (%)	Reducing sugars (%)	Energy value (kJ/100 g)
Adansonia digitata	Mw	Pulp	86.8	5.0	3.1	4.3	8.3	79.4	–	1480
		Kernel	92.1	9.0	28.7	29.6	7.28	25.4	–	–
Azanza garckeana	Mw	Pulp	52.8	6.3	12.0	1.1	45.3	35.2	–	810
	Tz	Pulp	–	–	0.02	14.9	5.05		–	–
Flacourtia indica	Mw	Pulp	19.2	5.7	4.2	3.6	5.7	80.7	–	1290
Parinari curatellifolia	Mw	Pulp	27.1	1.8	3.0	1.5	5.5	88.2	–	1517
		Kernel	97.1	–	–	20.4	–	–	–	–
	Tz	Pulp	–	–	0.71	0.07	23.5	–	3.13	–
		Kernel	–	–	47.0	–	–	–	–	–
Syzygium guineense	Mw	Pulp	22.1	4.1	5.4	31.2	17.6	42.1	–	1923
	Tz	Pulp	–	–	5.43		4.75		6.98	
Sclerocarya birrea	Mw	Pulp	15.0	1.0	–		–	–	–	–
		Kernel	95.7	–	–	74.8	–	–	–	–
	Kenya	Pulp	13.7		4.7	–	–	–	–	–
		Kernel	77.8		33.1	–	–	–	–	–
Strychnos cocculoides	Mw	Pulp	27.8	3.7	11.5	6.0	17.9	61.0	–	1390
	Tz	Pulp	–	–	0.47		9.86	–	1.91	–
Uapaca kirkiana	Mw	Pulp	58.1	4.5	17.0	22.9	8.1	47.5	–	1897
	Tz	Pulp			–	6.03	4.32			
Vitex doniana	Mw	Pulp	26.5	3.4	5.7	2.6	10.2	78.1	–	1445
	Tz	Pulp	–	–	0.26	0	4.48	–	3.44	–
Vitex mombassae	Tz	Pulp	–	–	0.03	18.8	3.88	–	0.01	–
Vangueria infausta	Mw	Pulp	27.2	2.2	1.8	1.1	8.4	86.5	–	1456
	Tan	Pulp	–	–	0.01	5.19	23.5	–	–	–
Ziziphus mauritiana	Mw	Pulp	14.8	10.1	4.1	9.5	3.4	73.0	–	1588

2.4 SUMMARY OF INDIGENOUS FRUIT TREE SPECIES IN SOUTH AFRICA

The indigenous fruit and nut trees (IFTs) of the tropics have been described as “Cinderella species” (Akinnifesi et al., 2008) or “orphan crops” because they have been overlooked by science and development. However, these crops now represent a unique asset that can be developed, domesticated, and owned by rural farmers given the challenges of growing exotic crops. There are more than twenty edible indigenous fruit tree species in South Africa (DAFF, 2011). In this section, we give a brief description of the most common species, their geographical distribution, and local uses and benefits.

2.4.1 Bridelia micrantha (Hochst.) Baill

2.4.1.1 Morphological description

Bridelia micrantha belongs to the Phyllanthaceae family and it is known as coastal golden leaf in (English (E)), umShange in (isiZulu (Z)), Bruin stinkhout in (Afrikaans (A)) (Fig. 2.3). *Bridelia micrantha* is a medium to large deciduous tree of up to 20 m height. The bark in older specimens appears greyish brown in colour. The leaf shape is alternate and elliptic to obovate. The flowers form clusters around the leaf’s axils. The fruit shape is oval. The fruits appear black in colour when ripe (Naidoo, 2010).

Fig. 2. 3. Fruits, leaves and flowers of B. micrantha (Source: Naidoo, 2010).

2.4.1.2 Geographical distribution

The coastal golden leaf naturally occurs in coastal, riverine and swamp forests. In South Africa, it is found in moist areas in Eastern Cape, KwaZulu-Natal, Limpopo and in the lowest sourveld of the Mpumalanga province (Naidoo, 2010).

2.4.1.3 Benefits and its use

The fruit of this tree is sweet tasting. The bark is used as a remedy for burns, wounds, venereal diseases, tapeworm, diarrhoea, and toothaches. The root is known to treat stomach pains and gastric ulcers. The root is also mixed with oil and can be used to rub the head to treat headache (Naidoo, 2010).

2.4.2 Carissa macrocarpa (Eckl.) A. DC.

2.4.2.1 Morphological description

Carissa macrocarpa (Fig. 2.4) is a small shrub belonging to Apocynaceae family and can grow up to 4 m in height. It is well known as Natal plum (E), Amatungulu (Z), Grootnoemnoem (A). This plant secretes milky, non-toxic latex. The thorns are Y-shaped. The leaves are egg shaped or oval. The flowers are white in colour and the flowering seasons start from spring to early summer. The fruits are oval shaped and they are red when ripe (Carolus, 2004a).

Fig. 2. 4. Fruits and leaves of C. macrocarpa (Source: Carolus, 2004b)

2.4.2.2 Geographical distribution

It grows in coastal areas from Eastern Cape northwards through KwaZulu-Natal to Mozambique (Carolus, 2004a).

2.4.2.3 Benefits and its uses

The fruit of *Carissa macrocarpa* is rich in Vitamin C, phosphorous and potassium. The fruit is edible and can be used to make jellies and jams. No medicinal uses of Natal plum have been recorded (Carolus, 2004b).

2.4.3 Cordia Caffra (Sond.)

2.4.3.1 Morphological description

Fig. 2.5 shows *Cordia caffra*. This crop belongs to Boraginaceae family, and it is locally known as Septee tree saucer-berry (E), iLalanyathi (Z), Septeeboom (A). *Cordia caffra* is a small to medium sized tree with a height of up to 20 m. The leaves are thin and alternate. The creamy-white flowers are borne in clusters at the end of each branch. The fruits are drupe shaped and deep orange in colour (Klapwijk, 2003).

2.4.3.2 Geographical distribution

This tree occurs naturally in coastal and riverine forests. It grows in KwaZulu-Natal, Mpumalanga, Limpopo, and Eastern Cape Provinces (Klapwijk, 2003).

Fig. 2. 5. Fruits and leaves of C. caffra (Source: Klapwijk, 2003).

2.4.3.3 Benefits and its uses

The fruits of *Cordia caffra* are not tasty but are edible. Plant parts are used as traditional medicine to treat sore eyes, fever, and wounds (Klapwijk, 2003).

2.4.4 Dovyalis Caffra (Hook. F. & Harv.) Hook. F.

2.4.4.1 Morphological description

Dovyalis caffra (Fig. 2.6) is an evergreen fruit tree with a height between 3.5 – 8 m. This crop belongs to Salicaceae family and its flowers form in November to December and are creamy green in colour. In South Africa, *Dovyalis caffra* is well-known as Kei apple (E), umQokolo (Z), Kei-appel (A). Its flowers are arranged in clusters and the fruit have a diameter of about 60 mm when mature and are yellow orange in colour (Ndou, 2003).

Fig. 2. 6. Fruits and leaves of D. caffra (Source: Ndou, 2003).

2.4.4.2 Geographical distribution

The Kei apple grows in dry areas, wooded grasslands from Eastern Cape through KwaZulu-Natal, and Limpopo Province (Ndou, 2003).

2.4.4.3 Benefits and its uses

The fruits are edible and used to make excellent jams. The leaves are used as fodder (Ndou, 2003).

2.4.5 Ficus Sur (Forssk.)

2.4.5.1 Morphological description

Ficus sur also known as Broom cluster fig (E), umKhiwane (Z), Besem-trosvy (A) is an indigenous specie belonging to Moraceae family. It is a large evergreen tree with a height of up to 35 m (Fig. 2.7). The leaves are large and oval shaped. The flowers are green in colour. Flowering starts during early summer or late summer (Hankey, 2003).

2.4.5.2 Geographical distribution

The species is widely distributed in Eastern Cape, KwaZulu-Natal, Limpopo, Mpumalanga, and Western Cape Provinces (Hankey, 2003).

Fig. 2. 7. Fruits of F. sur (Source: Hankey, 2003)

2.4.5.3 Benefits and its uses

Fig jam is produced from the fruits. The milky latex is given to cows with low milk production and used to treat lung and throat problems (Hankey, 2003). The root extract is used as a remedy for cough, diarrhoea, and syphilis (Maroyi, 2013).

2.4.6 Harpephyllum Caffrum (Bernh.)

2.4.6.1 Morphological description

Harpephyllum caffrum belong to Anacardiaceae family and it is a large evergreen tree that grows up to 15 m tall (Fig. 2.8). This tree is known as Wild plum (E), umGwenya (Z), Wildepruim (A) and has buttress roots. The leaves are pinnate in shape whereas leaflets are sickle shaped. The flowers are whitish green in colour. Flowering starts from November until February. The male and female flowers are on separate trees. The fruits are red when ripe (Dlamini, 2004).

Fig. 2. 8. Fruit and leaves of H. caffrum (Source: Dlamini, 2004)

2.4.6.2 Geographical distribution

The wild plum grows in riverine forests. In South Africa, it grows in Eastern Cape, KwaZulu-Natal, Limpopo, and Mpumalanga Provinces (Dlamini, 2004).

2.4.6.3 Benefits and its uses

The fruit is eaten raw and has been used to make jellies and jams. The fruits are sour tasting thus used to make alcoholic beverages. The bark treats acne and eczema and face pimples. The burnt powdered bark is a remedy for sprains and bone fractures (Dlamini, 2004).

2.4.7 Lannea discolor (Sond.) Engl.

2.4.7.1 Morphological description

Lannea discolor is a medium sized deciduous tree with a height of up to 15 m (Fig. 2.9). This tree belongs to Anacardiaceae family, and it is known as Tree grape (E), isiGanganyane (Z), Dikbas (A) in South Africa. The colour of the bark is dark grey. The leaves are compound with five pairs of leaflets and a terminal leaflet. Flowers bloom during the spring season. The fruits are green in colour when immature. The ripe fruits are purple in colour with a diameter of about 9 – 10 mm (Masupa, 2012).

Fig. 2. 9. discolor tree (Source: Masupa, 2012)

2.4.7.2 Geographical distribution

The species occur on rocky ridges. In South Africa *L. discolor* grows in Gauteng, Limpopo, Mpumalanga, and North-West Province (Masupa, 2012).

2.4.7.3 Food and medicinal uses

The fruits are eaten raw by people and birds. Different plant parts are used as traditional medicine to treat fevers and constipation in children (Masupa, 2012). The root extract treats sore eyes. The fibre extract is used as a remedy to reduce menstrual flow in women (Maroyi, 2013).

2.4.8 Pappea capensis (Eckl. & Zeyh)

2.4.8.1 Morphological description

Locally known Jacket plum (E), umVuna (Z), Dopprium (A), *Pappea capensis* is an evergreen tree with a height of about 2 – 8 m (Fig. 2.10), belonging to Sapindaceae family. The leaves of this tree are simple. The green flowers are borne on catkins in the leaf axils. Flowers bloom during the spring season. The fruits are round and green. The fruit flesh is red with black seeds embedded within (Hankey, 2004).

Fig. 2. 10. Fruits and leaves of P. capensis (Source: Hankey, 2004).

2.4.8.2 Geographical distribution

It occurs in wooded grasslands and valley bushveld (Motlhanka *et al*., 2008). This plant is widespread in KwaZulu-Natal, Eastern Cape, North-West, Gauteng, Free State, Mpumalanga, and Limpopo Province (Hankey, 2004).

2.4.8.3 Benefits and its uses

The fruit is tasty and edible. The fruits are used to make jelly, vinegar, and alcoholic drink (Hankey, 2004). The seeds produce edible oil. The flesh of the fruit is used to produce an alcoholic beverage (Motlhanka *et al*., 2008). The barks and leaves are used as traditional medicine to treat ringworms and chest pains (Hankey, 2004).

2.4.9 Phoenix reclinata (Jacq.)

2.4.9.1 Morphological description

Phoenix reclinata has a height of 12 m (Fig. 2.11). The tree belongs to Arecaceae family and in South Africa, it is known as Wild date plum (E), iSundu (Z), Wilde-dadelboom (A). The leaves are green and arching. Flowers bloom from August to October. The fruits are oval shaped and brown when ripe (Aubrey, 2004).

Fig. 2. 11. Fruit and leaves of P. reclinata (Source: Aubrey, 2004).

2.4.9.2 Geographical distribution

This plant grows along riverbanks and swamps. It is found in Eastern Cape, KwaZulu-Natal, Limpopo, and Mpumalanga Province (Aubrey, 2004).

2.4.9.3 Benefits and its uses

The fruit is edible. The roots are used to make gums, which are enjoyed by children. The spines of this plant have traditional medicinal use (Aubrey, 2004).

2.4.10 Podocarpus falcatus (Thunb.) R.Br. Ex Mirb.

2.4.10.1 Morphological description

Podocarpus falcatus is an evergreen tree with a height of up to 45 m (Fig. 2.12). The leaves are arranged spirally with parallel veins. The leaf tip is sharply pointed. The ripe fruits are yellow in colour (Klapwijk, 2002). Locally the tree is well-known as Outeniqua yellowwood (E), umSonti (Z), Outneikwageelhout (A) and it belongs to Podocarpaceae family.

Fig. 2. 12. P. falcatus leaves and fruits (Source: Klapwijk, 2002).

2.4.10.2 Geographical distribution

This tree is found in KwaZulu-Natal, Eastern Cape, Limpopo, Mpumalanga, and Western Cape Province (Klapwijk, 2002).

2.4.10.3 Food and medicinal uses

Ripe fruits are eaten by birds and monkeys. The sap is used to treat chest pains (Klapwijk, 2002).

2.4.11 Rhoicissus tomentosa (Lam.) Wild & R.B. Drumm.

2.4.11.1 Morphological description

Rhoicissus tomentosa belongs to Vitaceae family, and it is known as Wild grape (E), isiNwazi (Z), Bosdruif (A) in South Africa. The wild grape is an evergreen tendril climber with a height of up to 20 m (Fig. 2.13). The bark is greyish in colour. The leaves are simple, almost circular or kidney shaped. The flowers are creamy green and form clusters on a 20 mm long stalk. Flowering season starts from October to January. The fruits resemble grapes and appear deep purplish black when ripe (Notten, 2004).

Fig. 2. 13. Fruits and leaves of R. tomentosa (Source: Notten, 2004).

2.4.11.2 Geographical distribution

The species are grown in KwaZulu-Natal, Eastern Cape, Limpopo, Mpumalanga, and Western Cape Province (Notten, 2004).

2.4.11.3 Benefits and its uses

The fruits are pleasant tasting thus eaten by people and birds. The juicy pulpy ripe fruits are used to make jams and jellies. A sour wine with a pleasant fragrance is produced from the fruits. The fruits are also used to make vinegar. The root decoction is used to remove intestinal worms in calves (Notten, 2004). The root decoction is also used by women to enhance fertility (Corrigan *et al*., 2011)

2.4.12 Sclerocarya birrea (A. Rich) Hochst.

2.4.12.1 Morphological description

Sclerocarya birrea (Fig. 2.14) is a medium to large deciduous tree with an erect trunk and rounded crown (Mutshinyalo & Tshisevhe, 2003; Motlhanka *et al*., 2008). This tree is locally known as Marula (E), UmGanu (Z), Maroela (A) and belongs to Anacardiaceae family. The leaves of Marula tree are compound and are crowded at the end of the branches (Mutshinyalo & Tshisevhe, 2003). The fruit shape ranges between drupe, globular and spherical. The ripe fruit is yellow in colour (Motlhanka *et al*., 2008).

Fig. 2. 14. S. birrea leaves and fruits (Source: Mutshinyalo & Tshisevhe, 2003).

2.4.12.2 Geographical distribution

The Marula tree occurs naturally from Ethiopia in the north to KwaZulu-Natal in the south. In South Africa, it is more abundant in the Limpopo Province. It grows in woodlands with sandy soil or sandy loam (Mutshinyalo & Tshisevhe, 2003).

2.4.12.3 Benefits and its uses

The kernels of the stone produce edible nuts, which are rich in proteins (Motlhanka *et al*., 2008). The highly nutritious cooking oil is extracted from the nuts (Cock & Vuuren, 2015). The fat content produced by the seeds is higher than that of peanuts (Vinceti *et al*., 2013). The fruit is fermented to make the Marula alcohol and jam (Motlhanka & Makhabu, 2011). In addition, the fruit is also used to produce delicious jellies (Motlhanka *et al*., 2008).

An infusion of the bark has been used to treat dry cough and runny nose (York *et al*., 2011). In Northern Maputaland, the bark is used to treat dermatological conditions such as boils, burns and sores (Nciki *et al*., 2016). An infusion of the leaves or bark is used to treat candida infections (De wet *et al*., 2012). The dried seeds have been used in South Africa to repel mosquitoes thus preventing the outbreak of malaria (Mavundza *et al*., 2011). The stem and bark extracts are used as remedy in diabetes mellitus (Corrigan *et al*., 2011). The root steam is used to treat sore eyes (Maroyi, 2013).

2.4.13 Strychnos spinosa (Lam.)

2.4.13.1 Morphological description

Strychnos spinosa belongs to Loganiaceae family *and it* is a small to medium sized spiny deciduous tree (Fig. 2.15). Locally the specie is known as Monkey orange (E), umHlalakontshe (Z), doringklapper (A). The leaves of Monkey orange are glossy green. The fruits are yellow in colour when ripe (Le Roux, 2005). The greenish-white flowers are produced at the end of branches during the summer season.

Fig. 2. 15. S. spinosa fruit (Source: Le roux, 2005).

2.4.13.2 Geographical distribution

This tree grows in bushvelds and riverine fringes. It is widely distributed in Eastern Cape, KwaZulu-Natal, Limpopo, and Mpumalanga Provinces (Le Roux, 2005).

2.4.13.3 Benefits and its uses

The fruit is eaten raw by people. The dried fruit is used as a food preservative. The leaves root and seeds are used as traditional medicine. The root infusion treats snakebites. Leaf infusion is used as an analgesic (Le Roux, 2005). The juice extracted from the fruits is drunk to treat gonorrhoea and genital warts. The root extract treats abdominal pains (Maroyi, 2013).

2.4.14 Syzygium Cordatum (Hochst. Ex. C. Krauses)

2.4.14.1 Morphological description

Fig. 2.16 shows the leaves and fruits of *Syzygium cordatum*. In South Africa, *Syzygium cordatum* is known as Water-berry (E), umDoni (Z), Water-boom (A). This is a water-loving tree with a height of up to 15 m and it belongs to Myrtaceae family. The leaf shape varies from elliptic to circular. Young leaves are reddish in colour. The flowers bloom from August to September. These flowers produce nectar, and they are white to pinkish in colour. The fruit shape is oval. Ripe fruits are red to dark purple in colour (Carolus, 2004).

Fig. 2. 16. Leaves and fruits of S. cordatum (Source: Carolus, 2004).

2.4.14.2 Geographic distribution

It occurs naturally along streams on forest margins from Eastern Cape through KwaZulu-Natal to Mozambique. In KwaZulu-Natal and Mozambique, it forms stands of swamp forest (Carolus, 2004).

2.4.14.3 Benefits and its uses

The fruit of *S. cordatum* is edible and can be eaten raw (Corrigan *et al*., 2011). The fruits are processed to make jam and jellies. The leaves and bark possess antifungal activity, thus preventing microbial food spoilages. This reduces food wastages (Cock & Vuuren, 2015). The berries are fermented to produce an alcoholic beverage (Carolus, 2004).

In South Africa, the decoction of the *S. cordatum* bark is used to treat cough and blocked nose (York *et al*., 2011). In Northern Maputaland, the bark has been used to treat dermatological conditions like burns and sores (Nciki *et al*., 2016). The bark, leaves or roots extracts are used to treat respiratory complains and asthma (Cock & Vuuren, 2014). An infusion of leaves is used to disinfect mouth wounds (Corrigan *et al*., 2011). An infusion of the leaves or bark is used as a remedy for gonorrhoea (De wet *et al*., 2012). The leaves or bark can be used as food preservatives to treat foodborne diseases (Cock & Vuuren, 2015). In central Africa, the tree is used in the treatment of stomach ache and diarrhoea (Carolus, 2004).

2.4.15 Trichilia dregeana (Sond.)

2.4.15.1 Morphological description

Trichilia dregeana is an evergreen tree that can reach the height of 35 m (Fig. 2.17). Locally *Trichilia dregeana* is known as Forest mahogany (E), umKhuhlu (Z), Rooissenhout (A) and this specie belong to Meliaceae family. The main stem of forest mahogany has a diameter of about 1.8 mm. The leaves are compound with 3-5 pairs of leaflets and a terminal one. The leaflets are entire and opposite. The creamy white flowers are produced October to December. The fruits are round shaped (Burring, 2004).

Fig. 2. 17. T. dregeana fruits (Source: Blurring, 2004)

2.4.15.2 Geographical distribution

This tree grows naturally in areas with high rainfall. In South Africa, it grows in KwaZulu-Natal, Limpopo, and Mpumalanga Provinces (Burring, 2004).

2.4.15.3 Benefits and its uses

The fruit is edible (Blurring, 2004). The seeds are crushed to make juice or cooked as vegetable. The leaves and bark are used as a remedy for diabetes and inflammation (Cock and Vuuren, 2015). Various plant parts are used to treat stomach complaints and backache. The bark is used to treat kidney problems and as a blood cleaner. White flowers are produced during early summers (Burring, 2004).

2.4.16 Vangueria Infausta (Burch.)

2.4.16.1 Morphological description

Locally known as Wild meddler (E), umViyo (Z), Wilde mispel (A), *Vangueria infausta* (Fig. 2.18) belongs to Rubiaceae family. *Vangueria infausta* is a shrub or small deciduous tree of up to 7 m in height, with greyish to yellow brown bark (Behr, 2004). The shape of the leaves can either be elliptic or ovulate (Motlhanka *et al*., 2008).

This plant has simple leaves that are oppositely arranged (Behr, 2004). The fruit shape is drupe or sub-globose with a diameter of up to 35 mm (Motlhanka *et al*, 2008). The ripe fruit is light brown in colour with 3-5 seeds embedded in a soft pulp (Behr, 2004).

Fig. 2.18. Leaves and fruits of V. infausta (Source: Behr, 2004)

2.4.16.2 Geographical distribution

It is widespread in woodlands and bushvelds of South Africa from Eastern Cape, Free State, KwaZulu-Natal, Mpumalanga, Gauteng, Limpopo, North-West to Northern Cape Provinces (Behr, 2004). It also occurs naturally in East Africa and Madagascar (Mbukwa *et al*., 2007).

2.4.16.3 Benefits and its uses

The fruit is eaten fresh or mixed with milk (Motlhanka *et al*., 2008). The fruit can also be stored as a dried fruit to be consumed during food shortages. The fruit is fermented to make beer or distilled to make a brandy. The fruit have been also used to produce vinegar (Behr, 2004). The fruit is used to make mass (Corrigan *et al*., 2011). The fruit of *V. infausta* is also used to produce a fruit juice rich in Vitamin C (Motlhanka & Makhabu, 2011). The dried fruit flesh has been used in Botswana to produce a traditional recipe, which is consumed in the dry winter season (Motlhanka *et al*., 2008).

Different plant parts of *V. infausta* have been used as a remedy for menstrual and uterine problems (Mbukwa *et al*., 2007). An infusion of the leaves or roots is used to treat malaria and chest ailments such as pneumonia. An infusion of the leaves is used as a remedy for toothache (Corrigan *et al*., 2011). The decoction of the bark leaves or roots has been used in Mozambique to treat skin blisters and asthma. The leaves are macerated in water and drank to treat stomach aches (Brunchi *et al*., 2011). The sap from the roots is used as a remedy for diarrhoea (Maroyi, 2013). The leaves are put under chicken eggs to prevent spoilage (Corrigan *et al*., 2011).

2.4.17 Ximenia Caffra (Sond.)

2.4.17.1 Morphological description

Ximenia caffra is a large deciduous tree with a height of up to 6 m (Fig. 2.19). This tree belongs to Olacaceae family, and it is known as large sourplum (E), umThunduluka-obmvu (Z), grootsuurpruim (A). The bark is grey and rough. The leaflets form clusters on short branches. The leaves are simple with reddish hairs on branch-lets. Creamy green flowers are produced from August to October. The fruits are oval shaped (Baloyi and Reynolds, 2004).

Fig. 2. 19. Fruits and leaves of X. caffra (Source: Baloyi and Reynolds, 2004)

2.4.17.2 Geographical distribution

It grows in a bush clump. It is found in Gauteng, KwaZulu-Natal, Limpopo, Mpumalanga, and Northwest Provinces (Baloyi and Reynolds, 2004).

2.4.17.3 Food and medicinal uses

The fruits are rich in vitamin C, phosphorous and proteins. The seeds contain 65% oil content. Fruits are used to make jams, jellies, and desserts. The root infusion is used as remedy for diarrhoea (Baloyi and Reynolds, 2004). The root extract is drunk to treat diarrhoea and venereal diseases (Maroyi, 2013).

2.4.18 Ziziphus mucronata (Wild.) Subsp. Mucronata

2.4.18.1 Morphological description

Ziziphus mucronata is a small to medium sized tree belonging to Rhamnaceae family and can grow up to a height of 20 m (Fig.2.20). *Ziziphus mucronata* is known as Buffalo thorn (E), isiLahla (Z), Blinkblaar-wag-n-bietjie (A). The main stem of this tree is green in colour. The leaves are simple, alternate, or broadly ovate. Green to yellow flowers bloom from October to February. The fruit is a spherical drupe with a diameter between 12-20 mm (Mazibuko, 2007).

Fig. 2. 20. Z. mucronata fruits (Source: Mazibuko, 2007)

2.4.18.2 Geographical distribution

This tree is found in Eastern Cape, Free State, Gauteng, Limpopo, Mpumalanga, Northern Cape and Northwest Provinces (Mazibuko, 2007).

2.4.18.3 Benefits and its uses

The fruits are edible although not pleasant tasting. The berries have been used to make porridge (Mazibuko, 2007). The fruit is fermented to make beer (Cock and Vuuren, 2015). The roasted seeds are used to make coffee (Motlhanka *et al*., 2008). The leaf powder is applied on boils. The root extract is used as an infertility medicine by women (Maroyi, 2013). The bark decoction is used to treat respiratory ailments and skin diseases (Mazibuko, 2007).

2.5 INDIGENOUS FRUIT TREE SPECIES UTILISATION IN SOUTH AFRICA

Different parts of indigenous fruit are used for different purposes, for example, *Adansonia digitata* (baobab) and *Parinari curatellifolia* (mobola plum) have edible nuts, which are eaten raw or after processing. The nuts can be used as sources of vegetable oils, which are rich in protein and therefore can substitute for groundnut oil in rural cooking. Some fruits are eaten fresh, dried, or processed into commercial products. Processed products include jams, ice cream, butter and sweets, wines, beers, juice, yoghurt, etc. In Burkina Faso, for example, indigenous fruits are used in the preparation of meals as fats, spices, and soups (Ladipo *et al*., 1996). A summary of these products is shown in Fig. 2.21.

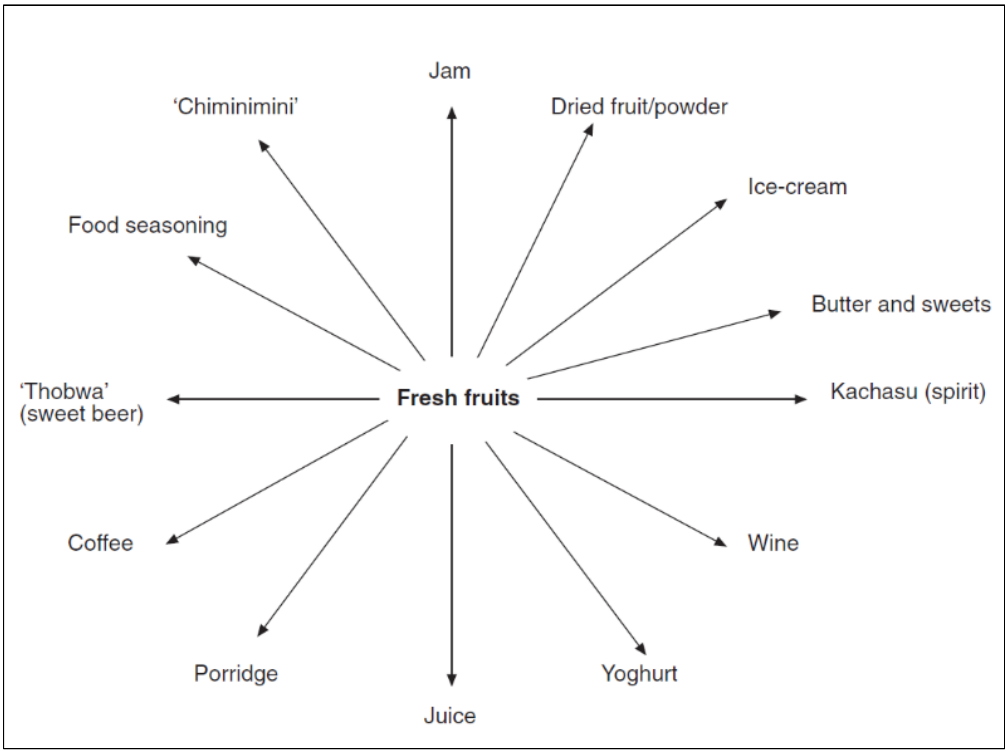


Fig. 2. 21. Products from indigenous fruit trees (after Saka et al., 2004)

Surveys conducted in several Southern African countries showed that communities in different countries preferred different indigenous tree species for domestication and commercialisation of their products (Akinnifesi et al., 2008). For example, while Marula is an important species in South Africa with its products exported to more than 63 countries worldwide, this species was not a high priority species in countries like Zambia, Tanzania, etc. This is because Marula fruits are not normally eaten raw, and they require processing which is complex and expensive for most rural households. Besides selling fruit and processed products, there are also opportunities for communities to make livelihoods from tree nursery activities. These can generate income, which can be used to pay children school fees, buying food and medicines. This activity is a source of livelihood for most communities in the Limpopo, Mpumalanga, and KwaZulu-Natal Provinces where several indigenous tree nurseries have been established by communities assisted by NGOs such as Conservation South Africa, Siyazisiza Trust, to name a few. Researchers from the Institute for Tropical and Subtropical Crops at the Agricultural Research Council (ARC) are working with more than 50 villages on the utility of indigenous fruit trees as alternative crops in the Eastern Cape and Limpopo Provinces of South Africa.

Processing of indigenous fruits into commercial products adds value to the raw fruits thereby increasing the net incomes to households. However, the establishment of commercially viable processing entities is often constrained by the limited or unreliable supply of fruit (Iranbaksh et al., 2009). Therefore, it is important to accelerate the pace of IFT domestication to increase productivity to ensure a reliable supply of fruit. Development of storage facilities is also important to handle excess fruit prior to processing. Drying the fruit is the most widely used practice of storing the fruit in villages for periods of up to 18 months so the fruit can be utilised off-season and to improve food security during times of hunger.

2.6 POLICIES AND STRATEGIES TO SUPPORT THE PRODUCTION OF INDIGENOUS CROPS

The fact that indigenous crops are essential for meeting the food and nutrition requirements of rural households in an environmentally sustainable manner is widely acknowledged (Rampedi, 2010, Iranbaksh et al., 2009). The Plant Production unit in the Department of Agriculture, Forestry and Fisheries (DAFF) established a directorate on Indigenous Crops mandated to focus on grains, vegetables, and fruit crops. The functions of the directorate are to develop and promote national policies, norms, standards, programmes, and guidelines to support the sustainable production of different crops. An example of its policies includes the National Policy on Food and Nutrition Security. This policy aims to increase the number of households benefiting from food and nutrition initiatives by 200 000 by 2019/20. This will be achieved through cultivating an additional 600 000 ha of neglected and underutilised land in communal areas to increase production (DAFF Strategic Plan, 2015).

Another DAFF programme intended for emerging farmers and rural households is the “Fetsa Tlala” program. This program is aimed at increasing the production of the staple maize and other key crops like beans. Ultimately, these initiatives should contribute to the National Development Plan, which aims, among other things, to eradicate poverty, hunger, and unemployment by 2030 while maintaining the country’s environment. However, emphasis in these programmes is on staple maize production and there is very little mention of enhancing the production of indigenous crops. Yet these crops are essential given the threat posed to maize production by climate change, which will render its production unreliable in parts of the country. While the nutritional value of indigenous fruit is well documented, clearly there is also a need to increase the quantity of indigenous crops produced to meet the food and income requirements of households especially during droughts whose frequency and severity seems to be increasing. Instead, IFT species are being lost to agricultural and urban expansion, and over exploitation through harvesting. Clearly there is a need for policies and land use management practices targeted at increasing the volume of indigenous crops to ensure sustainable crop production while maintaining biodiversity, creating income earning opportunities, preventing soil erosion, and protecting catchment water sources.

2.7 CHALLENGES IN DOMESTICATING AND COMMERCIALISING IFTS

According to Leakey et al (2005), the aim of domestication programmes is to promote the cultivation of IFTs with economic potential as new cash crops. It also provides incentives to subsistence farmers to plant trees that contribute towards sustainable food and nutritional security while preserving biodiversity.

There are several constraints to the success of IFT domestication programmes. These include the unavailability of good quality planting material and suitable multiplication methods have not yet been fully developed. There is also inadequate information, dissemination, knowledge sharing and training (Akinnifesi et al., 2008).

Thirdly, there are low production incentives due to limited markets and technology to store and process IFT products into value added commodities. However, the Department of Agriculture Forestry and Fisheries in South Africa has recently intervened by constructing Marula processing plants in some Provinces to encourage the involvement of rural communities in economic activities. Fourthly, there are limitations in harvesting methods. Most fruit is removed by shaking the trees or using a stick to knock off the fruit and this has serious consequences on fruit quality. There are also limitations in postharvest handling due to lack of storage facilities. Much of the fruit is wasted or the quality deteriorates substantially after harvesting. In most countries in Southern Africa, there is a general bias in favour of large-scale commercial agriculture and conventional forestry (Russell and Franzel, 2004) where most of the above constraints have been addressed.

The benefits of IFT domestication programmes include:

1) the development of trees with desired fruit traits in terms of yield and fruit quality through use of improved genetic material;

2) precocity thereby reducing the periods when the trees reach the fruit bearing age;
3) consistent supply of good quality fruit in sufficient quantities which is necessary for the viability of the fruit processing industry, and
4) conservation of biodiversity.

The most common mode of domesticating IFTs is through agroforestry systems where the trees are intercropped with conventional crops and in home gardens.

2.8 REVIEW OF WATER REQUIREMENTS, GROWTH, AND WATER USE EFFICIENCY OF INDIGENOUS FRUIT CROPS

2.8.1 Water requirements

South Africa is very reliant on its plantations of introduced tree species to meet its pulp and timber needs, while the commercial fruit production industry within the agricultural sector is also highly productive and contributes significantly to the Gross Domestic Product (GDP) of the country (Taylor and Gush, 2015).

However, these products come at some environmental cost, including the impact of commercial tree plantations on water resources (Gush et al., 2002; Dye & Versfeld, 2007; Dye, 2012), and the high water requirements of irrigated fruit production (Reinders, 2013). Many catchment areas are consequently now closed to further afforestation, and expansion of irrigated agriculture is limited due to competition for water resources, but economic growth and development continue unabated. Imports and improved productivity (including production of higher value end products) are potential solutions to continue meeting the demand for specific food, fuel, and fibre products, but further consideration of the feasibility of expanding indigenous tree resources is also warranted. With over 1000 species of indigenous trees in the country, South Africa is extremely rich in natural arboreal diversity (von Breitenbach, 1990).

The numerous benefits of indigenous trees and forests, in terms of the goods and services that they offer, are widely recognised (Lawes et al. 2004; Shackleton et al. 2007), as well as resilience through adaption to local biotic and abiotic factors; principally pests and diseases, drought and fire. There have also been widespread perceptions in the past that indigenous tree species use less water than introduced tree plantations (Wilson, 1982; Cawe and McKenzie, 1989). While there have been some earlier studies on the water-use efficiency (WUE) of common introduced plantation species in South Africa (Olbrich et al. 1996; Dye et al. 2001), knowledge of the relationships between growth and water-use of indigenous trees and forests have only started to be investigated in South Africa within the last 10 years (Dye et al., 2008). Information on the water-use, growth and economic value of indigenous trees has value in facilitating sustainable land-use planning from hydrological, ecological, and socio-economic perspectives.

Over the last 10 years there has been several studies in South Africa that have compared single-tree water use and water-use efficiencies between introduced (exotic) and indigenous tree species. Details of these studies are available from reports to the Water Research Commission (Dye et al., 2008; Gush and Dye 2015; Gush et al., 2015). Findings from these studies have also been published in international literature, reporting the water use, growth and resultant water use efficiencies of indigenous tree species growing in specific regions of South Africa. These include studies on *Trema orientalis*, *Celtis africana*, *Podocarpus falcatus*, *Ptaeroxylon obliquum*, *Olea europaea subsp. africana*, and *Berchemia zeyheri* in the KwaZulu-Natal midlands (Gush and Dye, 2009), *Vachellia* (formerly Acacia) *kosiensis* along the KwaZulu-Natal north coast (Gush, 2017), *Ilex mitis*, *Ocotea bullata* and *Podocarpus latifolius* in the Southern Cape region of South Africa (Mapeto et al., 2017).

In all these studies, the heat-pulse velocity method was used to collect hourly sap flow data over a 12-month period, while climate and soil-water data were concurrently recorded, and tree growth rates were determined for the year. Biophysical water-use efficiency was calculated, as the ratio of utilisable biomass gained per volume of water transpired. Patterns of water use through the year were different for the different species, but in general, the relatively lower water-use efficiencies observed in some indigenous species were more a consequence of slow growth rates attributed to competition for resources, and not high water-use rates.

A comparison of results from indigenous trees species against those for introduced plantation species shows that the indigenous species studied were generally less efficient than introduced species. However, while WUE was lower for the indigenous species, their overall water requirement was also lower. Sap flow, stem growth and water use efficiency results from the range of indigenous and introduced tree species studies are reported by Gush and Dye (2015). From their study, the authors recorded a total sap flow volumes of about 3 343 ± 1 242 ℓ tree^{-1} year^{-1} for the indigenous trees studied. This was substantially lower than for the introduced plantation species, which averaged 10 300 ± 2 890 ℓ tree^{-1} year^{-1} for *Eucalyptus clonal* trees, 7 994 ± 5 995 ℓ tree^{-1} year^{-1} for *Eucalyptus grandis* trees and 7 488 ± 4 473 ℓ tree^{-1} year^{-1} for Pinus species. Total sap flow volumes were lower in the indigenous species studied compared to introduced plantation species, despite growing conditions that could be considered ideal for most of the indigenous species sampled (readily available water, energy and nutrients, and limited competition). The indigenous tree annual cumulative sap flows were all less than 8 500 ℓ tree^{-1} year^{-1}, whereas sap flows in the more productive introduced plantation trees exceeded 20 000 ℓ tree^{-1} year^{-1}.

This suggests that there is a genetically determined maximum threshold to water use by indigenous tree species that is substantially lower than that for introduced plantation species. Similar findings have been reported by Kagawa et al. (2009) and Little et al. (2015), who found that the water use of native tree species, in Hawaii and Chile respectively, was considerably lower than that of introduced timber species. Measurements of water use in several *indigenous Afrocarpus falcatus* (Outeniqua Yellowwood) trees growing in a single species / even aged plantation (Dye et al., 2008) also showed that the water use of these trees was low compared to data for introduced plantation tree species.

An additional study that quantified the water use of some edible fruit bearing indigenous tree species was one by Clulow et al (2013). They measured the water use (transpiration) of *Syzygium cordatum*, *Eugenia natalitia* and *Drypetes natalensis* trees growing in peat swamp forest (PSF) and dune forest (DF) sites within the iSimangaliso wetland park of northern KwaZulu-Natal. Over a 12-month period, transpiration was approximately 10 000 ℓ of water for the *S. cordatum* (PSF), 3 500 ℓ for the *Eugenia natalitia* (DF) and just 600 ℓ for the *D. natalensis* (DF). They concluded that landscape position and site-specific conditions, such as soil water content profile, were important determinants of the water use by the trees. At the PSF site unconstrained by water availability, limits to transpiration were primarily driven by radiation interception levels and Vapour Pressure Deficit (VPD). At the drier DF site, however, soil water availability played a dominant role in limiting transpiration; with tree size and physiology playing a role at both sites.

2.8.2 Growth

Rates of stem growth in the indigenous trees studied by Gush and Dye (2015) were about 6 090 ± 4 762 g tree^{-1} year^{-1}. As with the rates of sap flow, this was also substantially less for the indigenous species relative to the average of 20 345 ± 6 118 g tree^{-1} year^{-1} for *Eucalyptus clonal* trees, 20 874 ± 14 361 g tree^{-1} year^{-1} for *Eucalyptus grandis* trees and 14 877 ± 7 357 g tree^{-1} year^{-1} for Pinus species. Consequently, evidence suggests that indigenous tree species cannot compete with plantations of introduced tree species for wood production, and this is confirmed through a comparison of the growth rates observed in respective indigenous and introduced tree species in this study. Certain instances of high 1-year stem growth rates in indigenous species were observed in the study, with *M. grandis*, *P. africana* and *C. africana* being the best performing species. However, it should be borne in mind that the conditions under which these indigenous trees were growing were far more favourable than the average plantation environment. These trees were freestanding, unshaded trees with little competition for resources and readily available water (the *C. africana* and *P. africana* trees were in a riparian zone).

2.8.3 Water use efficiency

Water use efficiency (WUE) in the indigenous species studied averaged 1.95 ± 0.88 g (stem wood) ℓ^{-1} (water) (Gush and Dye, 2015). This was marginally lower than for introduced plantation species, which averaged 2.01 ± 0.49 g ℓ^{-1} for *Eucalyptus clonal* trees, and 2.2 ± 0.64 g ℓ^{-1} for Pinus species, while *Eucalyptus grandis* showed a higher WUE of 2.91 ± 0.99 g ℓ^{-1}.

The slightly lower WUE of the indigenous species was more a consequence of slow growth rates as opposed to high water use rates – a finding supported by other studies (Binkley et al., 2004; Gyenge et al., 2008). Results therefore indicate that on average indigenous tree species appear to exhibit similar water use efficiencies to introduced plantation tree species. This supports the argument of a general correlation between growth and water use. The potential for substantial year-to-year variation in WUE of a particular tree species or even an individual tree is uncertain. WUE in any given year may be dependent upon the climatic conditions experienced, although it is possible that a year of above-average rainfall would result in above-average water use and growth (vice versa with a below-average year), rendering the overall effect on WUE insignificant unless certain thresholds in water use or growth were reached.

2.9 CHAPTER SUMMARY

Studies in other developing countries in Asia, Africa and South America show that IFTs can play a significant role in sustainable rural development. In South Africa however, this sector is still lagging, and implementation of policies directed at promoting this sector is essential. It is also necessary to increase investment in the IFT sector through developing infrastructure for handling and processing indigenous fruit products and seeking new markets. As land degradation persists, and droughts become more frequent and more severe, alternative crops and cropping systems are needed to support rural households and emerging farmers. To support IFT domestication and commercialisation programmes, accurate quantitative information on the water requirements, yield patterns and water productivity of a range of IFTs is needed for informed decision-making.

CHAPTER 3: WATER USE AND YIELD DYNAMICS OF SCLEROCARYA BIRREA (MARULA) AND STRYCHNOS SPINOSA IN NORTHERN KWAZULU-NATAL WITH A HOT SEMI-ARID CLIMATE

3.0 INTRODUCTION

Fruit tree species such as Marula (*Sclerocarya birrea subsp. caffra*) and monkey orange (*Strychnos spinosa*) are indigenous to many parts of Southern Africa. A stakeholder engagement workshop that brought together experts from universities, science councils, independent consultancies, and NGOs held in October 2017 at the University of Zululand identified these two species as having the greatest domestication and commercialisation potential. In South Africa, stands of Marula and *Strychnos* are found mainly in the tropical and subtropical regions in Limpopo, Mpumalanga, KwaZulu-Natal and the Eastern Cape Provinces. The economic value of fruit such as Marula, for example, is well documented (Wynberg et al., 2002; Akinnifesi et al., 2007; Petje, 2008; Molelekoa et al., 2018). It is a great resource for alleviating poverty and diversifying rural livelihoods as it is a major source of income for both rural and commercial entrepreneurs. Besides being eaten raw, the fruit can be processed into a range of products that include liquors, juices, jams, jellies, medicines, perfumes, skin care products, etc. Today, Marula products are marketed in over 100 countries highlighting the global significance of this tree crop while species like *Strychnos* also have growing commercial value.

At present, most indigenous fruit trees grow and are harvested in the wild unmanaged. A few commercial orchards of Marula have been established in recent years mainly in the Limpopo and Mpumalanga Provinces. However, there is need to accelerate the cultivation of indigenous fruit tree crops to increase production so as to create employment opportunities, enhance food security, and to alleviate rural poverty. Most funding for eco-physiological and agronomic research on fruit tree crops in South Africa has mostly been channelled towards exotic species. Examples include citrus and nectarines (Gush and Taylor, 2014; Taylor et al., 2014), apples (Volschenk et al., 2003; Dzikiti et al., 2018a; Gush et al., 2019), peaches and plums (Dzikiti and Schachtschneider, 2015), avocado and macadamia nuts (Taylor et al., ongoing), among others. Very little attention has been given to the so-called neglected underutilised indigenous tree crops. This, to some degree, has contributed to the slow pace of domestication and commercialisation of these crops in South Africa and in neighbouring countries.

Given the increasing soil degradation, rising cost of agricultural inputs, and the increasing frequency and severity of droughts due to global climate change, sustainable production of exotic fruit crops will be problematic in future (Midgley and Lotze, 2011; Everson et al 2012). Therefore, there is need to intensify research on indigenous tree crops that are known to thrive in nutrient poor soils (Mabhaudhi et al., 2017). They can tolerate droughts, and they are resistant to most pests and diseases that afflict exotic species (Du Preez pers. comm.). They also require limited management skills thereby bringing resource poor rural households into mainstream agriculture in line with key government policies such as the National Development Plan, the New Growth Path, and the United Nations' Sustainable Development Goals, especially goals number 1 to 3.

Numerous pre and postharvest research questions must be addressed in order to promote the cultivation of indigenous fruit trees on a larger scale. For example, there is need to remove the many unknowns around the performance of various species in different agro-ecological zones and to establish the limits of the species' adaptability to climates and soils. From a commercial fruit production perspective, there is also a need for selections for traits such as larger fruit size with smaller stone and thinner skins for stone fruit, improved precocity, higher yields, less alternate bearing, and greater tolerance to droughts, pests and diseases. Detailed research is also required on the phenology of the fruit trees in different agro-ecological zones to better understand the timing of leafing, blossoming, fruit drop, and other seasonal features. Related to this is the need to identify male plants that produce pollen when superior females are blossoming for pollination and to increase fruit set.

The selection of indigenous fruit trees with superior qualities is being done by the ARC Institute for Tropical and Subtropical Crops in Nelspruit. There are also NGOs that are involved in the domestication of indigenous fruit trees in South Africa. What is lacking is detailed eco-physiological and agronomic research to support these efforts. This project therefore provides information to close some of the knowledge gaps by focusing on Marula and *Strychnos spinosa* at a site in Northern Zululand. Two previous projects funded by the Water Research Commission (WRC K5/1462 & WRC K5/1876) quantified the water use and water productivity of indigenous trees (Dye et al., 2008; Gush et al., 2015; Gush and Dye, 2015). However, these studies focused only on trees for timber production and there is currently no information on the water requirements and water productivity of indigenous fruit tree crops. This information is essential for supporting indigenous tree crop domestication and commercialisation activities, which are increasingly becoming popular to ensure communities adapt to climate change and other hazards.

3.1 MATERIALS AND METHODS

3.1.1 Description of study site

Data were collected in the 4 000 ha Bonamanzi Game Reserve (S 28°03.404’; E 032° 17.705’; elev. 68 m ASL) located about 250 km north-east of the port City of Durban in the KwaZulu-Natal Province in South Africa (Fig. 3.1). The province has the highest rural population in South Africa and indigenous fruit trees are an important source of livelihood for many households.

The site has a sub-tropical climate with a long-term average rainfall of about 650 mm/year (Browne, 2009). Most of the rain falls during the summer months from October to March. The mean daily maximum temperature is around 35°C while the mean daily minimum temperature is about 13°C. The soils in the study area are predominantly yellow-grey sands derived from Quaternary marine sediments of the Maputaland Group (Mucina and Rutherford, 2006).

These deep sandy soils are highly leached and extremely nutrient poor. Table 3.1 summarises the key soil physical and chemical properties for samples collected in the study area and analysed at a commercial laboratory in Cape Town. As expected, the volumetric water content of the soils at field capacity (~ 100 kPa) was quite low at just over 8% with the water holding capacity around 110 mm/m.

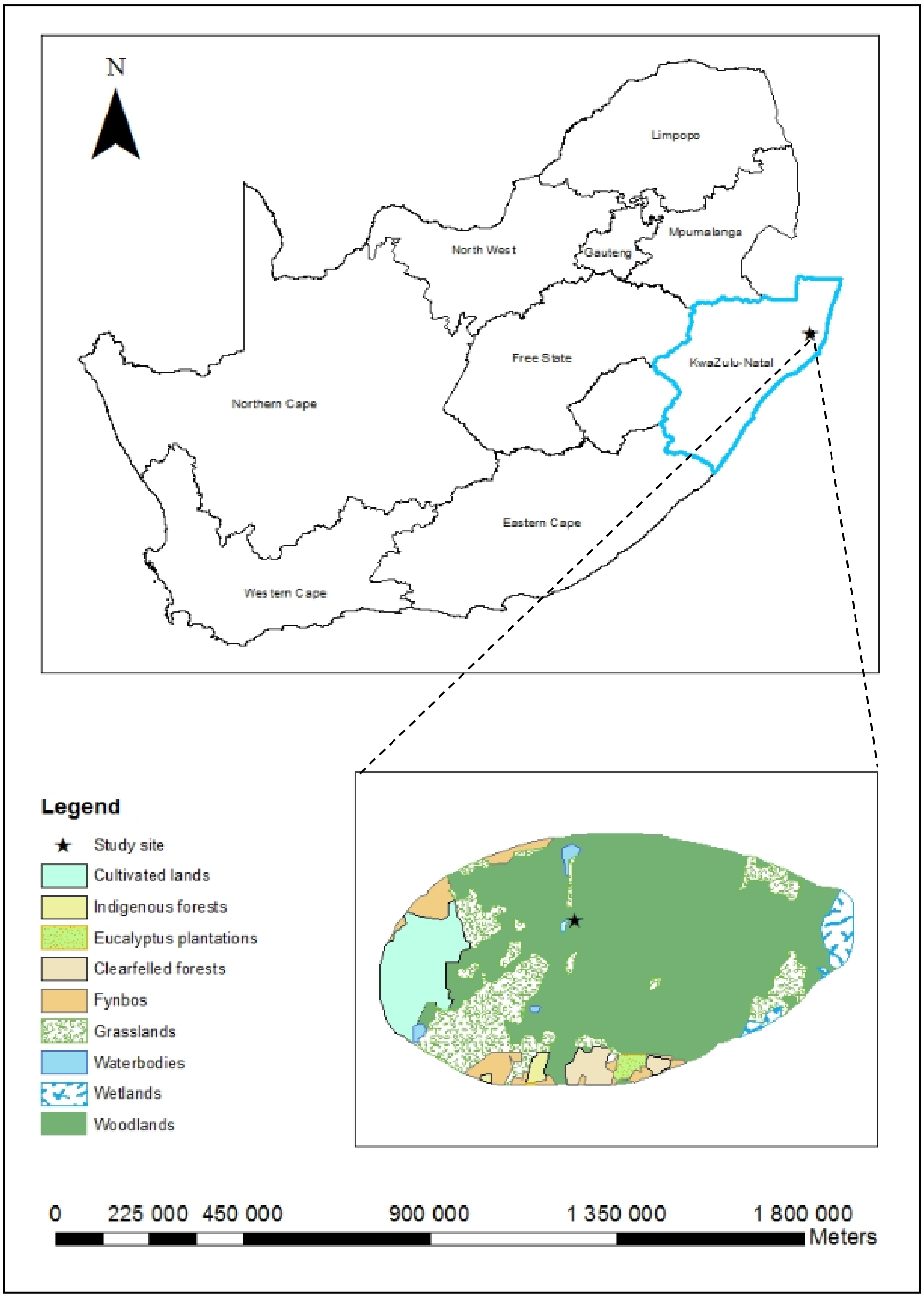


Fig. 3. 1. Study site at Bonamanzi Game Reserve in northern Zululand in the KwaZulu-Natal Province of South Africa.

The vegetation in the study area can be classified as part of the South African national vegetation type CB1 Maputaland Coastal Belt, with very small sections of Sand Forest described in detail by Mucina and Rutherford (2006). Trees selected for the study were chosen in such a way that they were freestanding trees with no overlapping canopies. Tree density was about 37 trees per hectare for *S. spinosa* and slightly higher for *S. birrea* at about 48 trees per hectare. The *S. spinosa* trees had a very short dormant period in winter when they shed their leaves lasting just under one month between June and July. On the other hand, the dormant leafless period was much longer for *S. birrea*, stretching roughly over three months from July to early October.

Data were collected over two years from January 2018 to December 2019 to account for the alternative bearing tendencies of the two species and to prevent skewed yield and water productivity calculations.

Table 3. 1 Physical and chemical properties of the soils at Bonamanzi Game Reserve.

	PHYSICAL PROPERTIES										
Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Fine sand (%)	Medium sand (%)	Course sand (%)	Stone (%)	Classification	Water holding capacity		
									10 kPa (%)	100 kPa (%)	mm/m
15	7	2	91	50.2	34.0	6.8	0	Sa	18.6	8.2	104.6
40	7	2	91	48.6	34.0	8.4	0	Sa	18.5	8.3	102.5
100	9	0	91	55.7	30.0	5.3	0	Sa	19.8	8.5	113.6
CHEMICAL PROPERTIES											
									Ex. Cations (cmol(+) /kg)		
	pH (KCL)	P (mg/kg)	K (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	B (mg/kg)	Fe (mg/kg)	Na	K	Ca
15	3.8	3.0	24	0.3	0.2	52.7	0.08	80	0.05	0.06	0.25
40	4.0	2.0	24	0.2	0.1	43.5	0.12	60	0.05	0.06	0.16
100	3.9	1.0	16	0.3	0.2	45.3	0.08	84	0.05	0.04	0.16

3.1.2 Climate and soil measurements

Weather conditions at the study site were measured using an automatic weather station installed within the Game Reserve, less than 500 m from the instrumented trees (Fig. 3.2). The station included a pyranometer (Model SP 212 Apogee Instruments, Inc., Logan UT, USA), which measured the solar irradiance. The sensor was installed on a horizontal levelling fixture mounted on a north facing cross bar to avoid self-shading.

Air temperature and relative humidity were measured using a temperature and humidity probe (Model: CS500, Vaisala, Finland) installed at a height of about 2.0 m above the ground. A three cup anemometer and wind vane (Model R. M. Young Wind Sentry Set model 03001, Campbell Scientific, Inc., Logan UT, USA) was used to measure wind speed and direction, respectively at 2.0 meters height.

Rainfall was recorded using a tipping bucket rain gauge (Model: TE525-L; Campbell Scientific, Inc., Logan UT, USA). All the sensors were connected to a data logger (Model: CR1000 Campbell Scientific, Inc., Logan UT, USA) programmed with a scan interval of 10 s. The output signals were processed at hourly and daily intervals, respectively.

The volumetric soil water content was measured at three depths at an average distance of about 2.5 m from the sap flow instrumented trees using time domain water content reflectometer probes (Model: CS616, Campbell Scientific, Inc., Logan UT, USA). The three sensors were installed at depths of 15, 50 and 120 cm and these data were collected at hourly intervals throughout the study period. This depth range is where the most active root system (feeder and other thin roots) responsible for taking up water and nutrients was located. Detailed information on the density of the fine roots (mg/cm^3) is shown in Fig. 3.3. There were also thicker, mostly anchor roots that sunk deeper into the soil profile and both species had a prominent taproot.

Fig. 3. 2. Automatic weather station measuring basic weather variables at Bonamanzi.

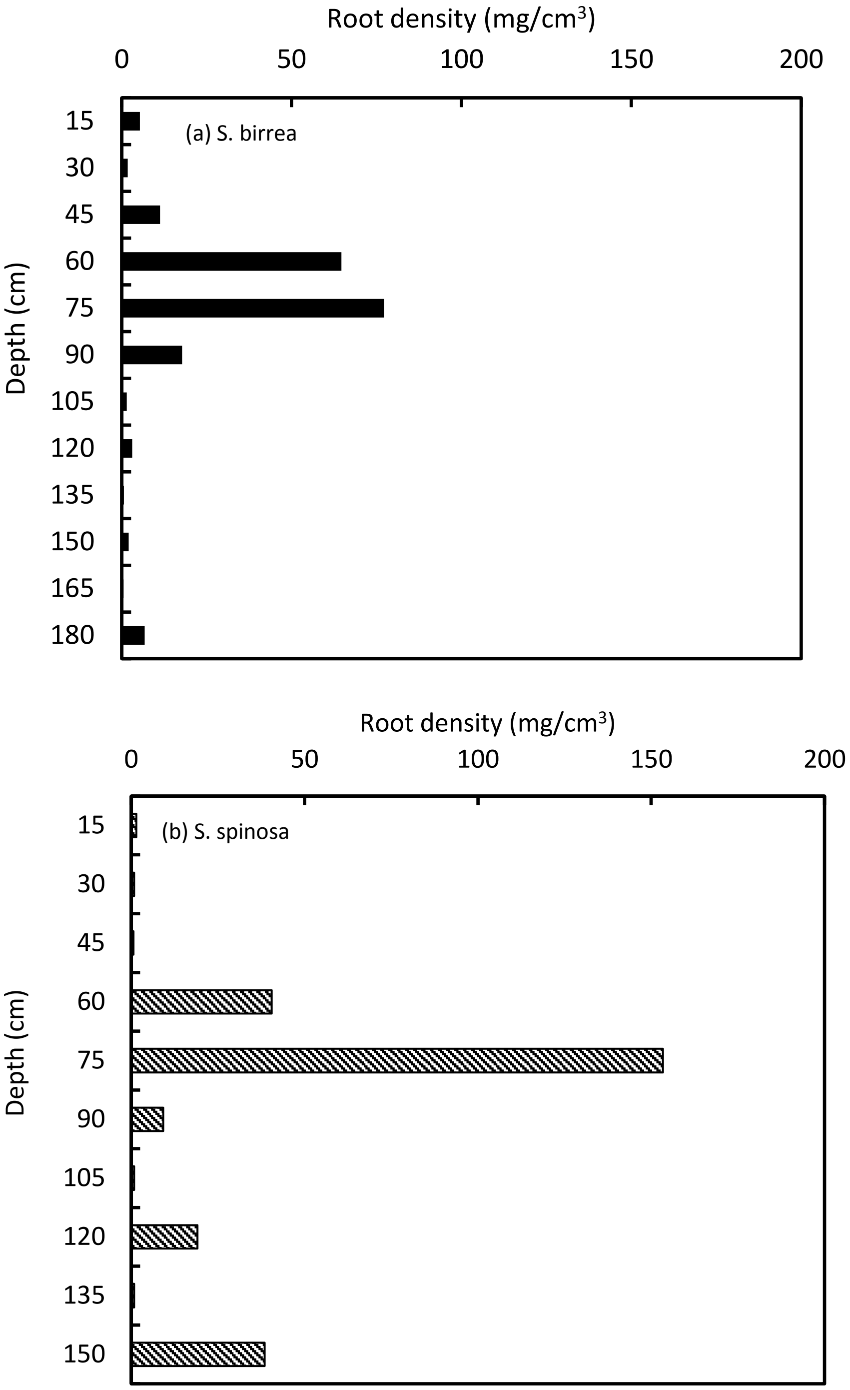


Fig. 3. 3. Variation in the root density (milligrams of fresh mass per cubic centimetre of soil) with depth for (a) S. birrea and (b) S. spinosa in the range 0 to 180 cm.

3.1.3 Sap flow, stomatal conductance, growth, and yield measurements

Transpiration was measured on four sexually mature individual trees, two *S. birrea* and two *S. spinosa* using the heat ratio method (HRM) of monitoring sap flow (Burgess et al., 2001) (Fig. 3.4). In order to produce sap-flow data that could be compared between individuals of the two species, trees with similar trunk diameters were chosen. However, the relatively small trunk size of a fully-grown *S. spinosa* tree therefore limited the maximum size of *S. birrea* tree that could be chosen. This limitation on the tree trunk diameter of *S. birrea* unfortunately forced us to select *S. birrea* individuals that were not fully-grown. So their yield was expected to be somewhat lower than that normally seen in fully-grown *S.*

birrea trees. The four sap flow instrumented trees are hereafter referred to as *S. spinosa* 1 and 2, and *S. birrea* 1 and 2, respectively. The trees grew in the same locality with the maximum distance between them being less than 6.0 m. The diameters at breast height were approximately 16.4 and 16.0 cm for *S. spinosa* 1 and 2, and 15.0 and 23.4 cm for *S. birrea* 1 and 2, respectively.

To install the sap flow sensors, a metal template with three precisely drilled holes aligned along the vertical axis of the trees and spaced at 5 mm apart was used to drill the holes to minimise errors due to probe misalignment. Four HRM probe sets were installed per tree. Each probe set comprised a central heater that injected heat into the stems and two T-type thermocouples that measured the sapwood temperature at equal distances (about 0.5 cm) up and downstream of the heater. The four probe sets were installed in the four cardinal directions around the trees and at different depths into the sapwood to account for the radial and circumferential variations in the sap velocity (Wullschleger and King, 2000). The probe installation depths were 1.5, 3.0, 4.5 and 6.0 cm from the outer bark for *S. spinosa* and for *S. birrea* 1. Because of the larger size of *S. birrea* 2, the probe installation depths were slightly different at 2.0, 4.0, 6.0 and 7.0 cm depth. The probes could not be installed at a larger depth for this tree because it also had a thicker heartwood. This was detected by observing the heat pulse velocity signals and adjusting the depth of the deepest probe until it gave good quality data.

Fig. 3. 4. (a) Strychnos and (b) Marula instrumented with the heat ratio method sap flow probes at Bonamanzi Game Reserve.

Each tree had a single thermally insulated tree box measuring about 35 x 25 x 10 cm, which contained the electronics of the HRM system. Eight T-type thermocouple sensors and four heater probes, each about 1.5 m long, were connected to the tree box, which also housed a precision thermistor, which gave the reference temperature for the thermocouples. The four tree boxes were connected to one data logger (Model: CR1000, Campbell Scientific, Inc., Logan UT, USA) and a multiplexer (Model AM16/32B, Campbell Scientific, Inc., Logan UT, USA) via a 25 core plain wire cable. Pulsing of the heat to the heaters, which lasted about one second, was done via a control port on the data logger. The electronics in each tree box was powered by a seven Ah battery and the sap flow data was collected at hourly intervals throughout the study period. The sapwood area was determined by injecting methylene blue dye into the stems of the trees to determine the extent of the active xylem vessels. The heat pulse velocity data was corrected for wounding due to sensor implantation according to the procedure by Swanson and Whitfield (1981). The sap flow volume per tree (in litres per hour) was calculated as a weighted sum of the products of the sap velocity and the sap wood area represented by each probe set.

The leaf area index (m^2 of leaf area per m^2 of ground area – LAI) was measured on the sap flow instrumented trees, and eight other trees of each species using a leaf area meter (Model: LAI-2000, Li-Cor Inc., Nebraska, USA). These data were collected at monthly or bi-monthly intervals either on overcast days, at sunset or before sunrise when there was no direct solar radiation on the leaves. Three campaigns were conducted to measure the stomatal conductance of the trees hourly from sunrise to late afternoon using a diffusion porometer (Model AP4: Delta-T Devices, Cambridge, UK (Fig.3.5)). These data were collected on *S. spinosa* in spring on 05 September 2018. *S. birrea* trees had no leaves at this time. The campaign was repeated in summer on 20 November 2018 on both species and again on 29 September 2019. The stomatal conductance data were collected on three sun exposed and three shaded leaves per tree. All the leaves were fully expanded and healthy.

To avoid bias due to alternate bearing of the trees growing in the wild, fruit yield data were collected on ten mature tagged trees per species. The average yield was calculated for each species over the two years. The procedure for estimating the yield per tree involved, firstly developing an index of fruit number per unit branch cross sectional area just before the fruit ripened. These data were collected before ripening to avoid loss of fruit due to predation by wild animals inhabiting the game reserve such as elephants, monkeys, baboons, birds, etc. To get a representative average of the fruit count per branch, an average count from four people was used.

Secondly, the index was applied to all the major branches and summed to estimate the total number of fruit per tree.

Thirdly, the average fresh mass of ten fruit was determined at maturity. Finally the total yield per tree was calculated as the average mass of an individual fruit multiplied by the estimated number.

Fig. 3. 5. Measurement of the stomatal conductance of S. spinosa using the AP4 porometer.

3.1.4 Modelling transpiration by indigenous fruit trees

The hourly transpiration of the individual trees (T_c, in g/h) was modelled using the combination Penman-Monteith equation for hypostomatous leaves according to Zhang et al. (1997) and Dzikiti et al. (2011):

$$\lambda T_c = L \frac{\Delta Rn_{tree} + 0.93\rho C_p \frac{(e_s - e_a)}{r_b}}{\Delta + 0.93\gamma(2 + \frac{\overline{r_s}}{r_b})} \tag{1}$$

where Rn_{tree} (W m^{-2}) is the net radiation absorbed by the tree canopy, ℓ (m^2) is the total leaf area of the tree, Δ (Pa/K) is the slope of the saturation vapour pressure vs temperature curve, ρ (kg/m^3) is the density of the air, C_p (J/kg/K) is the specific heat capacity of the air at constant pressure, e_s and e_a (in Pa) represent the saturation and actual vapour pressure of the air, γ (Pa/K) is the psychrometric constant, λ (J/kg) is the latent heat of vaporisation, $\overline{r_s}$ (s/m) the average stomatal resistance of the species, and r_b(s/m) is the aerodynamic resistance.

The total leaf area (L) of the instrumented trees was estimated as the product of the LAI and the canopy cross-sectional area of each tree. The net radiation absorbed by the tree canopy (Rn_{tree}) was approximated as half of that absorbed by a horizontal short grass surface (Rn) according to the approach followed by Zhang et al (1997). The Rn flux was calculated according to Carrasco and Ortega-Farias (2007) as:

$$Rn = (1-\alpha)R_s + \sigma(\varepsilon_a - \varepsilon_s)T_a^4 \tag{2}$$

where α is the surface albedo taken as 0.23, R_s (W/m^2) is the downward solar irradiance measured by the weather station, T_a (K) is the air temperature, σ is the Stefan-Boltzmann constant, ε_s is the emissivity of the surface, which was taken as 0.98, and ε_a is the emissivity of the atmosphere for both clear and cloudy conditions calculated as

$$\varepsilon_a = 1.31(\frac{e_0}{T_a})^{\frac{1}{7}}(a - mk_t) \qquad (3)$$

The expression (a-mk_t) in equation 3 accounts for cloudiness as proposed by Alados et al (2012) and the rest of the equation is the emissivity under clear sky conditions according to Brutsaert (1975). In this expression, e_0 is the actual vapour pressure of the air in hPa, a and m are constants with values of 1.002 and 0.303, respectively. The parameter k_t represents the ratio of the measured solar irradiance to the extra-terrestrial radiation, calculated according to Allen et al (1998).

The aerodynamic resistance was derived according to the logarithmic wind profile as:

$$r_b = \frac{\ln\left(\frac{z-d}{z_0}\right)\ln\left(\frac{z-d}{h-d}\right)}{k^2 u_z} \qquad (4)$$

where h (m) is the average height of the trees, z (m) is the measurement height for wind speed (u_z), d (m) is the displacement height calculated as d = 0.67h, z_0 (m) is the roughness length which was approximated as z_0 = 0.12h, k is the von Karman constant with a value of 0.4.

The stomatal conductance, g_s ($= {}^{1}/_{\overline{r_s}}$) was modelled using the multiplicative Jarvis (1976) method. In this method the g_s is calculated from the maximum stomatal conductance (g_{max}, m/s) moderated by stress factors for radiation (R_s), vapour pressure deficit (VPD), air temperature (T, in °C) and soil moisture (θ) written as:

$$g_s = g_{max} f(R_s) f(VPD) f(\theta) f(T) \qquad (5)$$

where $f(R_s)$, $f(VPD)$, $f(\theta)$ and $f(T)$ are the radiation, vapour pressure deficit, soil moisture and air temperature stress factors with values ranging from 0 to 1. The functional forms of the stress factors suggested by Jarvis (1976), Stewart (1988), Granier and Loustau (1994), Egea et al (2011), and Dzikiti et al (2018) are:

$$f(R_s) = \frac{R_s(1+0.001k_r)}{k_r + R_s} \qquad (6)$$

$$f(T) = \frac{(T-T_L)(T_h-T)^a}{(k_{Tp}-T_L)(T_h-k_{Tp})^a} \qquad (7)$$

$$f(VPD) = e^{-k_{vpd}VPD} \qquad (8)$$

$$f(\theta) = (\frac{\theta-\theta_{WP}}{\theta_{FC}-\theta_{WP}})^{\beta} \qquad (9)$$

where k_r, k_{Tp}, k_{vpd} and β are parameters obtained by model optimization, $a = (T_h-k_{Tp})/(k_{Tp}-T_L)$, T_h and T_L are the upper and lower temperatures at which g_s = 0, θ_{FC} and θ_{WP} are the volumetric water contents at field capacity and permanent wilting points of the soils, respectively. The Marquardt iterative method was used to derive model parameters that minimized the squared differences between the measured and modelled transpiration rates using the Model Maker software package (Cherwell Scientific, UK). The results of model calibration are shown in Table 3.2.

3.1.5 Statistical analysis

The performance of the Penman-Monteith transpiration model was evaluated based on the root mean square error (RMSE), mean absolute error (MAE), the slope, intercept and coefficient of determination (R^2). The predictive accuracy of the model was established using the Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970) calculated as:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n} (Y_i^{obs} - Y^{mean})^2} \right] \tag{10}$$

where Y_i^{obs} is the i^{th} observation of the daily T_c, Y_i^{sim} is the i^{th} simulated T_c, and Y^{mean} is the mean T_c value and n is the total number of observations. The NSE ranges between $-\infty$ and 1.0 with NSE = 1.0 being the optimal value and values between 0 and 1.0 are generally viewed as acceptable levels of performance.

Table 3. 2 Model parameters used for simulating the daily water use by S. spinosa and S. birrea trees growing in deep sandy dune soils.

Parameter	S. spinosa	S. birrea
a (-)	1.0	1.0
β (-)	0.1	1.2
g_{max} (mm s^{-1})	10.0	8.5
k_r (Wm^{-2})	150	50
kT_p (°C)	20	15
k_{vpd} (kPa^{-1})	0.30	0.10
m (-)	0.30	0.30
T_h (°C)	41	41
T_L (°C)	5	5
θ_{FC} (cm^3/cm^3)	0.083	0.010
θ_{WP} (cm^3/cm^3)	0.083	0.010

3.2 RESULTS

3.2.1 Site microclimate and soil moisture dynamics

A summary of the monthly weather conditions over the period January 2018 to December 2019 is shown in Fig. 3.6. The daily average solar radiation ranged from about 9.9 $MJ/m^2/d$ in winter (June 2018) to a peak around 23.3 $MJ/m^2/d$ in summer in January 2019 (Fig. 3.6a). The highest temperature recorded during the study period was about 40.4°C in October 2019 (Fig. 3.6b). For the same period, the vapour pressure deficit of the air (VPD) peaked at less than 1.5 kPa (Fig. 3.6c) which was quite low compared to values recorded elsewhere in South Africa which can reach up to 9.0 kPa in the drier parts of the country (Dzikiti et al., 2017). The low VPD can be explained by the fairly high minimum relative humidity, which averaged around 27% since the maximum temperature was reached during the summer rainy season. However, the proximity of the study site to the Indian Ocean, which was less than 10 km to the east, which was also the direction of the prevailing winds may have been another contributory factor. July was the coldest month reaching 4.4°C in 2018 and 4.5°C in 2019. Monthly average wind speeds were quite low being less than 1.5 m/s throughout the study period.

Rain fell throughout the year in the form of mainly subtropical thunderstorms in the summer months (October to March) and frontal rainfall in the winter months (May to August). February and March were the wettest months with rainfall exceeding 100 mm/month in the each of the two years. The annual rainfall total in 2018 was about 627 mm compared to the reference evapotranspiration of around 831 mm. The second year of the study (2019) was wetter receiving 819 mm of annual rainfall while the atmospheric evaporative demand, depicted by the reference evapotranspiration (ET_o) was also higher at 1045 mm.

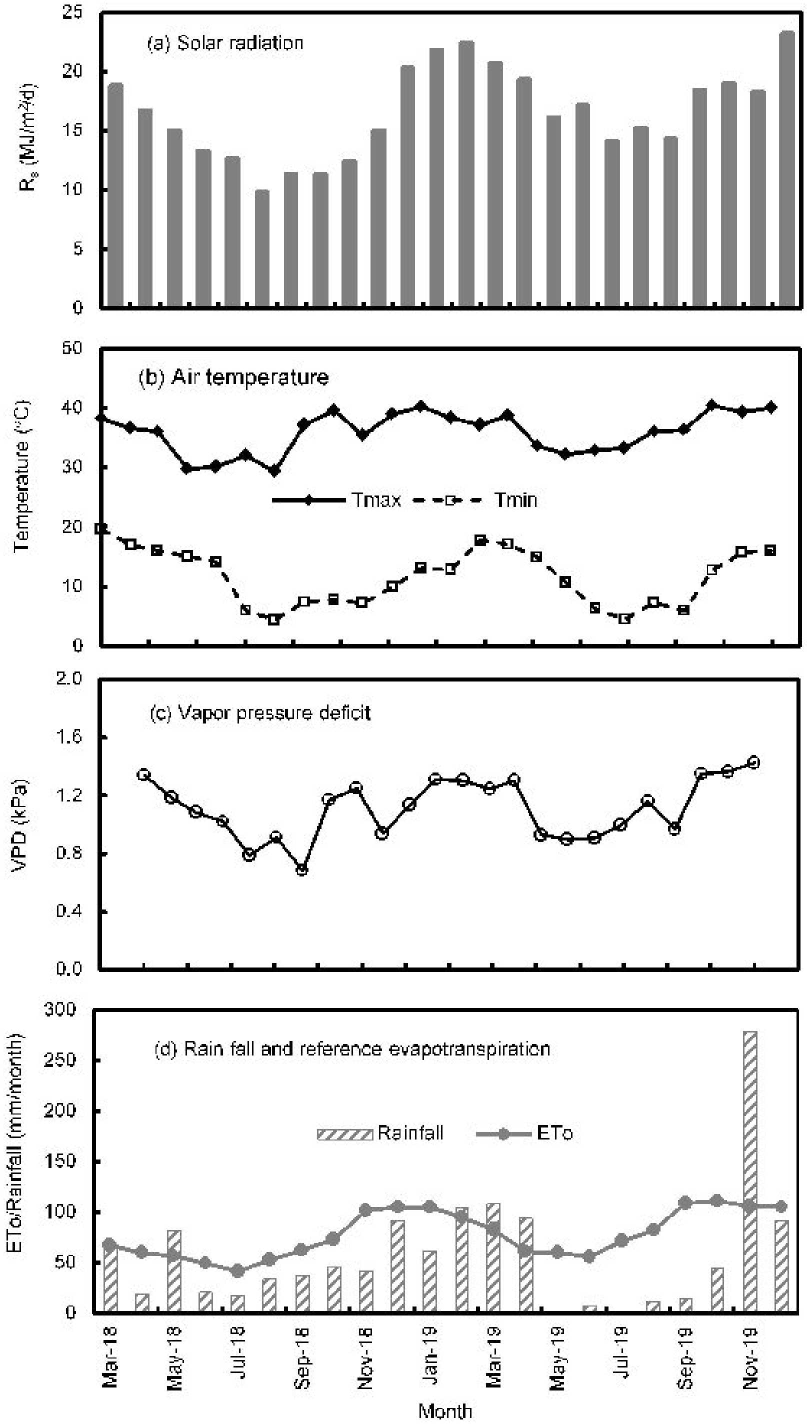


Fig. 3. 6. Measured monthly weather conditions for the period 01 January 2018 to December 2019 representing (a) the average daily total solar radiance for the month, (b) maximum and minimum temperatures, (c) vapour pressure deficit of the air, and (d) the monthly total rainfall and reference evapotranspiration, respectively.

As expected, the soil water content in the root zone of the trees responded to precipitation events (Fig. 3.7) although the collection of the soil water content data only started in April 2018. Most of the rainfall wetted the top 15 to 50 cm depths. Only five major storms wetted the soil profile down to 120 cm in May 2018, December 2018, March 2019, April 2019 and in November 2019 (Fig. 3.7).

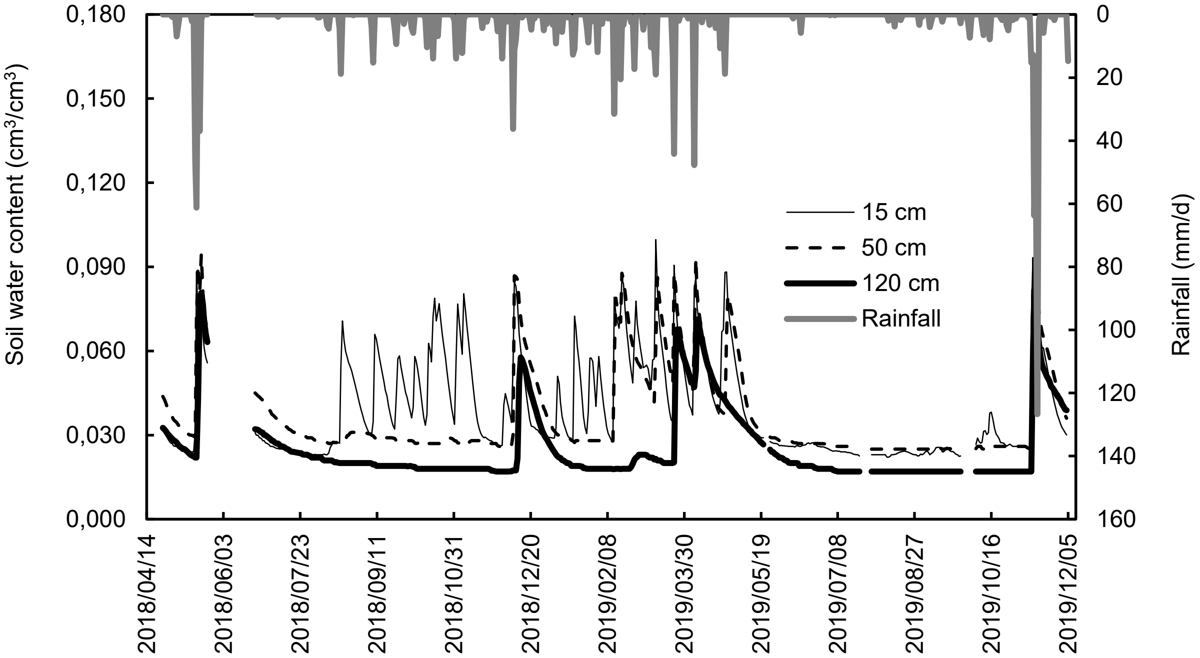


Fig. 3. 7. Effect of rainfall on the soil water content at various depths in the root zone of S. birrea and S. spinosa trees.

3.2.2 Stomatal conductance and sap flow dynamics

Changes in the stomatal conductance of both species were nonlinearly related to the climate driving variables. For example, Fig. 3.8 (a-d) shows typical trends in the hourly solar irradiance and VPD and on two clear days, one in spring (05 September 2018) and the other in summer (20 November 2018).

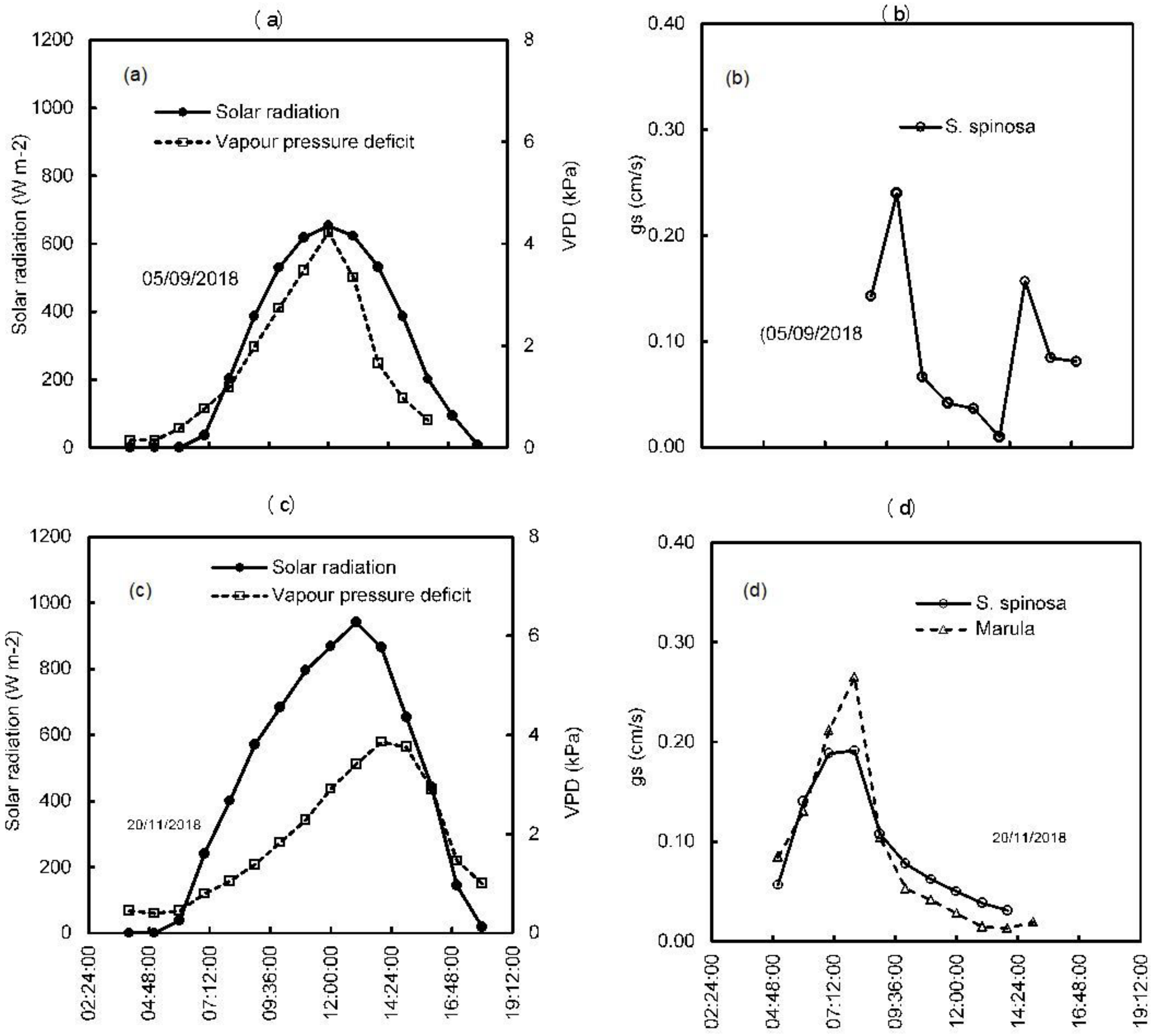


Fig. 3. 8. The diurnal course of the solar irradiance and vapour pressure deficit of the air on 05 September 2018 (a) and the corresponding stomatal conductance trend for S. spinosa (b). The hourly course of the solar irradiance and vapour pressure deficit on 20 November 2018 (c) and the corresponding stomatal conductance of both S. spinosa and S. birrea (d).

There was evidence of midday closure of the stomata for both species (Fig. 3.8 b & d), although the measurements on 20 November 2018 ended just after midday. The average volumetric soil water content in the root zone was approximately 0.03 cm^3/cm^3 for the spring and slightly higher for the summer campaign at about 0.06 cm^3/cm^3. However, it is not clear if this had an effect on the stomatal conductance, which peaked between 2.0 and 2.6 mm/s. Although *S. birrea* seemed to have a higher morning peak conductance, this dropped more sharply compared to that of *S. spinosa* (Fig. 3.8d) suggesting that *S. birrea* stomata responded more strongly to environmental stress factors.

The hourly sap flow signals for both species also showed, albeit mild, midday depressions consistent with the stomatal conductance trends (data not shown). Over the entire measurement period, the daily total sap flow of both species showed clear seasonal patterns related to the atmospheric conditions (Fig. 3.9a). The transpiring leaf surface areas of the two species were not vastly different, with the peak LAI of *S. spinosa* being about 1.42 m^2/m^2 compared to approximately 1.20 m^2/m^2 for *S. birrea*. However, the maximum transpiration per unit leaf area was higher for *S. spinosa* at approximately 2.3 ℓ/m^2/d compared to about 1.4 ℓ/m^2/d for *S. birrea.* The corresponding daily peak transpiration of *S. spinosa* (~ 36 ℓ/d) was almost double that of *S. birrea* (~19 ℓ/d) reached during the summer months. These transpiration values are averages for the two instrumented trees of each species. The annual total water use of an individual *S. spinosa* tree was about 6 061 litres while *S. birrea* used close to a third of this amount at only 2 160 litres per tree. These values represent averages for the two sap flow instrumented trees of each species over the two years.

Despite the fact that the two tree species grew in the same locality, and therefore experienced the same resource constraints, their water use patterns responded differently to environmental factors as illustrated in Fig. 3.10. *S. spinosa* transpiration, for example, was correlated to the atmospheric evaporative demand ($R^2 = 0.37$). However, the water use was poorly correlated to the soil water deficit ($R^2<0.10$) – see Figs. 10a & c. The influence of these water use drivers on *S. birrea* transpiration were the opposite of *S. spinosa*. The atmospheric evaporative demand explained less than 20% of the variation in *S. birrea* transpiration ($R^2 = 0.19$) but the soil water deficit in the root zone explained more than 65% of this variation ($R^2 = 0.66$) – see Figs 3.10b & d.

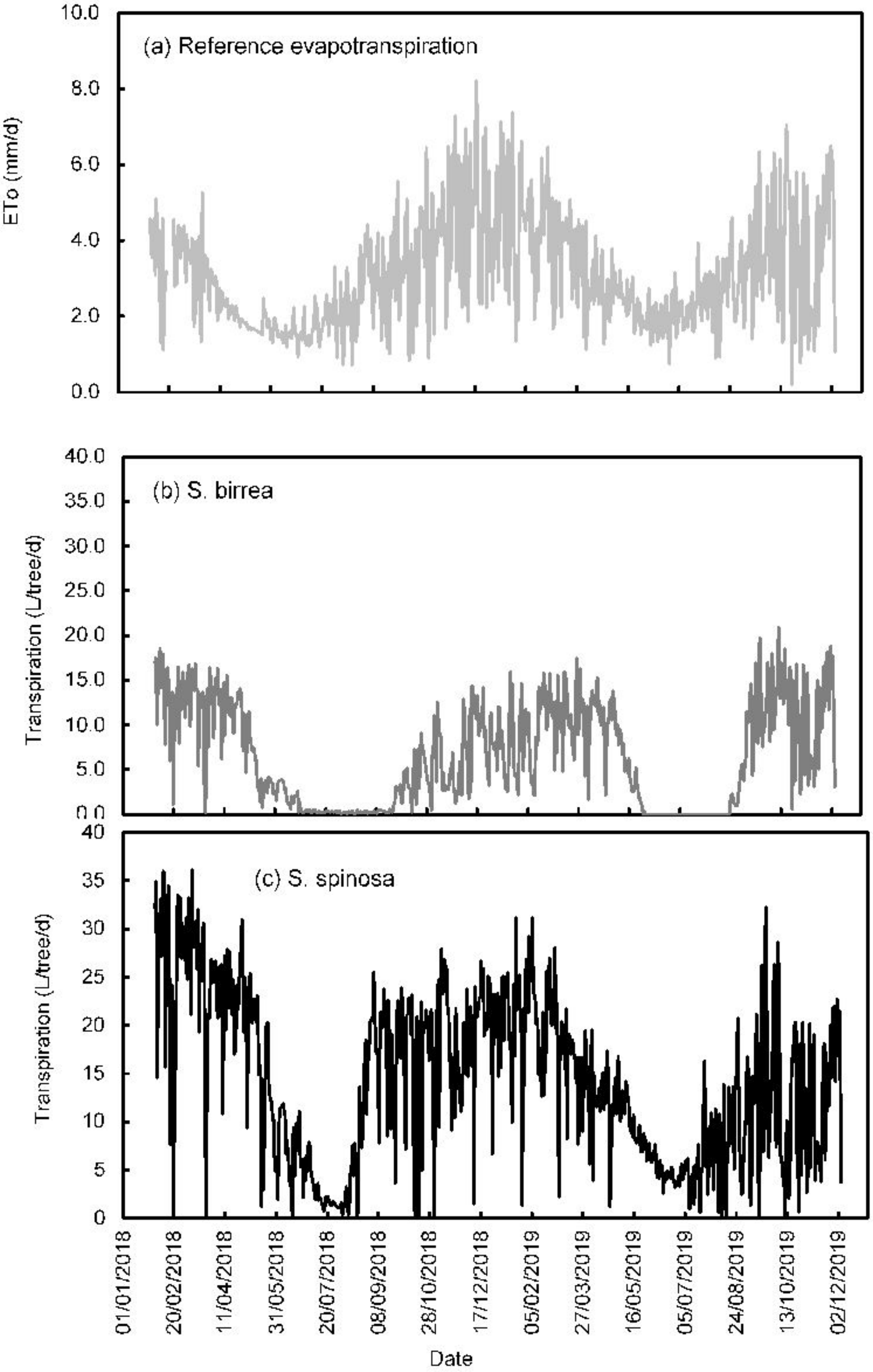


Fig. 3. 9. Effect of the atmospheric evaporative demand (a) on the daily total transpiration for S. birrea (b) and S. spinosa (c) at Bonamanzi Game Reserve.

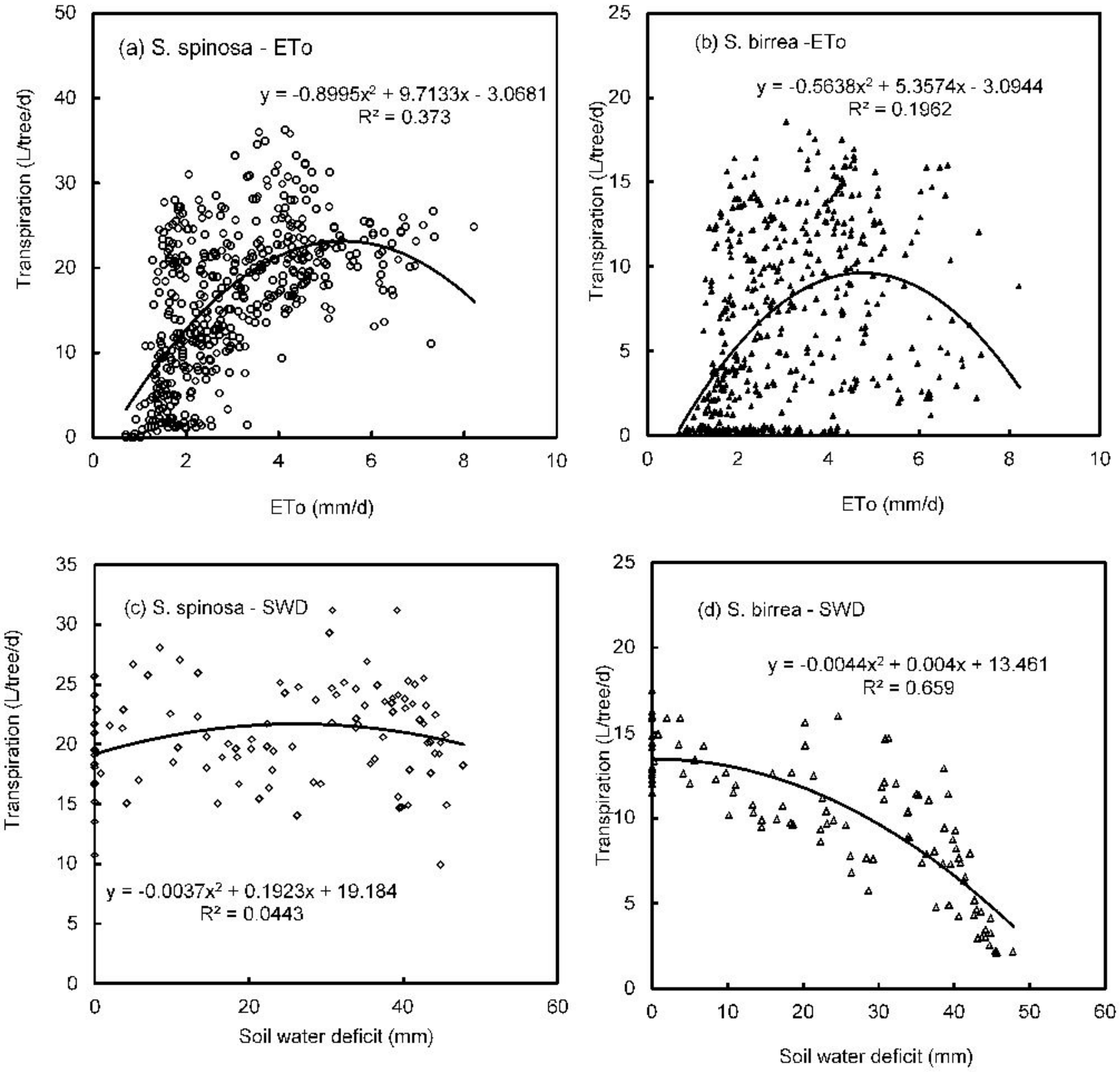


Fig. 3. 10. Effect of the atmospheric evaporative demand (ETo) on the daily transpiration for S. spinosa (a) and S. birrea (b). Effect of the soil water deficit (SWD) in the root zone on the daily transpiration of S. spinosa (c) and S. birrea trees (d).

3.2.3 Transpiration model performance and sensitivity tests

The physiological reasons for the observed variations in the transpiration response of these drought adapted woody species are not clear. This will be the subject of future studies aimed at understanding the resilience of these potential alternative fruit tree crops to climate change. What is evident however is the fact that to model the transpiration dynamics of these co-occurring species accurately, different model parameters are required (Table 3.3). Therefore, to gain further insights on the transpiration responses to environmental factors, we performed sensitivity tests on the transpiration model by varying key parameters by ±30% in four equal steps. The tests were performed using data for one clear day on 16 January 2019. As expected, changing the maximum stomatal conductance (g_{max}) by this margin had a significant impact on the modelled transpiration by both species (i.e. 28% for *S. spinosa*, and 29% for *S. birrea*) shown in Figs 3.11a & f, respectively. However, the radiation stress factor parameter (k_r) had the least impact on transpiration by both species (Fig. 3.11 b & g) while the VPD parameter (k_{vpd}) caused a 19% change in *S. spinosa* transpiration, but it had a negligible effect on *S. birrea* transpiration (Fig. 3.11h). This observation is consistent with the measured data shown in Figs 3.10 a & b where the strongly curvilinear response to ETo is related to the strong sensitivity of *S. spinosa* stomata to the ambient VPD changes (data not shown). On the other hand, the transpiration response of *S. birrea* was very sensitive to the soil water content stress factor (Fig. 3.11i) in which a 30% change in parameter β resulted in more than 32% change in transpiration. However, the soil water stress factor parameter had a negligible impact on the modelled transpiration for *S. spinosa*, again consistent with the measured response shown in Fig. 3.10c. The optimal temperature for growth had the largest impact on the transpiration response of both species Figs 3.11(e & j).

Overall, the modelled daily transpiration closely matched the measured values for both species from 01 July 2018 to 30 June 2019 (Fig. 3.12). A feature of *S. birrea* transpiration, which was captured by both measurements and by the model, is that peak transpiration occurred late in the growing season in autumn (March to April) when the atmospheric evaporative demand was dropping (Fig. 3.12b). This suggests a likelihood of heightened stomatal control of water loss during the hot summer weather.

A detailed summary of the transpiration model performance is shown in Table 3.3. The NSE was significantly greater than zero and closer to one for all the trees suggesting acceptable performance of the model. The RMSE for *S. spinosa* was largest at about ±3.4 ℓ/d, compared to ~ ±1.6 ℓ/d for *S. birrea,* which translated to about ±10% of the peak transpiration for both species.

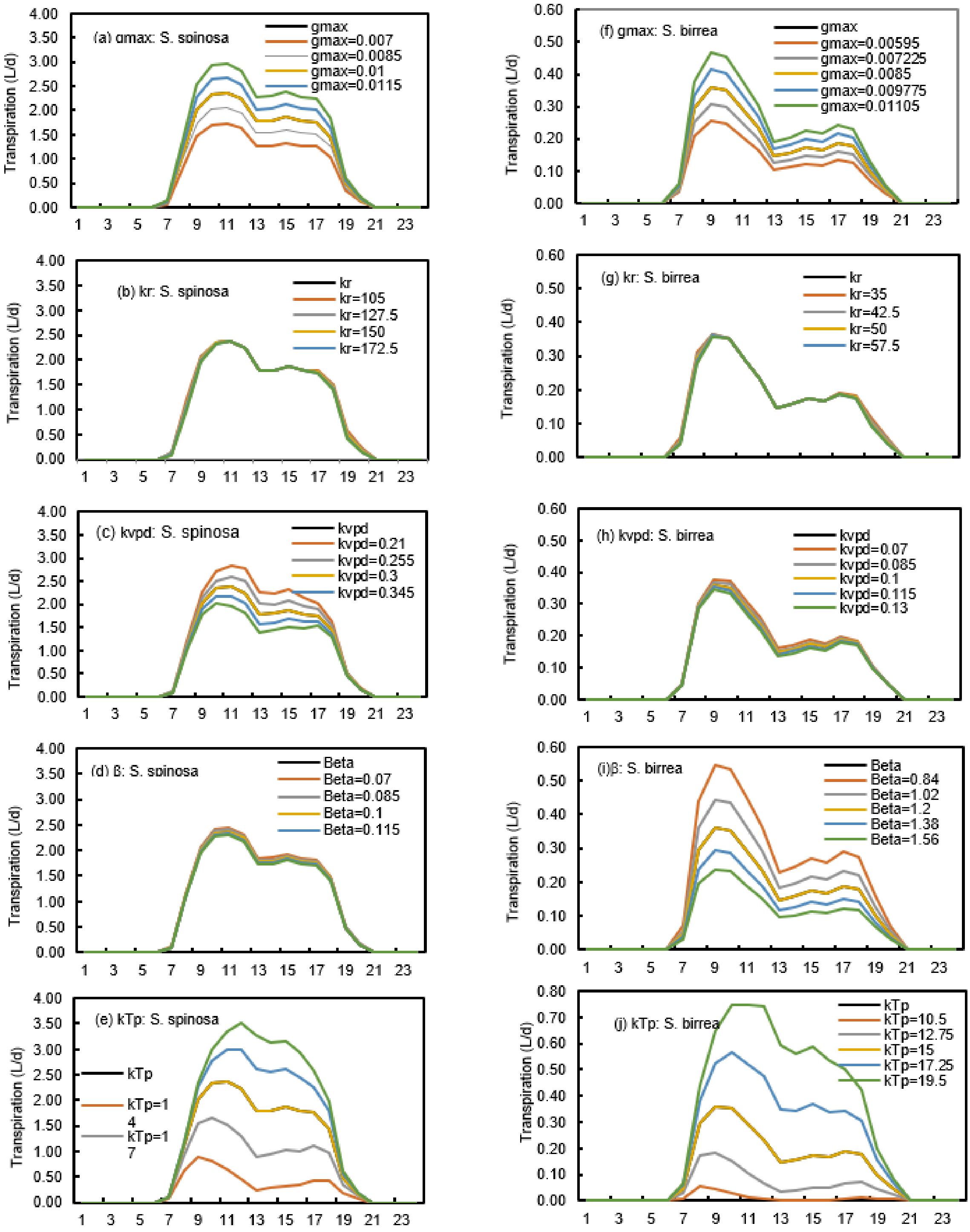


Fig. 3. 11. Sensitivity tests for parameters in the Penman-Monteith model. (a & f) shows the effect of the maximum stomatal conductance (g_{max}), (b-g) the radiation stress parameter (k_r), (c & h) the vapour pressure deficit stress factor parameter (k_{vpd}), (d & i) the soil water content parameter (β), and (e & j) the air temperature parameter (k_{Tp}) for S. spinosa and S. birrea.

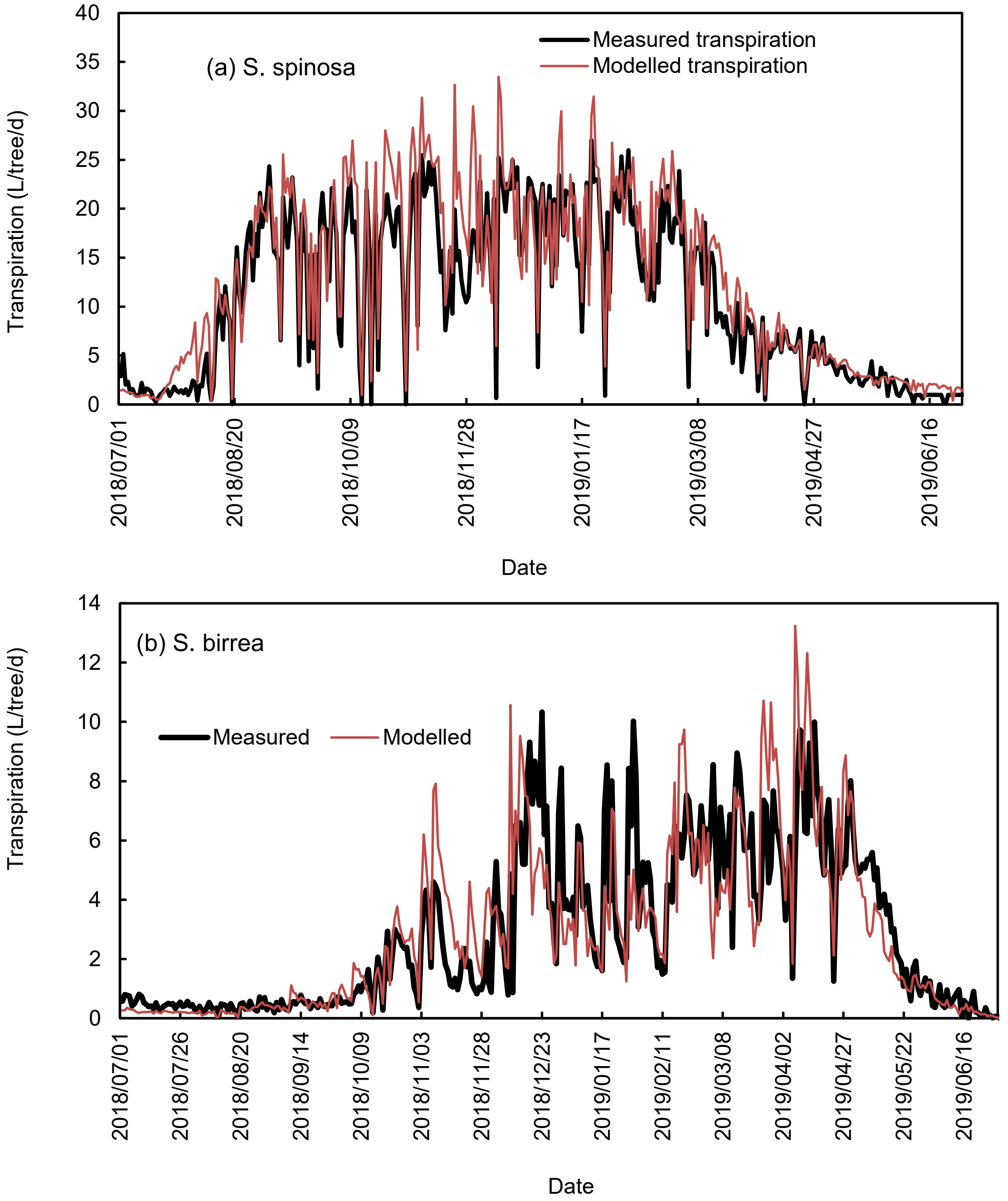


Fig. 3. 12. Comparison of the measured (black lines) and modelled (brown lines) daily transpiration for (a) S. spinosa, and (b) S. birrea trees for the period 01 July 2018 to 30 June 2019.

Table 3. 3 Statistical summary of the performance of the Penman-Monteith based model in predicting the daily transpiration of single S. birrea and S. spinosa trees over one year from 01 July 2018 to 30 June 2019.

Species	Tree no.	R^2	Slope	MAE (ℓ/d)	RMSE (ℓ/d)	NSE
S. spinosa	1	0.89	1.03	2.42	3.35	0.82
	2	0.86	0.94	2.25	3.01	0.85
S. birrea	1	0.74	0.89	0.92	1.43	0.71
	2	0.69	0.86	1.01	1.61	0.64

3.3 DISCUSSION

Both species studied here displayed isohydric responses closing their stomata with increasing atmospheric evaporative demand. There was a well-pronounced midday stomatal closure, which has also been reported in temperate, e.g. *Norway spruce* (Zweifel et al., 2002) and Mediterranean tree species, e.g. *Arbutus unedo* and *Quercus ilex* (Tenhunen et al., 1981). However, *S. birrea* stomata had a stronger response, particularly driven by soil water deficit than by climatic factors, and it is probable that this led to reduced photosynthesis rates. While indeed the low yield per tree of *S. birrea* at this site can be attributed to the small size of the trees, the comparatively small size of the fruit suggested reduced photosynthetic activity. According to Zhang et al. (2013), the midday stomatal closure in deciduous broad leaf tree species (such as *S. birrea* and *S. spinosa*) under sub-tropical conditions is strongly correlated to the decrease in the stem rather than leaf water potentials although these variables were not measured in this study. As expected, the diurnal sap flow trends of both species also showed, albeit a comparatively less pronounced, midday depression. Transpiration per unit leaf area was much lower for *S. birrea* than *S. spinosa*, but we are unclear about the reasons. While indeed the more drastic stomatal response to drought by *S. birrea* could be a factor, other possible causes may include differences in stomatal density on the leaves (Steppe et al., 2006), narrower xylem vessel diameters for *S. birrea* causing higher hydraulic resistances, although we did not measure these variables.

Despite the small difference in canopy size between the monitored plants, the annual water use of *S. birrea* trees was roughly a third of that used by *S. spinosa* and there are several reasons for this. The first reason relates to the lower daily transpiration per unit leaf area even when soil water was not limiting discussed earlier. Secondly, extended dry spells led to significant stomatal closure and subsequently to a decline in *S. birrea* transpiration while *S. spinosa* maintained high water use rates. The high transpiration rates of *S. spinosa* even under water limiting conditions were possibly a result of its very dense and extensive network of fine roots (see Fig. 3.3). The combination of the relatively small tree size for the *S. birrea* studied here and the harsh growing conditions culminated in low average yields (fresh mass) of only about 4.3 kg/tree (Table 3.4). Fully-grown *S. birrea* trees at other sites have been reported to yield more than 40 kg/tree (Akinnifesi et al., 2008). On average, the yield of *S. spinosa* trees was about 15.2 kg of fruit calculated as an average from 10 trees over two years. The water productivity, defined as the fruit yield per unit volume of water transpired, was about 2.0 kg/m^3 for *S. birrea* and 2.5 kg/m^3 for *S. spinosa* (Table 3.4). These water productivity values are quite low compared to those of exotic irrigated commercial deciduous fruit under management. For example, Dzikiti et al (2018) and Gush et al (2019) reported water productivity values in the range 8 to 18 kg/m^3 in different apple orchards in the Western Cape Province of South Africa. According to Steduto et al (2012), the transpiration of fruit trees is correlated to their yield. Therefore, it is possible that the water productivity of the indigenous fruit tree crops could be improved with supplemental irrigation, e.g. for high value species like *S. birrea* whose transpiration response, and possibly yield appear to be sensitive to soil water deficit in nutrient poor deep sandy soils.

The second reason for the low annual water use by *S. birrea* relates to its relatively long leafless period (> 3 months) compared to *S. spinosa* (~ < 1 month). These differences in the water requirements have implications on the conservation of the species. *S. birrea* for example, is classified as an endangered protected species in many parts of Southern and Eastern Africa (Taylor, 2008; Cemansky, 2015) due to extensive deforestation for timber and firewood and the extensive harvesting of its products, e.g. leaves, roots, bark, etc. for medicinal purposes. Our study suggests that under conditions of severe water limitations, *S. spinosa* appears to be more resilient to drought stress than *S. birrea*, likely because of its dense network of mostly fine roots, which can scavenge for water and nutrients.

Table 3. 4 Summary of the water use, yield and water productivity of the S. birrea and S. spinosa trees calculated as averages over two years.

Variable	S. spinosa	S. birrea
Maximum daily transpiration (ℓ/tree/d)	36	19
Average annual total transpiration (ℓ/tree/year)	6 061	2 160
Average number of fruit per tree	56	128
Average fresh mass of a single fruit (g)	276	16
Average yield per tree (kg)	15.2	4.3
Water productivity (kg/m^3)	2.5	1.99

Despite the differences in the water relations of *S. birrea* and *S. spinosa* trees, for the first time, we demonstrate that their transpiration can be accurately modelled using a simple combination Penman-Monteith equation. However, different model parameters are required to capture the complex responses of individual species under the harsh growing conditions, even for trees growing close to each other. Given the simple and readily available inputs required, the model can be used for estimating the water requirements of individual trees of these species in support of various agroforestry and biodiversity conservation and management programmes in natural forests.

3.4 CONCLUSION

This study illustrates how two key fruit tree species with potential for domestication and commercialisation that are indigenous to sub–Saharan Africa interact with their environment. Because both *S. birrea* and *S. spinosa* co-occur within drought prone landscapes, we expected them to respond to environmental stress factors in a similar way. However, this was not the case with *S. birrea's* water use mostly driven by soil water availability while that of *S. spinosa* responded largely to the atmospheric evaporative demand. From the results of this study, it would seem that *S. birrea* trees might survive in deep sandy soils even with limited rainfall amounts. However, their fruit production is likely to be quite low given the high stomatal sensitivity to drought stress demonstrated here. Therefore, *S. birrea* trees could benefit from supplemental irrigation to enhance fruit yield if high productivity is the target or to keep the trees alive during extreme droughts. However, the differences in typical life history strategies followed by the two species are also important to understand their water use and potential fruit yield capabilities. *S. birrea* trees for example, tend to accumulate vast amounts of resources over many years, storing them within their substantially larger bodies. These resources are then released in mast years in order to produce large quantities of fruit. This ability to shift its phenology in order to capitalise on favourable conditions and to avoid adverse conditions complicates the interpretation of short-term data such as that reported here. This study also highlights the complexity of accurately modelling the transpiration dynamics of Africa's highly biodiverse biomes, which are often needed in general circulation models, climate change, and in natural forest conservation and management studies. In view of the apparent greater resilience of *S. spinosa* to drought stress, agroforestry programmes in areas with poor sandy soils and low rainfall amounts could possibly derive higher production levels from this species.

CHAPTER 4: WATER USE AND YIELD DYNAMICS OF SCLEROCARYA BIRREA (MARULA) IN HAZYVIEW, MPUMALANGA WITH A TEMPERATE HIGHLAND TROPICAL CLIMATE

4.0 INTRODUCTION

Sclerocarya birrea (A. Rich) Hochst. subsp. caffra (Sond.) Kokwaro (Marula), a member of the Anacardiaceae family, is an indigenous fruit tree species that grows in natural forests across large parts of sub-Saharan Africa. Within the sub-continent *S. birrea* fruit are mostly harvested from the wild unmanaged populations (Akinnifesi et al., 2008). However, its products that include skin care products, oils, jams, liquors, beverages, etc. can be found in more than 100 countries globally (Wynberg et al., 2002). Therefore, *S. birrea* trees play an important role in supporting industries, sustainable rural development, and in providing sustenance to a range of wildlife. Given the significant potential for commercial development, *S. birrea* plant material has now been introduced to major fruit producing countries such as Israel and China (Nerd and Mizrahi, 2000; Li et al., 2015).

Effective management of specific tree species in natural forests requires a detailed understanding of the factors that drive their water use, growth, and productivity. In semi-arid countries such as South Africa and Australia, for example, specific provisions have been made in the water legislation to avail water to the environment, highlighting the need for accurate data on the water use of natural forest species (National Water Act, 1998; National Water Commission, 2014). Water for the environment is essentially water, which is allocated and managed specifically to improve the health of rivers, wetlands and flood plain ecosystems. Within these initiatives, there is a particular focus on endangered water sensitive tree species, e.g. *S. birrea* in South Africa (Dye et al., 2008) and several eucalypt species in Australia. Regarding utilisation of natural forest species as alternative fruit tree crops, the first commercial *S. birrea* (Marula) orchards, growing under management, were established in Israel in the 1980s (Nerd and Mizrahi., 2000).

Numerous pre and postharvest research needs must be addressed in order to promote the cultivation of Marula and the utilisation of its products on a larger scale. For example, there is need to remove the many unknowns around the performance of Marula in different agro-ecological zones and to establish the limits of the species' adaptability to climates and soils. From a commercial fruit production perspective, there is also a need for selections for traits such as larger fruit size with smaller stone and thinner skins, improved precocity, higher yields, less alternate bearing, and greater tolerance to droughts, pests, and diseases.

The selection of indigenous fruit trees (including Marula) with superior qualities is being done by the ARC Institute for Tropical and Subtropical Crops. There are also NGOs that are involved in the domestication of indigenous fruit trees in South Africa. However, what is lacking is detailed eco-physiological and agronomic research to support these efforts, hence this study is focusing on the water use of this plant and also taking other eco-physiological measurements to better understand the interaction of this plant species with the environment. The main Marula producing regions are in Limpopo, Mpumalanga, and KwaZulu-Natal Provinces. These provinces also have the highest density of rural populations that depend on indigenous fruit trees for income generation.

4.1 MATERIALS AND METHODS

4.1.1 Description of study site

The Burgershall study site is situated within the Agricultural Research Council (ARC) campus near the town of Hazyview in Mpumalanga. The site comprises more than 15 fully-grown Marula trees (Fig. 4.1) that were planted in the 1990s in an orchard format as part of the ARC's indigenous fruit tree crops program. The trees at this site are not irrigated, but they appear quite healthy and actively growing.

Fig. 4. 1. Marula orchard at the Burgershall campus of the ARC Subtropical crops division in Mpumalanga.

The climate at Burgershall is subtropical with rain falling during the summer months from October to March or early April. The site receives fairly high annual rainfall with the long-term average rainfall in the range 700 to 800 mm. Numerous subtropical crops are grown in the neighbourhood of the study site that include banana, mango, macadamia nuts, pecan nuts, citrus, etc. There are also commercial forest plantations mostly in high lying areas of eucalyptus and pine species.

Soils at the study site were shallow dark red clayey soils with a fairly high stone content and Fig. 4.2 shows a typical soil profile. There exists an impenetrable hard pan at a depth between 1.0 and 1.5 m.

Fig. 4. 2. Profile pit at the Marula study site at Burgershall, Mpumalanga.

4.1.2 Data collection at Burgershall

Equipment was installed during the first week of October 2019. Data collected at Burgershall included sap flow, on three trees, volumetric soil water content at 15, 50 and 100 cm depths, site microclimate and fruit growth rate. These variables were measured at hourly intervals for the duration of the study. Data was collected over two seasons in order to capture the alternate bearing tendencies of the trees. Sap flow was measured using the heat ratio method (HRM) of the heat pulse velocity sap flow technique (Fig. 4.3) described by Burgess et al (2001). The HRM method used was the one adapted by Everson (pers. comm.) to monitor trees that are far apart.

Fig. 4. 3. Heat ratio sap flow monitoring systems installed on the mature Marula trees at the ARC Burgershall research site

The sapwood depth was determined by auguring a wood sample using a stem corer (Fig. 4.4a). This information confirmed the insertion depths to use during installation. The heartwood was visually distinguishable from the rest of the sapwood once the core was out, as shown in Fig. 4.4b.

(a) (b)

Fig. 4. 4. (a) Extracting a stem sample for the Marula trees using a stem corer. (b) Cross sectional area for a Marula tree stem showing the position of the heartwood.

4.1.3 Site microclimate

Site microclimate at Hazyview was monitored using an automatic weather station that belongs to the ARC, measuring basic weather variables such as the solar irradiance, air temperature, relative humidity, wind speed and direction and rainfall. The data were recorded at hourly and daily intervals. The station was located on a short grass surface (Allen, 1998) stationed less than 1 km from the studied trees.

4.1.4 Soil water content and soil physical and chemical properties

The soil water content in the root zone of the trees was measured using water content reflectometers (Model CS616: Campbell Scientific, USA) installed at various depths (Fig. 4.2). The soil physical & chemical properties at the study site are presented in Table 4.1.

Table 4. 1 Physical and chemical properties of the soils at Burgershall

Sample Name	Crops	pH(water)	Res(ohms)	Ca mg/kg	Mg mg/kg	K mg/kg	Na mg/kg	P (Bray 1)	Al mg/kg	Ca/Mg	Ca+Mg/K	Sand %	Silt %	Clay %
Top	Marula	5.92	1500	771	107	285	4	9.1	4	7.21	3.08	52	8	40
Middle	Marula	5.68	1800	551	99	230	8	1.8	7	5.57	2.83	54	8	38
Bottom	Marula	5.74	2400	399	115	139	9	1.3	5	3.47	3.7	62	12	26

4.1.5 Plant measurements

4.1.5.1 Stem size distribution

Trees with different stem sizes were measured at breast height using a tape measure. The stem diameters were then categorised into three size classes namely the small (0–20 cm), medium (21-30 cm) and large (> 30 cm). Trees whose stem diameters were close to the median stem sizes in each diameter class were selected. The sap flow sensors were installed on the stems. Stand level transpiration by the trees was calculated as the weighted sum of transpiration by trees in three stem size classes with the weighting functions being the number of trees in a particular stem size class per hectare.

4.1.5.2 Canopy dimensions and leaf area index

The dimensions of the sap flow instrumented trees were measured and they are summarised in Table 4.2. The thermocouples were installed at the depths of 10, 20, 30 and 40 cm from the bark. Deeper installation depths were not feasible given the limitations in the length of the brass sleeves that facilitates heat transport from the heater to the sapwood.

Table 4. 2 Dimensions of the Marula sap flow instrumented trees in Mpumalanga

Tree measurements	Tree 1	Tree 2	Tree 3	Notes
Height (m)	6.7	7.5	6.5	10-Oct-19
Canopy width (E-W) (m)	6.2	11	11.2	10-Oct-19
Canopy width (N-S) (m)	9.1	12.4	14.3	10-Oct-19
Stem diameter (cm)	23.2	13	55	10-Oct-19
Leaf Area index	0.52	1.65	1.28	10 Oct 19
Leaf area index	0.27	2.35	1.13	22 Oct 19

Canopy dimensions were measured as the proportion of a fixed area of the ground covered by tree crowns. The canopy cover was determined by the tree species, as they have different crown sizes, shapes, and heights. Plant height was measured using a calibrated telescopic rod.

4.1.6 Fruit yield of Marula trees

To sample fruit from the Marula trees, a fruit pick up method was adopted. When the fruit had reached a ripening stage, they fell randomly under the tree, they would then be picked up and counted as shown in Fig. 4.5. This was especially the case when it was windy the fruit would fall from the trees, this fruit was collected and recorded. To determine the fruit mass, the fruit were measured using Vernier callipers, the overall quality of the fruit was eventually analysed in the laboratory.

Fig. 4. 5. Fruit pickup at the Marula study site in Hazyview

4.1.7 Tree water status and photosynthesis of Marula

Processes such as photosynthesis and transpiration are strongly regulated by the water status of the trees. Information relating the water flow and storage to the water status of indigenous fruit tree species in South Africa and elsewhere on the African continent is currently not available. Tree water status affects the stomatal conductance, which in turn controls the rates of photosynthesis and transpiration and hence water use efficiency (WUE) in the short term and water productivity (WP) in the long-term. In this study, we present data in which we track the flow of water from the roots, through the stem and its eventual exit from the trees as transpiration in the leaves. We determined the time lags in water flows through the different organs and related this information to leaf gas exchange for Marula trees.

Root- and branch-level sap flow was quantified according to the Stem Heat Balance method via the installation of Dynagage sap flow sensors (Dynagage®, Dynamax Inc., USA) on two Marula trees of different sizes. Two SGA-13ws (12-16 mm stem diameter) and two SGA-16ws (15-19 mm) sap flow gauges were installed (one on the root, one on the branch) on both Marula Tree number 2 and Tree number 3, respectively (see Fig. 4.6). For root gauges, small patches of soil were excavated around the base of the tree until a root of sufficient size and health was obtained. After carefully removing the soil around the root, a large enough portion of the root was exposed for sensor installation (Fig. 4.6).

The root was lightly sanded with medium-fine sandpaper to prepare a smooth surface without irregularities, which would otherwise interfere with proper contact between the sensor and the root surface. After sanding, the contact area was gently cleaned with water, allowed to dry, and then sprayed with a mineral oil-based release spray. This was done to 1) prevent the sensor from sticking to the root surface, and 2) prevent sensor damage due to daily shrinkage and expansion of the root. SGA-13ws (Tree 3) and SGA-16ws (Tree 2) gages were gently fitted over the prepared root surface in the direction of sap flow, ensuring proper contact between the heater strip and the entire root circumference before securing the Velcro straps on the insulation jacket.

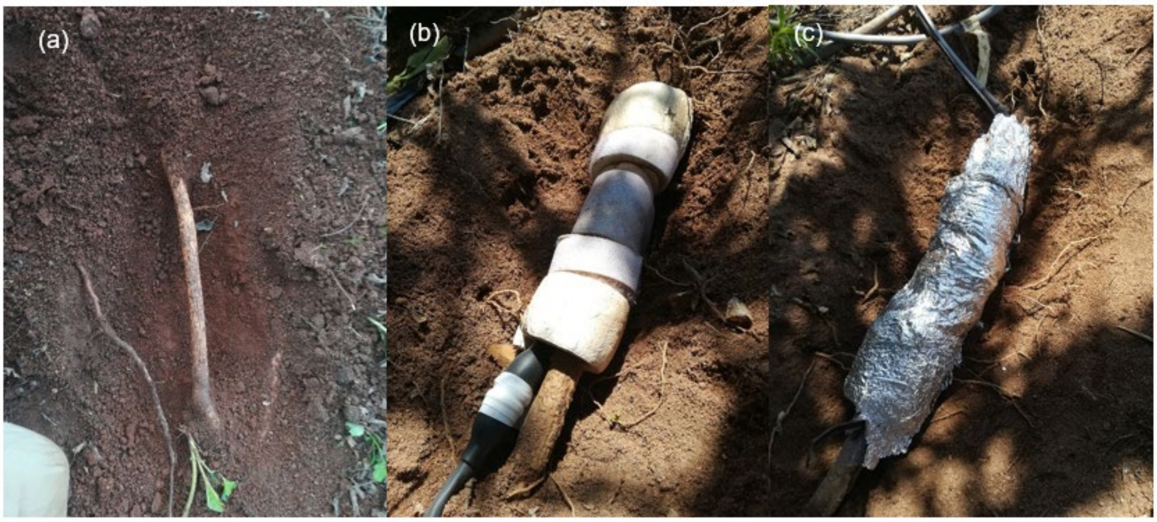


Fig. 4. 6. Installation procedure for the root sap flow sensors.

A strip of waterproof rubber-based adhesive putty (Prestik) was placed at the ends of the insulation jacket to ensure no water can penetrate the sensor area, and two insulation sleeves were installed on each end (Fig 4.6c.). The cable connection between the sensor and the logger was tightly wrapped with electrical insulation tape to prevent any potential short circuits due to water infiltration. The entire area was then covered with 1) a layer of clear plastic, 2) two layers of aluminium foil, and 3) another layer of plastic, and then sealed off with electrical insulation tape.

The purpose of these layers was to further weatherproof the area and prevent environmental heat fluxes from affecting the readings. After ensuring proper weatherproofing, the root was once again covered with soil. The same general steps were followed for SGA-16ws (Tree 2) and SGA-13ws (Tree 3) gauge installation on sun-exposed branches, as seen in Fig. 4.7. Sap flow gauges were then connected to CR1000 data loggers (Campbell Scientific, Logan, UT, USA), AM16/32B multiplexers, and an AVRD voltage regulator. Sap flow data was logged hourly from 16/11/2021 to 20/11/2021 for this campaign.

Fig. 4. 7. Sap flow gauges installed on the indigenous fruit tree branches

4.1.10 Modelling water use of single Marula trees

The hourly transpiration of the individual trees (T_c, in g/h) was modelled using the combination Penman-Monteith equation for hypostomatous leaves according to Zhang et al. (1997) and Dzikiti et al. (2011), as explained in chapter 3 above. Adjustments were made to accommodate the differences in tree physiology and climate.

4.1.11 Statistical analysis

The performance of the Penman-Monteith transpiration model was evaluated based on the root mean square error (RMSE), mean absolute error (MAE), the slope, intercept, and coefficient of determination (R^2). The predictive accuracy of the model was established using the Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970).

4.2 RESULTS AND DISCUSSION

4.2.1 Weather conditions

The seasonal course of key climate variables is shown in Fig. 4.8. As expected, the radiation intensity was greatest in the summer months declining through winter rising again in spring (Fig. 4.8a). The daily average solar radiation was highest at the beginning of the monitoring, reaching a peak at ~32 MJ $m^{-2}d^{-1}$ on 15 December 2019 (Fig. 4.8a) while recording a minimum of ~2 MJ m^{-2} d^{-1} on 13 August 2021 (Fig. 4.8a).

November 2020 was the hottest month with maximum temperatures exceeding 38°C on 8 November 2020 (Fig. 4.8b). While in the year 2021, October had the hottest temperatures, recording ~38°C on 23 October 2021. The lowest minimum temperature recorded was 2°C, measured on 16 July 2020. The minimum relative humidity occurred in the dry winter months of June to August, and it was lowest in August 2020 at 9% (Table 4.3). The vapour pressure deficit of the air peaked at more than 2 kPa (Fig. 4.8c) in November 2020 when the air was driest.

The largest rain event occurred on 31 January 2021 when the site received ~107 mm of rainfall (Fig. 4.8d). This led to January 2021 being the wettest month that received more frequent rainfall events with large quantity, and eventually recording a total rainfall of ~403 mm while May 2020 was the driest month that received zero precipitation (Table 4.3). This large amount of rain was recorded during the time of tropical cyclone Eloise that started in Northern Madagascar and affected parts of Mozambique, Malawi, & South Africa. The monthly total reference evapotranspiration (ETo) was highest in November 2020 with ~156 mm recorded. The recorded total rainfall was slightly lower than the total ETo in both years of monitoring (Table 4.3).

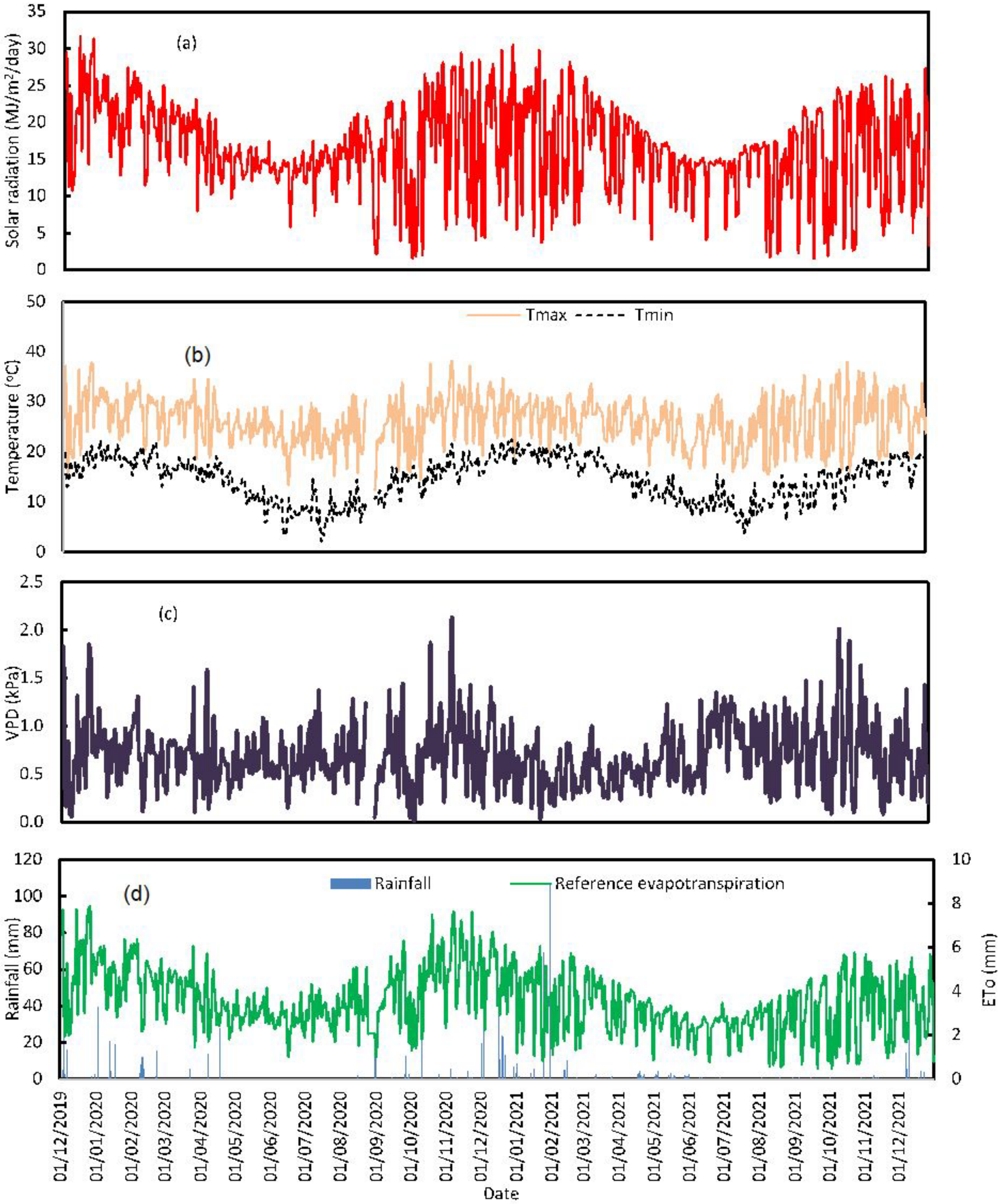


Fig. 4. 8. Climatic conditions at the Hazyview site from 01 December 2019 to 31 December 2021 representing (a) daily mean solar irradiance, (b) maximum and minimum air temperature, (c) vapour pressure deficit of the air and (d) reference evapotranspiration and rainfall.

Table 4. 3 Summary of monthly weather conditions at Hazyview from January 2020 to December 2021

Month	R_s (MJ/m^2/d)	T_{max} (°C)	T_{min} (°C)	T_{avg} (°C)	RH $_{max}$ (%)	RH $_{min}$ (%)	RH $_{avg}$ (%)	VPD (kPa)	Rain (mm)	ETo (mm)
Jan 20	21.3	33.7	15.2	24.5	98.9	34.0	66.4	0.7	225.8	147.7
Feb 20	20.6	34.3	13.1	23.7	99.8	30.1	64.9	0.7	89.4	132.7
Mar 20	19.0	36.2	14.5	25.3	99.3	26.8	63.0	0.7	62.2	128.9
Apr 20	14.9	34.9	11.2	23.1	100.0	19.8	59.9	0.6	214.9	95.2
May 20	14.5	28.9	5.9	17.4	100.0	17.2	58.6	0.7	0.0	94.8
Jun 20	13.2	28.9	3.2	16.0	100.0	13.5	56.8	0.6	15.5	82.0
Jul 20	14.3	29.7	2.1	15.9	100.0	11.4	55.7	0.7	25.7	92.6
Aug 20	16.1	31.4	5.8	18.6	99.5	9.0	54.3	0.7	19.8	100.2
Sep 20	15.5	33.8	8.9	21.4	99.8	19.0	59.4	0.7	40.6	113.9
Oct 20	17.5	37.5	10.6	24.1	100.0	15.0	57.5	0.7	175.0	132.6
Nov 20	17.6	38.1	13.2	25.7	99.6	18.8	59.2	0.9	92.2	156.1
Dec 20	19.2	34.5	15.1	24.8	99.8	29.7	64.7	0.7	282.7	148.0
Totals									1243.8	1424.7
Jan 21	18.2	31.5	17.1	24.3	100.0	34.4	67.2	0.5	403.7	114.0
Feb 21	16.8	31.7	15.2	23.4	98.5	42.7	70.6	0.4	89.3	93.3
Mar 21	18.4	33.6	14.0	23.8	100.0	36.9	68.5	0.5	16.4	112.8
Apr 21	17.3	31.2	10.4	20.8	98.9	26.4	62.7	0.5	26.0	95.9
May 21	14.4	30.2	9.1	19.7	99.0	19.0	59.0	0.7	57.7	80.4
Jun 21	13.1	31.2	7.1	19.1	100.0	13.5	56.8	0.7	13.9	70.2
Jul 21	13.6	31.5	3.6	17.6	100.0	11.4	55.7	0.9	8.3	74.6
Aug 21	13.0	33.0	6.1	19.5	99.6	13.1	56.3	0.7	12.2	79.9
Sep 21	15.8	35.0	7.6	21.3	99.2	13.7	56.5	0.8	6.6	93.3
Oct 21	13.7	38.0	8.1	23.1	100.0	13.6	56.8	0.8	9.4	90.3
Nov 21	16.2	36.2	13.1	24.6	100.0	22.6	61.3	0.7	12.7	100.0
Dec 21	16.5	33.8	12.8	23.3	99.6	19.4	59.5	0.6	266.2	101.1
Totals									922.3	1105.6

4.2.2 Soil moisture dynamics

Recording of the soil water content data at the Hazyview site started around December 2019. As expected, the soil water content changed in response to rainfall events (Fig. 4.9) such as the one that fell during the week of 9 January 2020 where more than 70 mm of rain were recorded. The soil water content kept rising during the wettest months, especially during the period of tropical cyclone Eloise (January 2021), where soil water content values of more than 0.45 cm^3/cm^3 were recorded, and the rainfall affecting the sensors at all depths. Throughout the measuring period, the soil sensors at all the three depths responded to the different rainfall events with more moisture content recorded at the shallowest sensor and least at the deepest sensor. During the dry period of May 2020 to August 2020 only the 15 cm sensor responded to the lighter rainfall events, with a slight increase in soil moisture (0.01-0.05 cm^3/cm^3) observed from the 100 cm sensor. There could have been a preferential flow path in the profile as this did not affect the medium sensor but affected the deepest one (Fig.1.9).

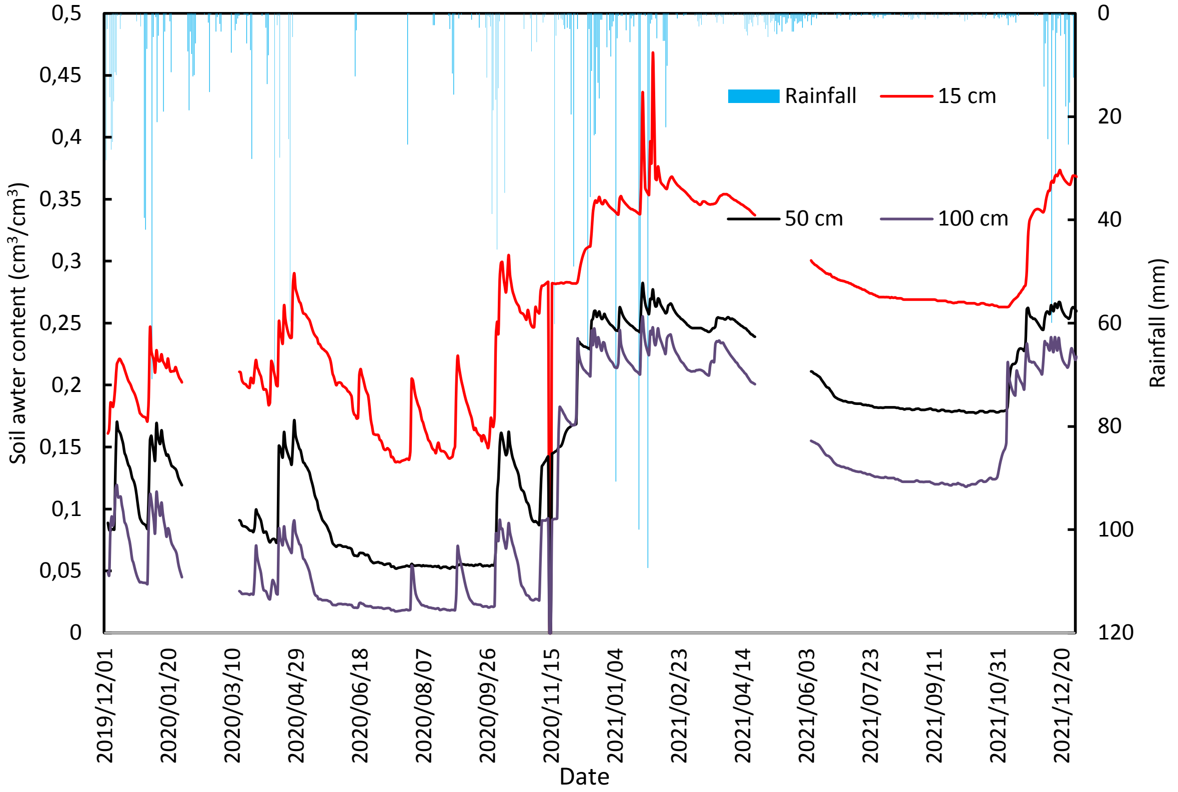


Fig. 4. 9. Soil water content dynamics at 15, 50, and 100 cm depths at the Hazyview site.

4.2.3 Fruit yield of Marula trees

Marula trees had higher yields in the first year of the study, with tree number 3 of the instrumented trees giving the highest yield of 82 kg, while tree number 1 had the lowest yield of 1.4 kg. Overall, in the 2019/20 fruit growing season, the average yield for all the instrumented trees was 44.9 kg (Table 4.4). In the 2020/21 growing season, tree number 3 was consistent with producing the highest yields, producing 48.8 kg, while trees 1 and 2 produced 2.8 and 22.2 kg of fruit, respectively. Overall yield for the 2020/21 growing season was 24.6 kg (Table 4.4).

Table 4. 4 Fruit yield of Marula trees growing in Mpumalanga

Growing season	Species	Tree 1 (kg)	Tree 2 (kg)	Tree 3 (kg)	Average (kg)
2019/20	Marula	1.4	51.3	82	44.9
2020/21	Marula	2.8	22.2	48.8	24.6

4.2.4 Sap flow dynamics of Marula trees in Mpumalanga

The typical course of the atmospheric evaporative demand (ETo) at the Burgershall site from October 2019 to April 2021 is shown in Fig. 4.10a. The corresponding daily transpiration of a small Marula tree, average stem diameter at breast height about 13 cm and a big Marula tree, average stem diameter at breast height about 55 cm are shown in Fig. 4.10b.

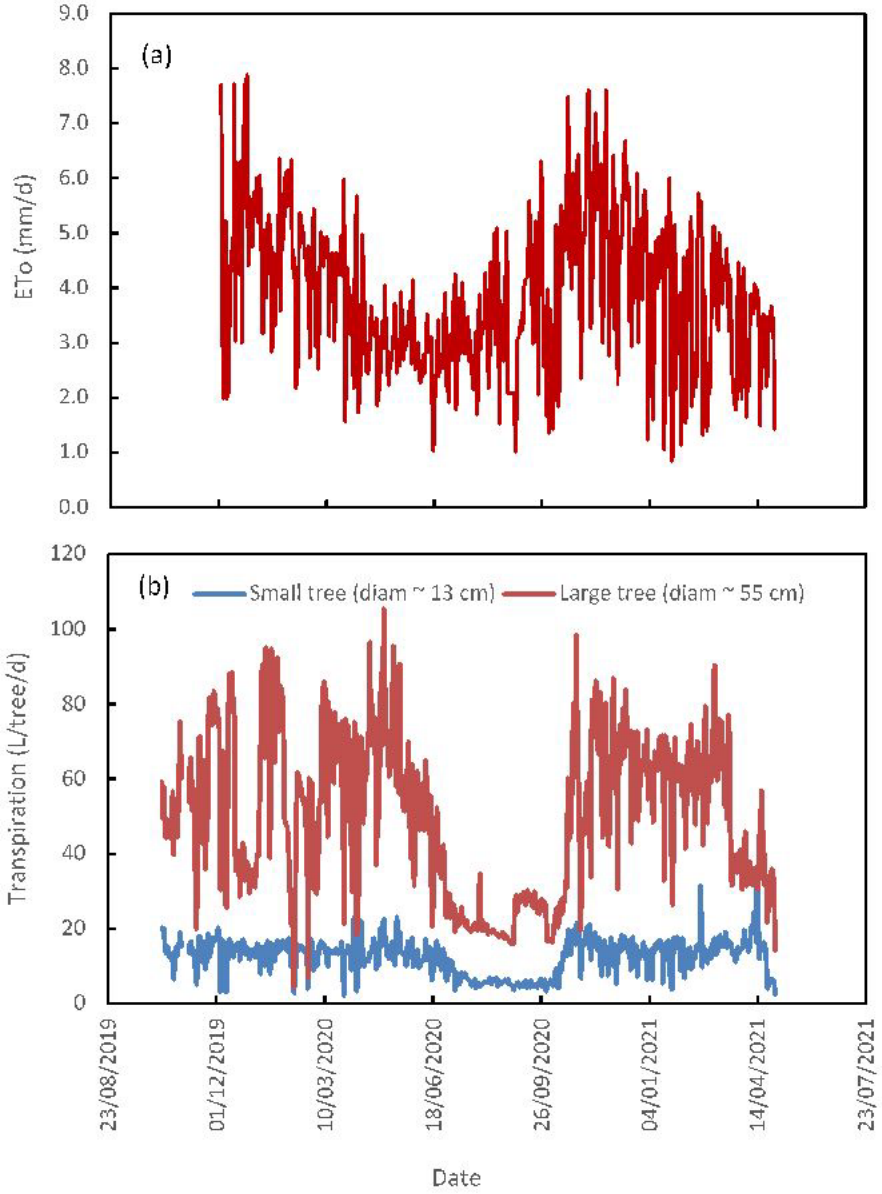


Fig. 4. 10. Time series of (a) the daily reference evapotranspiration and (b) transpiration by two Marula trees with different stem sizes at Burgershall near Hazyview.

The peak daily ETo reached about 8.0 mm in December 2020 and the lowest value was less than 1.0 mm/d reached during the winter months. The transpiration course of the Marula trees followed that of the atmospheric evaporative demand, and we show an example for two trees in Fig. 4.10. Transpiration data from the third instrumented Marula tree was of a poor quality, it is therefore not presented here. The maximum water use by the small Marula trees barely reached 20 litres per day, consistent with the values for the KwaZulu-Natal trees, which were of a similar size. The maximum transpiration of the big Marula tree was more than five times that of the small tree reaching 105 litres per day (Fig. 4.10b). An interesting feature of both trees is that the wintertime transpiration values did not drop to zero for unclear reasons. It is probable that some leaves remained on the trees thereby supporting some transpiration.

4.2.5 Drivers of water use for Marula in Mpumalanga

Climatic factors, namely the daily total solar radiation and the vapour pressure deficit of the air were not very strong drivers of transpiration by the Marula trees, again consistent with the observations in KwaZulu-Natal as shown in Figs. 4.11 and 4.12.

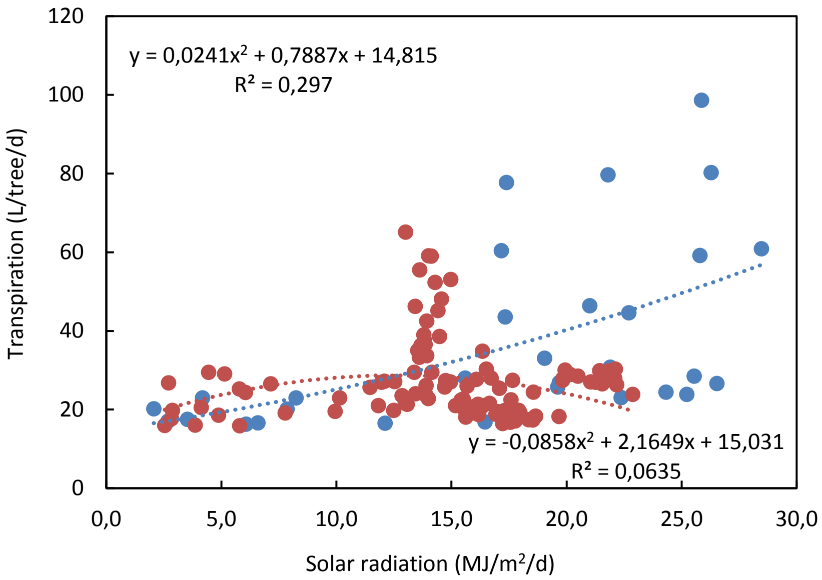


Fig. 4. 11. Seasonal changes in the relationship between the daily total solar radiation and tree transpiration for Marula, blue dots and curve showing the growing season while red dots and curve represent the dormant season

However, what is apparent in Fig. 4.11 is that there were different relationships between the daily transpiration and the daily solar radiation for the summer and winter seasons. This distinction is even clearer for the VPD in Fig. 4.12. There are relatively stronger correlations between the climate drivers with the summertime transpiration than with the wintertime values.

The larger transpiration leaf area and the higher atmospheric evaporative demand may be reasons for the strong relationships in summer. Internal water gradients created by transpiration by the few remaining leaves and water losses through the green plant tissues may explain the wintertime water losses which are clearly not strongly driven by climatic factors alone. Further research is thus necessary to understand the sap flow dynamics of Marula trees. Transpiration by both trees was non-linearly related to the reference evapotranspiration (Fig. 4.13).

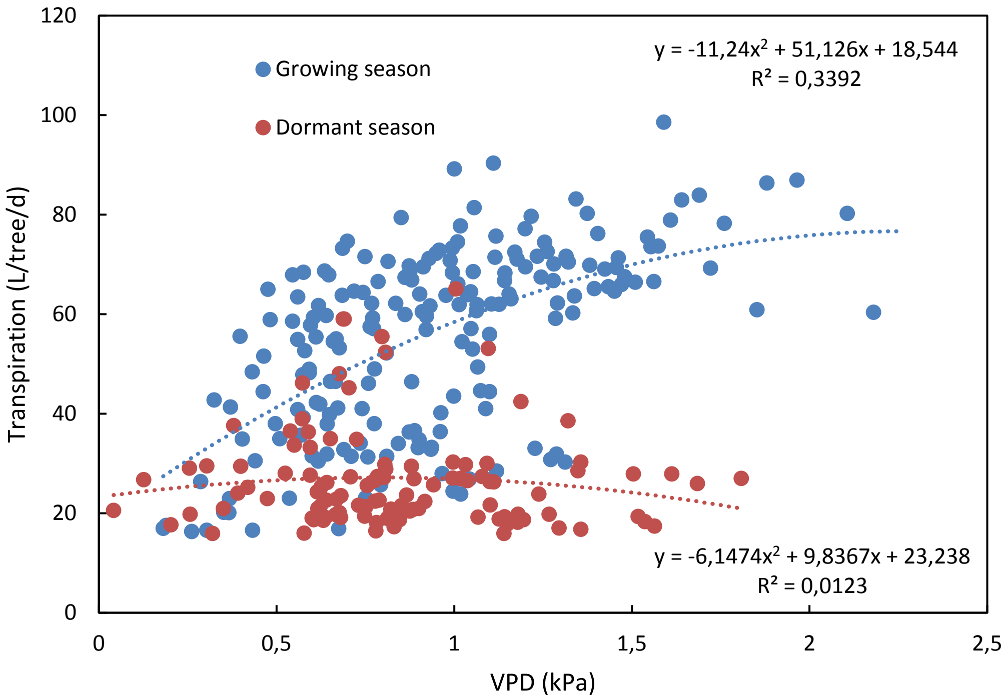


Fig. 4. 12. Seasonal changes in the influence of the VPD on transpiration by Marula trees.

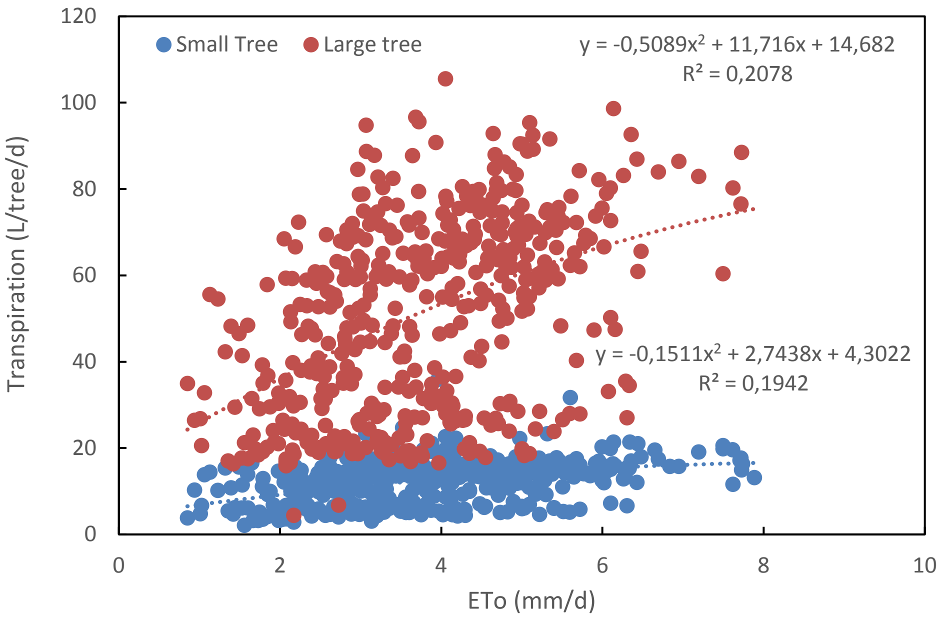


Fig. 4. 13. Transpiration response to the atmospheric evaporative demand for a small and large Marula tree at Burgershall, near Hazyview.

As with the case of the KwaZulu-Natal data, transpiration by the Marula trees was much more strongly influenced by the soil water deficit in the root zone than by climatic factors (see Fig. 4.14) although the relationship was non-linear. Figure 4.14 suggests that transpiration rates were lower not only when there was greater soil water deficit, but also when the soils were wet with a low soil water deficit. This suggests that water use levels of Marula could be low under waterlogging conditions. This can be explained by the anaerobic conditions in the root zone that affect the functioning of the water transporting protein channels around cell walls called aquaporins.

According to Taiz et al (2018), the diffusion of water across cell walls is mostly facilitated by the aquaporins, which are gated membrane proteins that open and close as a function of the soil pH and other stresses. For example, under waterlogging conditions, the soil pH around the roots tends to be acidic which causes these membrane channels to close thereby reducing root water uptake. Consequently, the plant suffers similar symptoms to those of water deficit stress (Lambers et al., 2008).

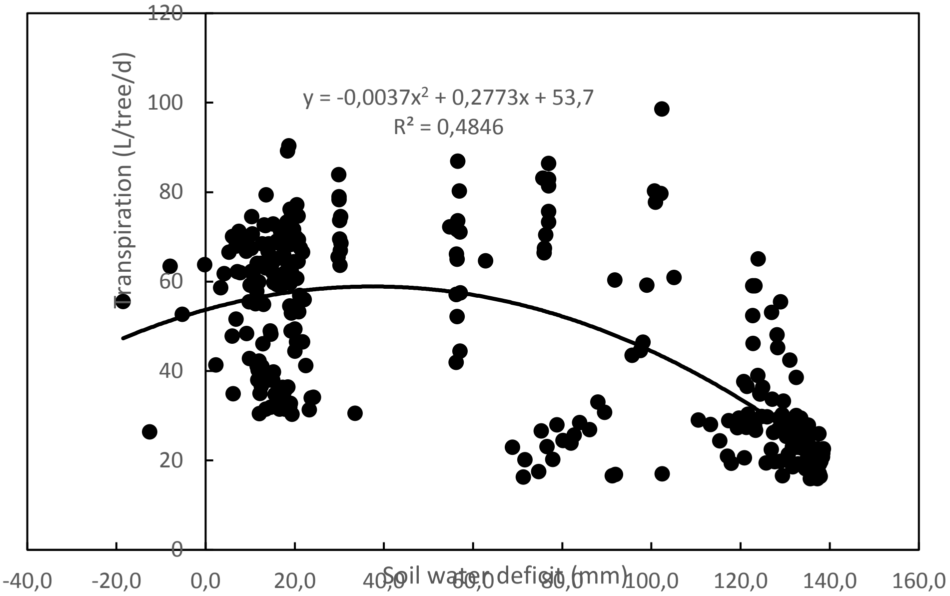


Fig. 4. 14. Transpiration response of Marula to soil water deficit.

4.2.6 Water relations and stomatal conductance

The typical course of the root water uptake and branch sap flow for a fully-grown Marula tree is shown in Fig. 4.15. Both the root and branch sap flows showed clear diurnal trends. The fluctuation in the signals is a result of the partly cloudy conditions that prevailed during the measurement week. It is interesting to note that the roots signal was much smoother than the branch signal, possibly because of the large volume of water stored in the trees that acted as a buffer between the roots and the atmosphere. The smooth roots diurnal trends likely depicted the soil to xylem water potential gradient, which possibly did not change rapidly with the weather conditions.

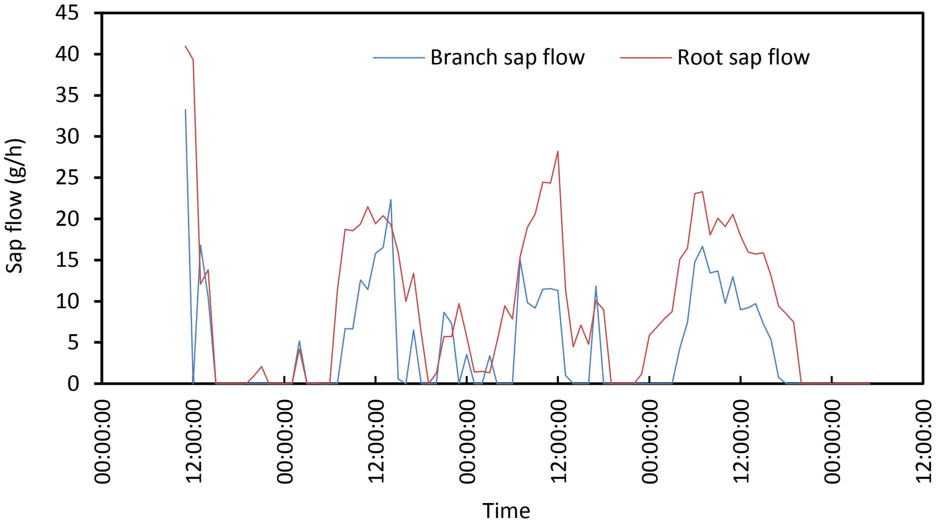


Fig. 4. 15. Branch and root sap flow dynamics for Marula.

The imbalance between root water uptake and transpiration by the leaves is an important driver of the tree water status, which in turn affects the transpiration rates and the water use efficiency. Fig. 4.16 shows the time lags between the onset of transpiration, depicted by the branch sap flow and that of root water up take. Root water uptake commenced more than an hour after transpiration had started.

This is a very short time lag given the size of the trees and this suggests an efficient hydraulic system for Marula in terms of water uptake. The hydraulic conductance and capacitance could not be calculated given that sap oozed out of the leaves immediately after they were plucked. Therefore, the water potential of the trees, which is required to calculate the hydraulic properties, could not be determined.

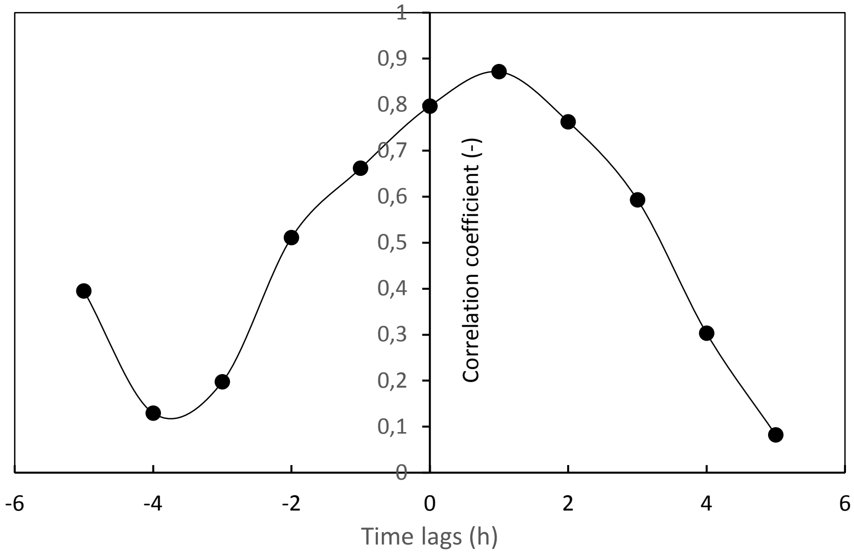


Fig. 4. 16. Time lags between water uptake by the roots and transpiration by the leaves for a fully-grown Marula tree.

4.2.7 Model evaluation on Marula trees at Burgershall

Model performance with the original parameters was poor, mostly because of the different soil types between the site where the model was first developed and the Burgershall site. After model re-calibration, performance was significantly improved as shown in Figs. 4.17 and 4.18.

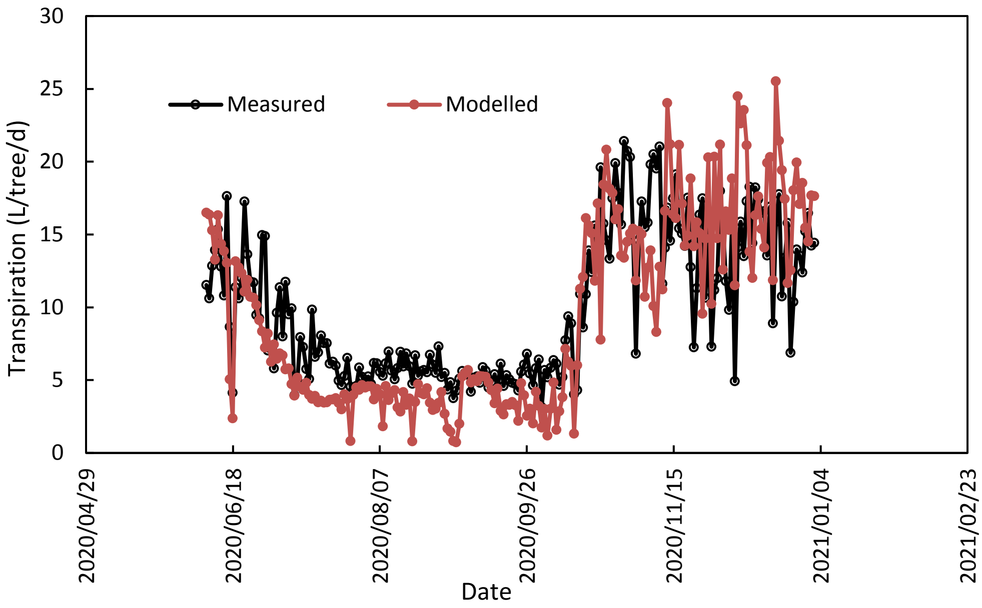


Fig. 4. 17. Comparison of the measured and modelled daily transpiration in litres per day by a small Marula tree with a mean stem diameter about 13 cm.

Figure 4.17 shows the results when the model was applied to predict the transpiration of the small Marula with an average stem diameter of about 13 cm. Simulations for the larger tree (Fig. 4.18) were also reasonable although the error margins tend to be larger in winter. The reason for this is that there are uncertainties about the drivers of the water use in winter when the trees have minimal leaf cover. In these simulations, we retained a 15% leaf cover relative to the peak summer values.

Table 4. 5 Statistical summary of the performance of the Penman-Monteith based model in predicting the daily transpiration of single Marula trees over the study period

Site	Species	Tree no.	R2	Slope	MAE (ℓ/d)	RMSE (ℓ/d)	NSE
Burgershall	Marula	1	0.64	1.03	3.09	3.91	0.69
		2	0.55	0.97	15.4	20.3	0.43

A summary of the statistics of the model fit are shown in Table 4.5. The R^2 values were 0.64 and 0.55 when the measured water use was compared with the modelled values for the small and big trees, respectively.

The root mean square values were ±3.91 and ±20.3 ℓ/tree/d, respectively with positive Nash-Sutcliffe Efficiency values. The RMSE values may appear large, and these also reflect the effect of tree size. If we normalise the RMSE with the maximum daily transpiration by each tree, we get values of ± 20% for each of the two trees.

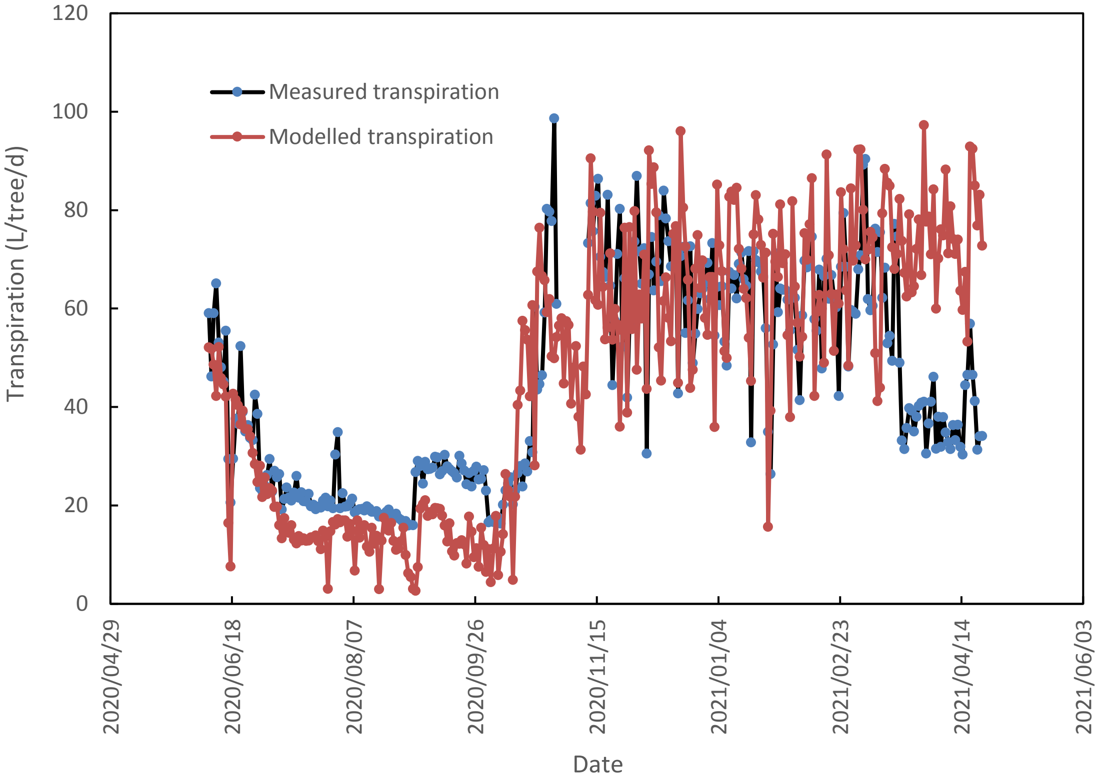


Fig. 4. 18. Comparison of the measured and modelled daily transpiration in litres per day by a large Marula tree with a mean stem diameter of about 55 cm.

4.2.8 Performance of the transpiration model on Marula

This model has been developed, calibrated, and validated for the Marula and *S. spinosa* trees at Bonamanzi Game Reserve as reported in Chapter 3. In the current chapter, we focus on the performance of the model on the Marula data collected from the Burgershall site near Hazyview in Mpumalanga. There are important differences between the Marula trees at the KwaZulu-Natal site and those in Mpumalanga. The trees in KwaZulu-Natal were smaller and they grew on deep sandy soils. These trees experienced severe water stress quite frequently. Therefore, their water use is unlikely to reflect the maximum unstressed values for this species. In contrast, the trees in Mpumalanga were growing on heavy clayey loam soils. The trees were much bigger, they appeared to experience less water stress, and they had substantially higher yields.

Our approach to the modelling for Marula was firstly to run the model as developed for the KwaZulu-Natal site. However, this did not yield good simulations. We attribute this to the differences in soil types between the KwaZulu-Natal site, where the model was developed, and the Burgershall site as explained above. The next step was to use a small subset of the data to recalibrate the model, only for the soil moisture stress function. This was a reasonable thing to do, given the strong sensitivity of Marula transpiration to soil water deficit as explained in the previous chapters. The results of model calibration are shown in Table 4.6 below.

Table 4. 6 Parameters for the Penman-Monteith model applied to the Marula trees growing in Mpumalanga

Parameter	Description	Marula
β (–)	Describes the curvature of the f (□) function	0.25
g_{max} (mm s^{-1})	Maximum stomatal conductance	10
k_r (Wm^{-2})	Describes the curvature of the f(Rs) function	500
kT_p (°C)	Optimal temperature for plant growth	18.5
k_{d1} (kPa^{-1})	Describes the influence of the VPD stress factor	0.0001
k_{d2} (kPa^{-1})	Describes the influence of the VPD stress factor	9
T_h (°C)	Maximum temperature for plant growth	41
T_L (°C)	Minimum temperature	5
θ_{FC} (cm^3/cm^3)	Volumetric soil water content at field capacity	0.27
Θ_{WP} (cm^3/cm^3)	Volumetric soil water content at the permanent wilting point	0.06

4.3 CONCLUSIONS

There are important differences between the Marula trees at the KwaZulu-Natal site and those in Mpumalanga. The trees in KwaZulu-Natal were smaller and grew on deep sandy soils experiencing severe shortages, making it unlikely to reflect the maximum unstressed values for this species. However, the trees in Mpumalanga were growing on heavy clayey loam soils, appeared to experience less water stress, and produced substantially higher yields. All Marula trees seemed to be affected by soil water deficits.

CHAPTER 5: WATER USE AND YIELD DYNAMICS OF *DOVYALIS CAFFRA* IN NELSPRUIT, MPUMALANGA

5.0 INTRODUCTION

Kei apples are botanically classified as *Dovyalis caffra*. These fruits belong to the Flacourtiaceae family. These trees are native to Southern Africa, where they have been primarily gathered from plants used for natural fencing. Outside of Africa, Kei apples have been introduced to subtropical climates around the world, where they have been known as a coastal hedge. These fruits are an excellent source of vitamin C (Augustyn et al., 2018), an antioxidant that reduces inflammation and strengthens the immune system. *Dovyalis caffra* fruit are said to be a good source of potassium (Waweru et al., 2022), and therefore balance fluid levels within the body. The *Dovyalis caffra* trees can survive in almost any soil type; these trees are drought-resistant and have been reported to have tolerance for saline soils (Materechera and Swanepol, 2011). In South Africa, these trees are mainly found in the Eastern Cape, KwaZulu-Natal, Mpumalanga, and Limpopo Provinces.

Up to 40% of South Africa's population lives in rural areas. These are mostly poor former "Homelands" where poverty, unemployment, and illiteracy are high. Poverty levels are estimated to exceed 70% in some areas while many households are headed by women and children. As much as 43% of households in provinces like rural KwaZulu-Natal are headed by women and children (Stats SA., 2015). These population groups are most vulnerable to food shortages and to rises in food prices given the increasing reliance on food purchases by both urban and rural households reaching up to 90% of the food supplies in some instances (Baiphethi and Jacobs, 2009).

Despite the fact that South Africa is a food secure country at the national level producing enough staple foods and having the capacity to import food if needed, many rural households are in fact not food secure (du Toit, 2011; Altman et al., 2009). According to the General Household Survey by Statistics South Africa (2011), about 25.5% of South African households, mostly in rural areas, have inadequate or severely inadequate food access. This is because yield of staple crops like maize, which is mostly grown under subsistence farming, is generally low and declining as fewer families engage in subsistence farming. Other contributory factors to the low yields include infertile and degraded soils, limited use of technology, and chemical fertilisers, which are beyond the reach of most households. On the other hand, large proportions of the produce from commercial farms is geared towards the export market or processed into commercial products.

Exacerbating food insecurity in rural South Africa is climate change, which is projected to cause frequent droughts and rising air temperatures in parts of the country (Schulze, 2005). This means that the production of conventional crops using conventional agricultural practices will encounter greater problems in the future, hence worsening food insecurity. Therefore, identifying and promoting alternative crops and cropping systems, for example, through agroforestry and reverting to and increasing the production of indigenous crops is an important strategy to adapt to climate change especially for the resource poor rural households and emerging farmers (Everson et al., 2012; DAFF, 2011). It is also important to understand the water requirements of the indigenous fruit trees that have a potential of domestication and commercialisation to understand their environmental impacts.

5.1 MATERIALS AND METHODS

5.1.1 Description of study site

This site is an indigenous fruit tree orchard that was established by the ARC for research on indigenous fruit trees in the 1980s and 90s (Fig. 5.1). The orchard comprises of more than 10 different indigenous fruit tree species planted in rows about 5 m apart and about 2 to 2.5 m tree spacing along the row.

Before the trial started, these trees were irrigated by a micro-sprinkler irrigation system that delivered about 30 litres of water per hour with one sprinkler for every tree. However, there was no irrigation taking place during the course of this study. In this orchard, three *Dovyalis caffra* (Kei apple) trees of different sizes were selected and instrumented. This species was ranked in the top five of species with the highest domestication and or commercialisation potential in the stakeholder workshop. Besides the high value fruit products, *Dovyalis* is also widely used as a fence in some households due to its thorny make up.

Fig. 5. 1. Indigenous fruit tree orchard with Dovyalis caffra trees at the ARC Nelspruit campus, Mpumalanga.

The microclimate at the *Dovyalis* site is very similar to that at Burgershall, being subtropical and with relatively high rainfalls. The soils are deep sandy soils that are well drained and have a moderate number of stones. The distance between the two study sites is close to 150 km. Sap flow at the *Dovyalis* site was also monitored using the heat ratio method of the sap flow technique. However, installation of the sensors was a challenge given the low branching pattern of this species and the huge number of long sharp thorns in its physique (Fig. 5.2).

Fig. 5. 2. Installation of sap flow sensors on a Dovyalis tree at the ARC campus in Nelspruit

5.1.2 Site microclimate

Site microclimate at ARC Nelspruit was monitored using an automatic weather station that belongs to the ARC, measuring basic weather variables such as the solar irradiance, air temperature, relative humidity, wind speed and direction and rainfall. The data were recorded at hourly and daily intervals. The station was located on a short grass surface that was regularly irrigated, located less than 1 km from the studied trees. The data was downloaded on monthly intervals from all monitoring stations.

5.1.3 Soil water content and physical/chemical properties

As with the Burgershall site, soil water content was measured using soil water content reflectometers (Model CS616: Campbell Scientific, USA) installed at various depths down the soil profile. ARC Nelspruit study site has soils with 90% sand content as shown in Table 5.1.

The soil samples were taken from different levels down the soil profile, up to 1.2 meters using an auger as shown in Fig. 5.3. The analysis for physical and chemical properties showed that the soil was the same from the surface down to 1.2 m. Table 5.1 shows results for one layer of the soil and not for different layers within the soil profile, as was done at the Burgershall site, which had different compositions at different levels.

Table 5. 1 Physical and chemical properties of the soil at the ARC Nelspruit study site

INDICATOR	
pH(water)	6.46
Res(ohms)	2400
Ca mg/kg	218
Mg mg/kg	42
K mg/kg	35
Na mg/kg	11
P (Bray1)	27.5
Al mg/kg	3
Ca/Mg	5.19
Ca+Mg/K	7.43
Sand %	90
Silt %	2
Clay %	8

Fig. 5. 3. Soil sampling at the D. caffra study site in Nelspruit

5.1.4 Plant measurements

5.1.4.1 Stem size distribution

Same as with the Marula study site, trees with different stem sizes were measured at breast height using a tape measure. Then stem diameters were categorised into three size classes; the small (0-6 cm), medium (7-10 cm) and large (> 10 cm). As with the Marula site, trees whose stem diameters were close to the median stem sizes in each diameter class were selected, then sap flow sensors installed on the stems. Stand level transpiration by the trees was calculated as the weighted sum of transpiration by the trees in three stem size classes with the weighting functions being the number of trees in that particular stem size class per hectare.

5.1.4.2 Canopy dimensions and leaf area index

Canopy dimensions were measured as the proportion of a fixed area of the ground covered by tree crowns. The canopy cover was determined by the tree species, as they have different crown sizes, shapes, and heights. Plant height was measured using a calibrated telescopic rod. Leaf area index (LAI) was measured using an LAI 2000 meter. The LAI and canopy dimensions information is presented in Table 5.2.

Table 5. 2 Characteristics of the instrumented Dovyalis trees

Tree measurements	Tree 1	Tree 2	Tree 3	Date measured
Height (m)	3.3	4.6	5.7	11-Oct-19
Diameter (E-W) (m)	2.4	4.24	5.07	11-Oct-19
Diameter (N-S) (m)	2.16	4.83	4.8	11-Oct-19
Stem diameter (cm)	5.2	9.5	10.5	11-Oct-19

Tree measurements	Tree 1	Tree 2	Tree 3	Date measured
Leaf area index	1.16 ±0.11	1.92 ±0.24	1.13 ±0.17	14-Oct-19
Leaf Area Index	2.16 ±0.25	2.61 ±0.22	1.63 ±0,16	22-Oct-19
Leaf Area Index	1.54 ±0.11	2.78 ±0.13	1.92 ±0.15	10-Nov-20

5.1.5 Fruit yield of D. caffra

To sample fruit from the *Dovyalis* trees, the same method used for the Marula in the previous chapter was adopted. Where fruit randomly fell on the surface, under the tree once they became ripe, and the fruit was collected into sample bags as shown in Fig. 5.4. To determine their mass, the fruit were measured using Vernier callipers, and the overall fruit quality analysed in the laboratory.

Fig. 5. 4. Fruit yield (a) fruit picked into sample bags (b) Kei apple tree showing ripe fruit that fell on the floor ready to be picked up and counted.

5.1.6 Tree water status

To establish the quantitative relationships between leaf water status and the extent of stomatal opening for *Dovyalis* trees, both leaf and stem water potential were measured concurrently with the stomatal conductance when the available soil water was not limiting. The leaf water potential was measured using a Scholander-type pressure chamber (Model: 615 PMS Instrument Company, Albany, OR, USA) while the stomatal conductance was also manually measured using a diffusion porometer (Model AP4: Delta-T Devices, Cambridge, UK).

The same methods used for gas exchange measurements in the above chapter on Marula, were used for *Dovyalis.* The only difference was with the light response curves (LRCs). For the Marula, trees seemed to close their stomata when using 2000 μmol.m^{-2}.s^{-1} as the PAR starting point, potentially indicating the tree's sensitivity to higher light intensities or excessively high VPD levels. Hence, the starting point for Marula was 1750 μmol.m^{-2}.s^{-1}. However, *Dovyalis* trees could withstand the starting point of 2000 μmol.m^{-2}.s^{-1}, hence the sequence followed was (2000, 1800, 1500, 1200, 1000, 800, 600, 300, 200, 100, 50, 0 μmol.m^{-2}.s^{-1}).

5.1.7 Modelling water use of single D. caffra trees

The hourly transpiration of the individual trees (T_c, in g/h) was modelled using the combination Penman-Monteith equation for hypostomatous leaves according to Zhang et al. (1997) and Dzikiti et al. (2011). This modelling technique was done in the same way as the earlier mentioned species.

5.1.8 Statistical analysis

The performance of the Penman-Monteith transpiration model was evaluated based on the (RMSE), (MAE), the slope, intercept, and coefficient of determination (R^2) in the same manner as the earlier species.

5.2 RESULTS AND DISCUSSION

5.2.1 Weather conditions

The seasonal course of key climate variables is presented in Fig.5.5. There was not much difference in the climatic conditions of the two Mpumalanga sites. As with the Burgershall site, Fig. 5.5 shows similar trends especially for solar radiation and temperature (Fig. 5.5a & b). Though the VPD trend is also the same, the Nelspruit site peaked at higher VPD values, exceeding 2.5 kPa in the summer months (Fig. 5.5c).

November 2020 was the hottest month with maximum temperatures exceeding 40°C on 24 November 2020 (Fig. 5.5b). The lowest minimum temperature recorded was 0.4°C, recorded on 17 July 2020 (Fig. 5.5b). The minimum relative humidity occurred in the dry winter months of June to August, and it was lowest in August 2020 at 5.4% (Table 5.3). As much as the weather variables from the two Mpumalanga study sites were similar in many aspects, the conditions at the Nelspruit study site were on the extreme side, temperatures were hotter and rainfall events more intense.

The largest rain event occurred on 24 January 2021 when the site received ~166 mm of rainfall as tropical cyclone Eloise had the greatest impact. This led to January 2021 being the wettest month that received more frequent rainfall events with large quantity, and eventually recording a total rainfall of ~286 mm while May 2020 was the driest month that received no precipitation (Table 5.3). The monthly total reference evapotranspiration was highest in December 2020 with ~186 mm recorded. The total rainfall recorded in 2020 was 812 mm, while the total ETo was 1676. In 2021, the total rainfall recorded was 1236 mm, which was slightly higher than the total recorded ETo of 1206 mm (Table 5.3).

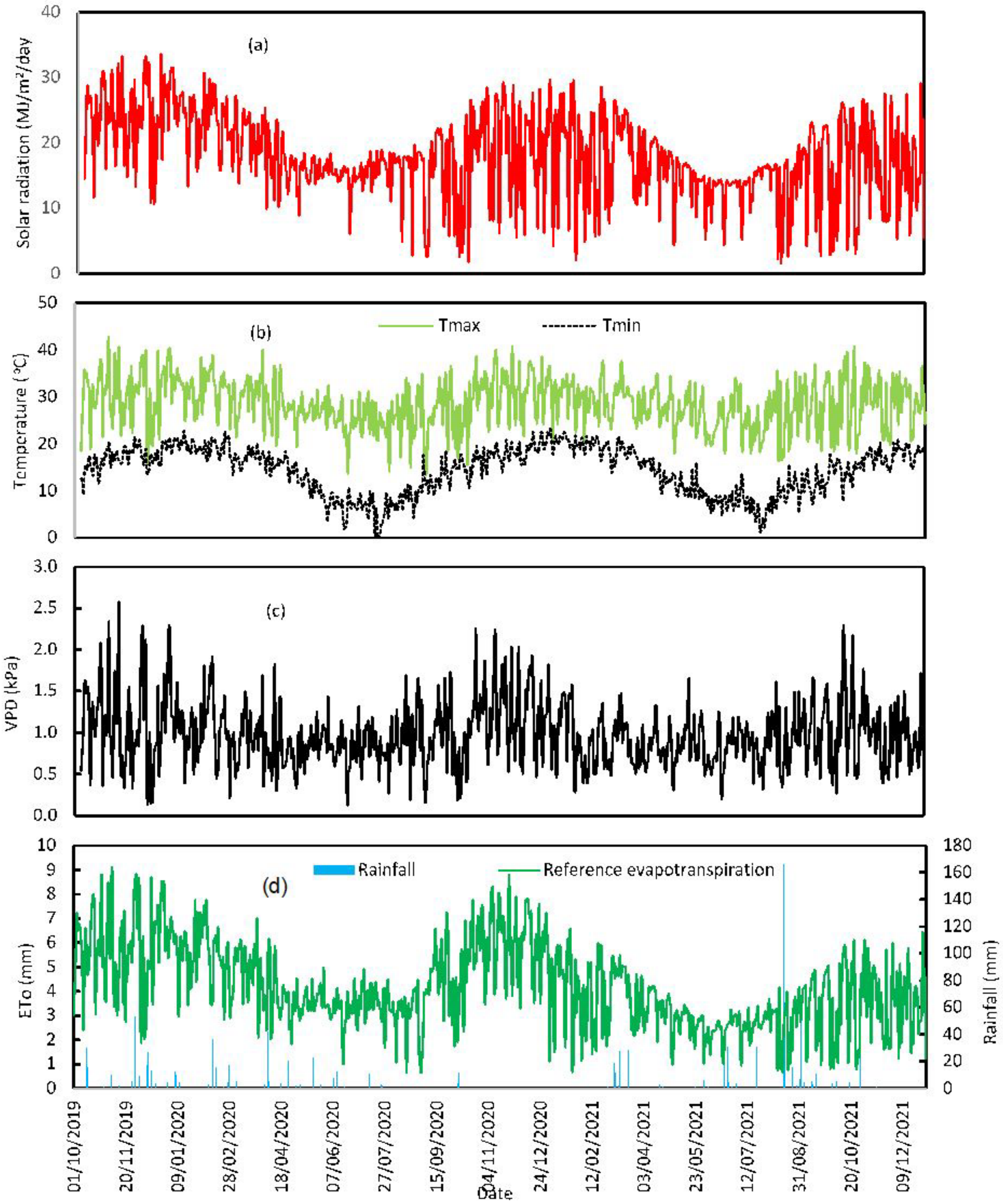


Fig. 5. 5. Climatic conditions at the Nelspruit site from 01 October 2019 to 31 December 2021 representing (a) daily mean solar irradiance, (b) maximum and minimum air temperature, (c) vapour pressure deficit of the air and (d) reference evapotranspiration and rainfall.

Table 5. 3 Summary of monthly weather conditions at Nelspruit from January 2020 to December 2021.

Month Year	R_s (MJ/m^2/d)	T_{max} (°C)	T_{min} (°C)	T_{avg} (°C)	RH $_{max}$ (%)	RH $_{min}$ (%)	RH $_{avg}$ (%)	VPD (kPa)	Rain (mm)	ETo (mm)
Jan 20	23.6	38.4	16.4	27.4	100.0	23.9	61.9	1.0	154.4	175.7
Feb 20	22.9	31.4	18.9	25.2	95.9	41.6	68.8	1.0	84.1	159.1
Mar 20	20.8	39.8	13.8	26.8	100.0	16.5	58.3	1.0	90.7	152.6
Apr 20	16.2	36.9	11.7	24.3	100.0	16.2	58.1	0.8	140.5	110.8

Month Year	R_s ($MJ/m^2/d$)	T_{max} (°C)	T_{min} (°C)	T_{avg} (°C)	RH $_{max}$ (%)	RH $_{min}$ (%)	RH $_{avg}$ (%)	VPD (kPa)	Rain (mm)	ETo (mm)
May 20	16.0	32.5	3.4	17.9	100.0	12.0	56.0	0.9	0.0	112.8
Jun 20	14.6	30.9	1.9	16.4	100.0	6.7	53.3	0.8	22.9	95.0
Jul 20	16.3	31.1	-0.1	15.5	100.0	7.8	53.9	0.8	8.9	111.4
Aug 20	15.3	35.0	4.2	19.6	94.4	5.4	49.9	1.0	6.9	93.6
Sep 20	15.9	36.6	9.1	22.9	93.7	13.3	53.5	1.0	16.2	136.7
Oct 20	17.7	38.7	10.6	24.7	96.9	10.9	53.9	1.0	94.0	159.2
Nov 20	19.2	40.8	14.0	27.4	92.9	14.3	53.6	1.3	56.4	183.7
Dec 20	19.3	38.4	15.6	27.0	98.0	22.5	60.3	1.2	137.4	185.8
Totals									812.2	1676.2
Jan 21	19.3	34.9	17.1	26.0	92.2	22.8	57.5	1.0	285.9	130.8
Feb 21	16.5	37.9	14.6	26.2	92.5	25.1	58.8	0.8	279.1	98.9
Mar 21	20.1	37.7	13.9	25.8	92.9	24.5	58.7	0.9	127.5	128.8
Apr 21	17.0	35.0	9.5	22.2	92.5	14.5	53.5	0.8	13.5	102.1
May 21	14.0	33.3	8.2	20.7	91.6	10.6	51.1	0.9	8.4	83.1
Jun 21	12.7	34.1	4.7	19.4	100.0	9.4	54.7	0.8	25.7	71.4
Jul 21	14.0	32.6	1.2	16.9	100.0	7.8	53.9	0.8	7.6	80.8
Aug 21	13.2	35.4	5.3	20.3	99.0	9.0	54.0	0.9	4.1	83.7
Sep 21	16.7	36.7	7.2	21.9	97.5	7.7	52.6	1.1	16.8	104.9
Oct 21	15.2	40.5	7.8	24.2	99.1	8.8	54.0	1.0	78.7	101.5
Nov 21	17.3	37.3	14.0	25.7	94.0	19.7	56.8	1.0	143.8	110.4
Dec 21	16.5	36.6	14.8	25.7	92.7	16.3	54.5	0.9	244.6	109.2
Totals									1235.5	1205.5

5.2.2 Soil moisture dynamics

The presented soil water content data for the Nelspruit site is from December 2019 to December 2021. As with the other Mpumalanga site, the soil water content changed in response to rainfall events (Fig. 5.6), such as the one that fell on the first week of January 2020 where more than 30 mm of rain was recorded. The rainfall event of the first week of October 2020 gave an even bigger rise in the soil water content from the shallowest sensor, reaching a water content of almost 0.16 cm^3/cm^3. The soil sensors at all the three depths responded to the different rainfall events, with the signals from all three sensors almost crossing in January 2020 (Fig. 5.6). A sharp rise is soil water content was observed during the flooding period of January 2021, when tropical cyclone Eloise affected Mpumalanga province; soil water content values of more than 0.2 cm^3/cm^3 were recorded by the shallowest sensor. The deepest soil moisture sensor consistently recorded less than 0.01 cm^3/cm^3 of soil moisture content during the dry months of May to August 2020, but 2021 was a much wetter year and even the deepest soil moisture probe recorded a minimum of 0.04 cm^3/cm^3. As much as the deepest sensor received less water, it responded to every rainfall event, no matter how small the change in soil water content values (Fig. 5.6). This is probably because the soils at the Nelspruit site comprise of 90% sand content, making it easy for the water to infiltrate to the deepest layers of the soil.

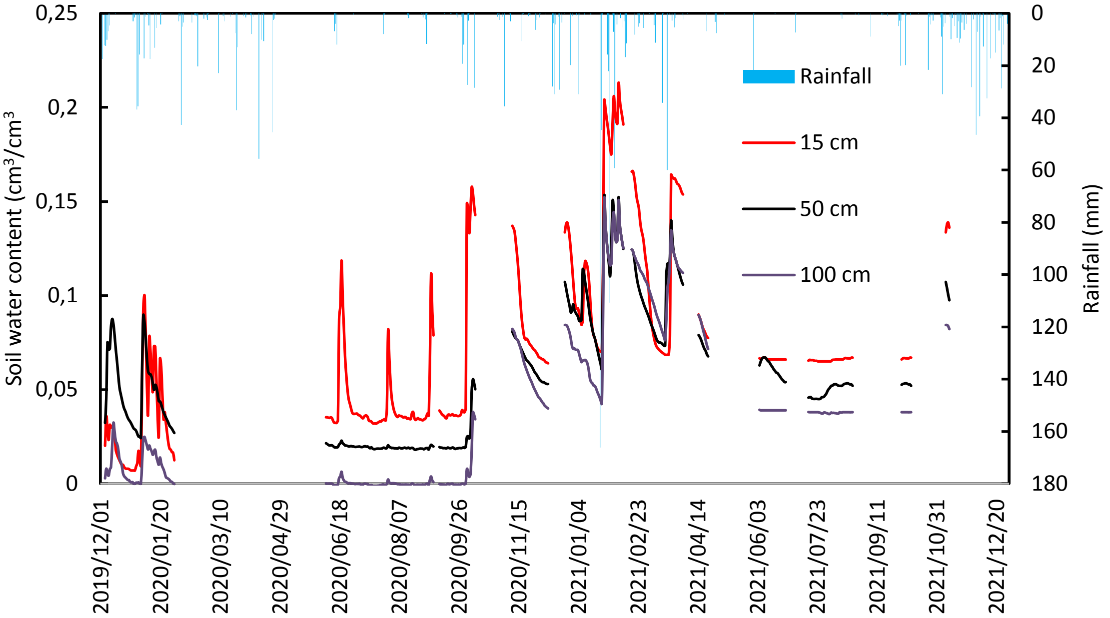


Fig. 5. 6. Soil water content dynamics at 15, 50, and 100 cm depths at the Nelspruit site.

5.2.3 Fruit yield of *D. caffra* trees

Dovyalis caffra (Kei apple) trees had higher yields in the first year of the study, with tree number 2 of the instrumented trees giving the highest yield of 127 kg, while tree number 1 had the lowest yield of 5 kg. Overall, in the 2019/20 fruit growing season, the average yield for all the instrumented trees was 53.2 kg (Table 5.4). In the 200/21 growing season, tree number 3 had the highest yield of 53.2 kg, while tree number 1 had the lowest yield of 15.3 amongst the monitored trees, but this was still a much higher yield as compared to the yield of the same tree in the previous year. Overall yield for the 2020/21 growing season was 35.7 kg (Table 5.4).

Table 5. 4 Fruit yield of Kei apple trees growing in Nelspruit, Mpumalanga Province

Growing season	Species	Tree 1	Tree 2	Tree 3	Average
		(kg)	(kg)	(kg)	(kg)
2019/20	Dovyalis	5	127	27.5	53.2
2020/21	Dovyalis	15.3	38.7	53.2	35.7

5.2.4 Sap flow dynamics of *D. caffra* trees

Kei apple is a widely occurring tree species. It is used right across South Africa as a hedge, but its water requirements have not been measured as far as we are aware. Results of the water use dynamics of two trees growing next to each other in Nelspruit, and how this is affected by the atmospheric evaporative demand, are shown in Fig. 5.7. This data was collected over two seasons from October 2019 to May 2021. The seasonal trend in water use by the trees of different sizes clearly follows that of the atmospheric evaporative demand.

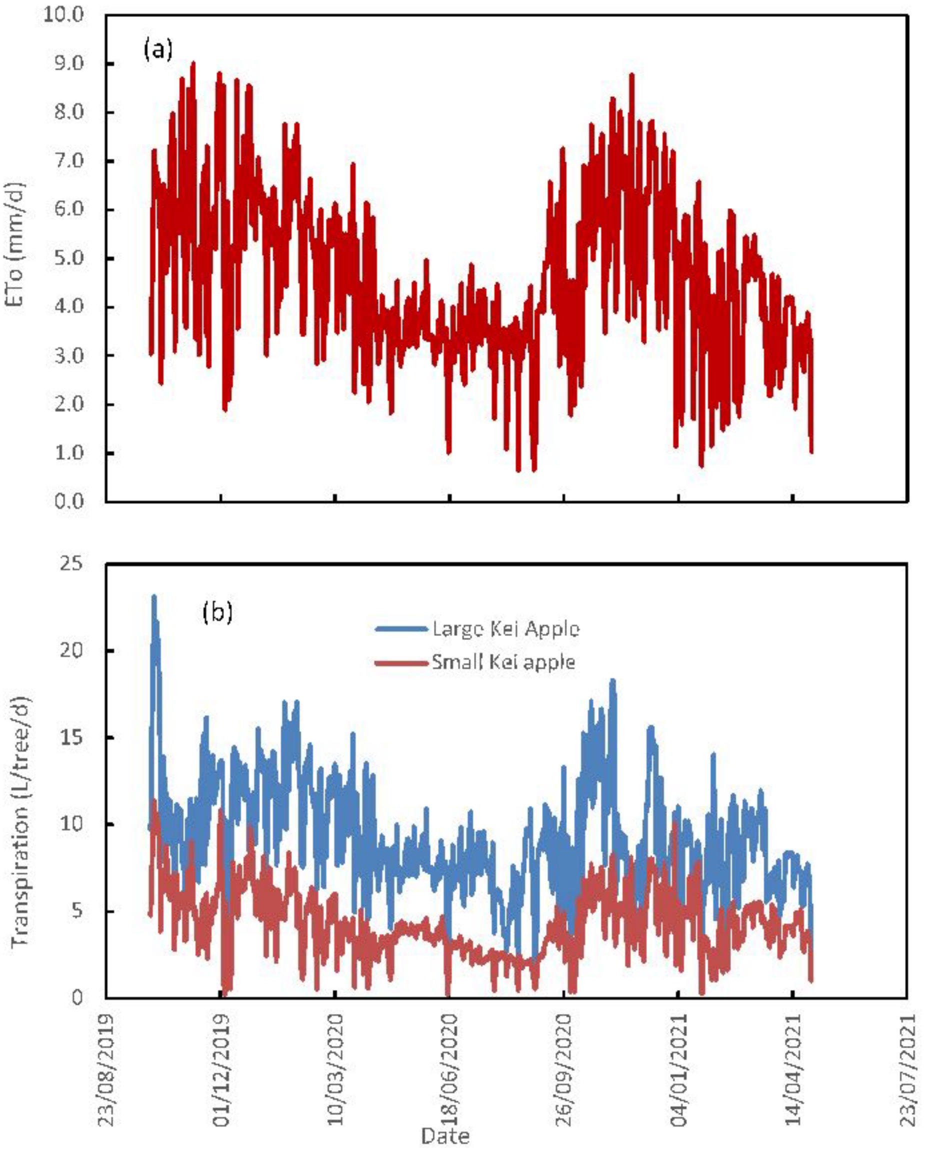


Fig. 5. 7. Seasonal changes in the; a) daily reference evapotranspiration, and b) transpiration dynamics of Kei apple trees with average stem diameters of 5.2 cm (small) and 9.5 cm (large) at the ARC orchard in Nelspruit.

5.2.5 Drivers of water use for *D. caffra*

The phenology of Kei apple is shown in detail in Appendix D. These trees retain leaves throughout the year with new ones appearing before the old ones have been shed in winter. The water use data shown in Fig. 5.7 & 5.8 shows that this species uses water throughout the year. Transpiration rates are low in winter and higher in summer as expected.

However, water use by the Kei apple trees is quite strongly driven by the atmospheric conditions, as illustrated in Fig. 5.8 (a-c). In fact, the relationship between the water use of the trees and the climatic drivers follows that of a classical exotic apple tree as reported by Ntshidi et al (2018). There is a strongly curvilinear relationship between the transpiration and the vapour pressure deficit of the air (Fig. 5.8a) and this is in sharp contrast with that of the Marula. Stomata of the Kei apple open, as the VPD increases from zero to a threshold between 1.0 and 1.5 kPa. Any further increase in VPD beyond the 1.5 kPa threshold causes stomata to close, and this is very similar to the response of exotic apple trees. The exact mechanism via which the stomata respond to increasing VPD are not well known, and this is worthwhile investigating in future.

As with exotic commercial apple trees, there exists a linear relationship between the transpiration of the Kei apple and the solar irradiance as illustrated in Fig. 5.8b. This suggests that increasing radiation levels do not cause stomatal closure and inevitably lead to higher levels of water use. However, this statement contradicts the observation in commercial apple trees that the maximum water use rates do not occur in full sunlight, but rather under milder light conditions.

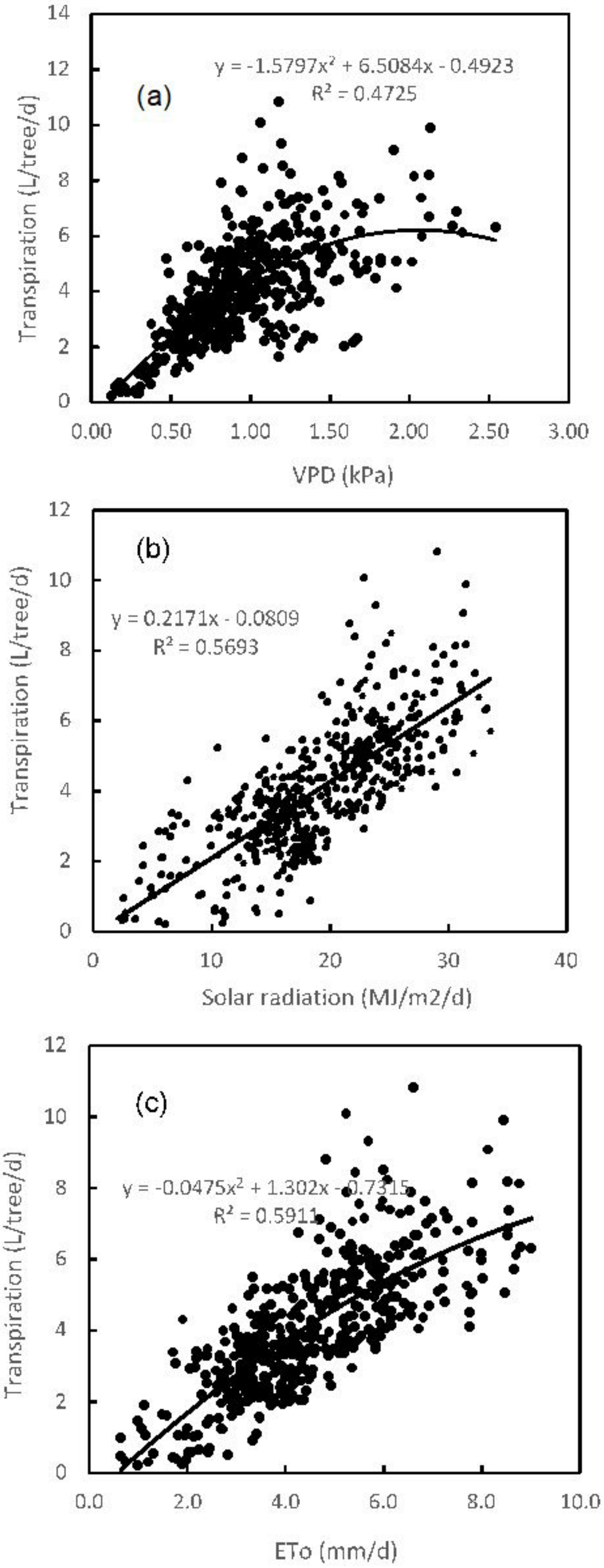


Fig. 5. 8. Effect of climate driving variables namely: a) the daily average VPD, b) daily total solar radiation, and c) the reference evapotranspiration on the transpiration of Dovyalis Caffra.

We suspect that dynamic photoinhibition under high light levels may affect the functioning of the photosynthetic apparatus leading to a reduction in the demand for CO_2. This will in turn cause the stomata to close somewhat, thereby reducing the transpiration rates. However, this theory is not supported by the results in Fig. 5.8b and those we have published in commercial apple orchards (Ntshidi et al., 2018).

The effects of the VPD and radiation on transpiration are captured in the ETo response as shown in Fig. 5.8c. The curvilinear response shown in Fig. 5.8c suggests that the VPD has a stronger influence on the diurnal transpiration dynamics of Kei apple than the radiation, again consistent with observations on the exotic species.

5.2.6 Plant water status

The diurnal trend in the stomatal conductance of the *Dovyalis* tree species was strongly related to water use signals. There was a time lag between stomatal opening (in response to light stimuli) and the commencement of heat pulse velocity signals (Fig. 5.9a). The ranges of the measured stomatal conductance (Gs) were approximately 90 to 350 mmol/m^2/s.

The stomatal conductance trend was clearly consistent with the heat pulse velocity signals, while the trees also tended to close their stomata at midday. Both leaf water potential and stem water potential were affected by the opening of the stomata, as soon as the stomata was open and transpiration started, the drier the leaves became (Fig. 5.9b).

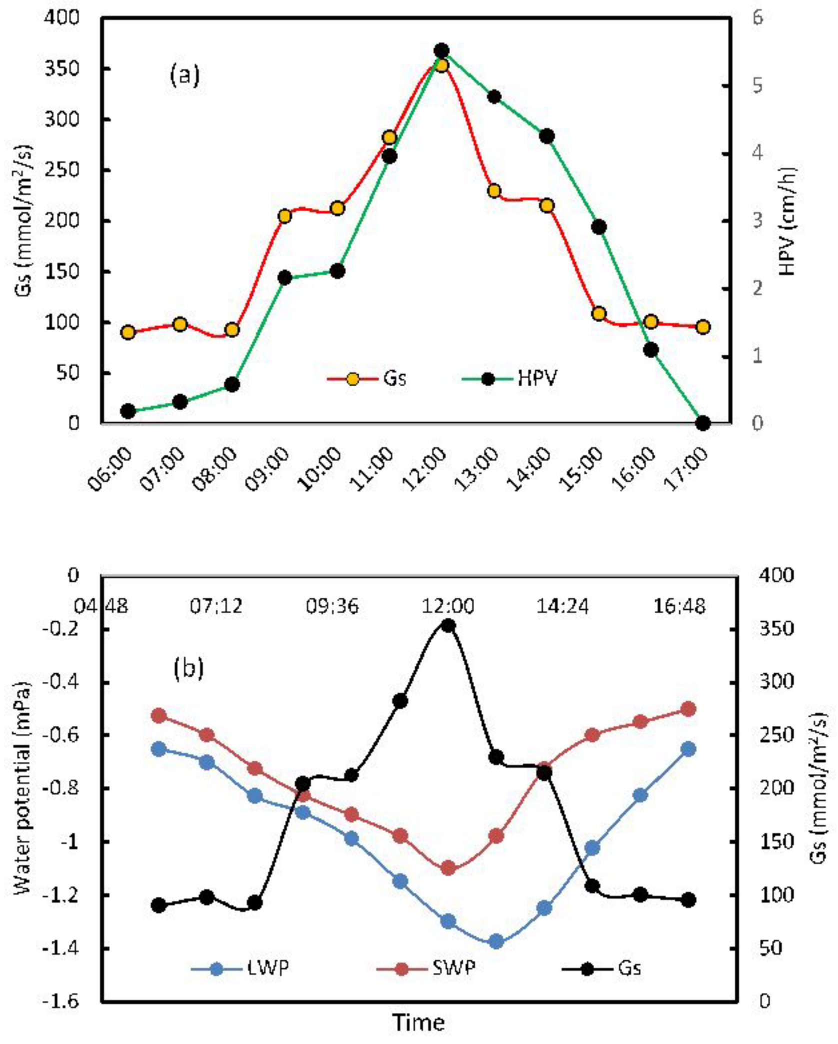


Fig. 5. 9. (a) Water use signals and stomatal conductance (Gs) of a Dovyalis tree on a clear day (10/11/2020).

5.2.7 Performance of the transpiration model on D. caffra

Typical results of the validation of the model on Kei apple trees are shown in Fig. 5.10. A small subset of the data was used to calibrate the for the Kei apple trees. Parameter values that gave the best fit for this species are summarised in Table 5.5. The model results for the Kei apple trees were not as accurate as those of Marula were.

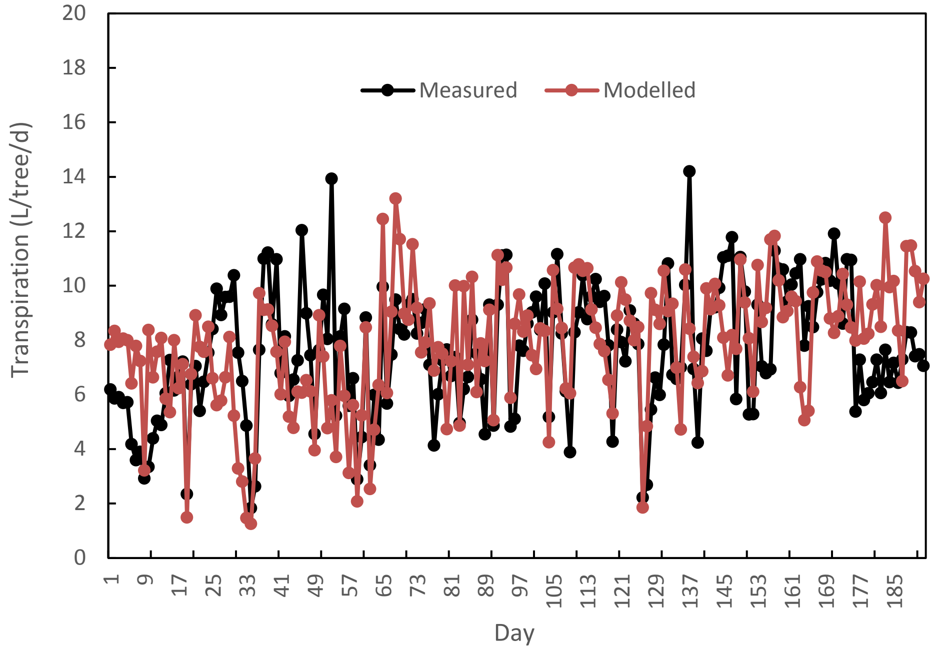


Fig. 5. 10. Comparison of the measured and modelled transpiration for a Kei Apple tree, with an average stem diameter of about 19 cm.

Table 5. 5 Parameters for the Penman-Monteith model applied to Kei apple trees in Mpumalanga

Parameter	Description	Kei apple
β (–)	Describes the curvature of the f(□) function	0.1
g_{max} (mm s^{-1})	Maximum stomatal conductance	10
k_r (Wm^{-2})	Describes the curvature of the f(Rs) function	500
kT_p (°C)	Optimal temperature for plant growth	18.5
k_{d1} (kPa^{-1})	Describes the influence of the VPD stress factor	0.0001
k_{d2} (kPa^{-1})	Describes the influence of the VPD stress factor	8
T_h (°C)	Maximum temperature for plant growth	41
T_L (°C)	Minimum temperature	5
θ_{FC} (cm^3/cm^3)	Volumetric soil water content at field capacity	0.1
Θ_{WP} (cm^3/cm^3)	Volumetric soil water content at the permanent wilting point	0.015

A summary of the statistics of the model fit are shown in Table 5.6. The R^2 values were 0.40 and 0.62 when the measured water use was compared with the modelled values for tree number 1 and tree number 2, respectively.

The root mean square values were ±0.21 and ±0.32 ℓ/tree/d, respectively. The RMSE values may appeared quite small, especially when compared with those of Marula in the previous chapter, but then these also reflect the effect of tree size. The model could still be improved by applying further subsets for the Kei apple species.

Table 5. 6 Statistical summary of the performance of the Penman-Monteith based model in predicting the daily transpiration of single Marula, S. spinosa and Kei apple trees over the period October 2019 to May 2021

Species	Tree no.	R2	Slope	MAE (ℓ/d)	RMSE (ℓ/d)	NSE
Kei apple	1	0.4	0.72	1.87	2.3	0.21
	2	**0.62**	**0.77**	**1.44**	**2.01**	**0.32**

5.3 CONCLUSIONS

Kei apple water use was strongly affected by the atmospheric evaporative demand as opposed to soil water deficits. The relationship between the water use of these Kei apple trees and climatic drivers seemed to follow the same trend as that of classical exotic apple trees reported in previous studies. The indigenous fruit tree water use model, developed in this study, did not perform best for the Kei apple trees and could still be improved. The stomatal conductance of these trees was strongly related to water use signals and unlike the Marula, Kei apple plants experienced water stress.

CHAPTER 6: WATER USE EFFICIENCY OF THE FOUR STUDIED INDIGENOUS FRUIT TREES

6.0 INTRODUCTION

Most indigenous fruit trees growing in the wild contain large amounts of vitamins, minerals, starch, vegetable oils, and protein (Chirwa et al., 2007), thereby contributing towards the United Nations' Millennium Development Goals through ensuring food and nutritional security especially for poor rural households (Nkosi et al., 2020). Water use efficiency (WUE) is defined in this study as the ratio of the fruit yield/net photosynthetic assimilation to the transpiration/water use. This definition is widely used in ecophysiological studies that seek to relate the amount of carbon dioxide (CO_2) assimilated during photosynthesis to the water transpired (Taiz et al., 2015). WUE defined in this way depicts leaf level gas exchange representing the amount of water lost in exchange for a single molecule of CO_2.

The main aim of this study was to measure the water use of indigenous fruit trees with domestication and commercialisation potential and monitor the fruit yield, and eventually calculate the water use efficiency. In this study, the yield and the whole tree transpiration of indigenous fruit tree species was also quantified, as described in earlier chapters. It is important to understand the water use of indigenous fruit trees, especially those that have a potential of domestication and commercialisation (Nkosi et al., 2020; Dzikiti et al., 2022). The goal of this chapter is to quantify the differences in the WUE of the studied indigenous fruit tree species (*Marula, Dovyalis, Kei apple and Vangueria*). This information will provide insights on the performance of these species in terms of both their physiological responses to the environment in the short term and how this translates to yield in the long term.

6.1 MATERIALS AND METHODS

The workshop, which comprised of specialists in the field and people from rural communities where IFTs are used as sources of food and for medicinal purposes, was held towards the end of the year 2017. The main purpose of this gathering was to identify indigenous fruit trees that have domestication and commercialisation potential. In their selection, the participants considered attributes such as:

1) range of uses
2) abundance
3) commercial value of the products
4) ease of propagation
5) drought and disease tolerance
6) ease of harvesting, transportation
7) storage

A list of ten species were first identified and further trimmed, resulting in the top four species listed in order of priority: 1) *Sclerocarya birrea* (Marula) 2) *Strychnos spinosa* (Strychnos), 3) *Dovyalis caffra* (Kei apple) and 4) *Vangueria infausta* (Vangueria).

After the selection of these species, the next step was to identify suitable study sites and instrument the trees with water use monitoring equipment. Sap flow was measured using the heat ratio method (HRM) of the heat pulse velocity sap flow technique (Burgess et al., 2001). Leaf gas exchange measurements were taken using an Infrared Gas Analyser while Root- and branch-level sap flow was quantified using the HRM. Light response curves were conducted as described in Chapter 4. The water use efficiency of the species was calculated as the kilograms of fruit produced, per litres of water consumed, WUE = Fruit yield / Water consumption. To sample fruit from the indigenous trees, when the fruit had reached a ripening stage, they fell randomly under the tree; they were then picked up as they were counted as explained in earlier chapters. To determine fruit mass, the fruit were measured using Vernier callipers.

Further analysis included plotting correlations between the water use and climate variables. All methods used in this chapter were described in detail in earlier chapters.

6.2 RESULTS AND DISCUSSION

6.2.1 Plant water use

The first four indigenous species with domestication and commercialisation potential showed a variable overall water consumption when the total was summed up for yearly consumption (Fig. 6.1). Water use mainly depends on the density of the monitored plant species as well as the plant leaf area index (LAI). The LAI for the KwaZulu-Natal Marula trees was ~1.2, while *Strychnos* had a LAI of ~1.4. Kei apple had an LAI of ~1.8 and *Vangueria* had an LAI of ~1.7, while the LAI of the Mpumalanga Marula trees reached LAI values of ~2.6. The seasonal water use amounted to 6061 ℓ/Tree/year for *Strychnos*, while this was ~2160 for Marula and Kei apple 3478 while *Vangueria* water use amounted to 5960 ℓ/tree/year. The *Strychnos,* Kei apple and *Vangueria* trees had a very short dormant period in winter lasting just under one month between June and July when they shed their leaves, while dormancy period for Marula lasted from July to early October (Akinnifesi et al., 2008; Dzikiti et al., 2022). This extended dormancy period is likely a contributing factor to the observed low water use rates of Marula.

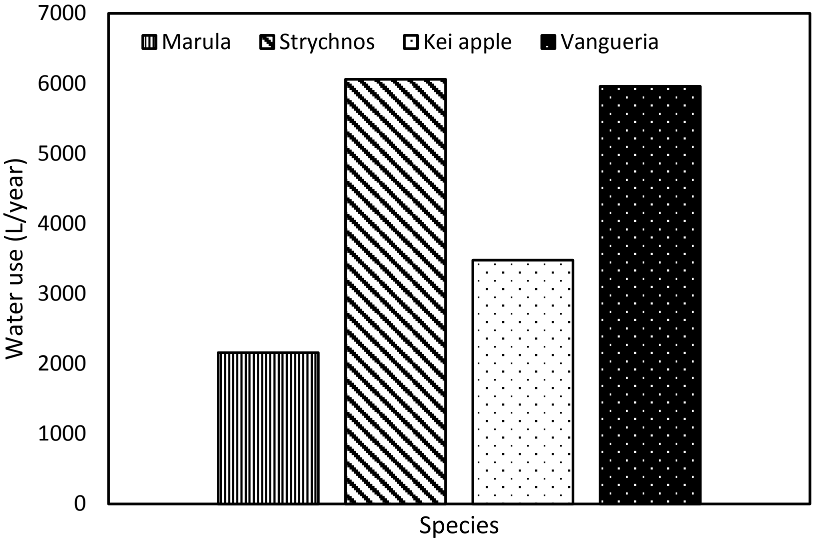


Fig. 6. 1. Water use of four indigenous fruit tree species with domestication and commercialisation potential

6.2.2 Water Use Efficiency

The Marula trees studied at our KwaZulu-Natal study site were relatively small in size, growing in harsh conditions resulted in low average yields ~4.3 kg/tree, as stated in chapter 3. Fully-grown Marula trees in the same country but different provinces produce higher yields (Akinnifesi et al., 2008; Dzikiti et al., 2022), Table 6.1 presents higher yields observed at the Mpumalanga study site. The Marula trees in Mpumalanga yielded up to 82 kg (Table 6.1). Strychnos yielded ~15.2 kg, while Kei apple yielded ~8.9 kg and Vangueria 14.6 kg.

The WUE of these indigenous fruit trees has differed slightly across the different species studied. It was found that the WUE of the species growing in the wild was lower when compared to the species grown in an orchard setting. The WUE of Marula trees growing in the wild was 2 kg/m^3 while that of the same species growing in an orchard setup at ARC Burgershall site had recorded a WUE of 12.2 kg/m^3 (Table 6.1). When comparing these WUE results to exotic species that have been measured in previous studies (Dzikiti and Schachtschneider, 2015; Dzikiti et al., 2018; Gush and Taylor, 2014), they vary, but exotic fruit seem to have generally higher WUE.

This could be argued that the exotic fruit are irrigated and well managed, while the indigenous fruit trees are not irrigated and mostly grow in the wild. Even those in an orchard setting were not irrigated. Gush and Taylor (2014) measured the WUE of citrus and recorded values in the range 4.4 – 6.1 Kg/m^3. Water productivity (WP) of apple trees was found in the ranges of 4 Kg/m^3 and 18 Kg/m^3 (Dzikiti et al., 2018; Gush et al., 2019). WP of plums (5.97 Kg/m^3) and peaches (3.5 Kg/m^3) were recorded by Dzikiti and Schachtschneider, 2015.

Table 6. 1 Summary of the water use, yield and water use efficiency of indigenous fruit with domestication and commercialisation potential

Season	Species	Tree #	Diameter (cm)	Annual T (ℓ)	Yield (Kg)	WUE (kg/l)
2019/20	Marula	2	13	4209.3	51.3	12.2
		3	55	18102.8	82	4.5
	Kei apple	1	5.2	1517.1	5	3.3
		2	9.5	3478.4	27.5	7.9
2020/21	Marula	2	13	2079.3	22.2	10.7
		3	55	8205.3	48.8	5.9
	Kei apple	1	5.2	1715.7	15.3	8.9
		2	9.5	3869.5	53.2	13.7
	Vangueria	1	13.6	5960.2	14.6	2.4
	Vangueria	2	8.4	4880.4	12.3	2.5

6.2.3 Leaf water use efficiency for Marula and Kei apple

Photosynthesis peaked for the Mpumalanga Marula and Kei apple trees at light levels lower than 1000 μmol/m^2/s which is lower than around 1 500 μmol/m^2/s found in exotic tree crops (Gush and Taylor, 2014). The results shown in this section are from the bigger Marula trees growing in Mpumalanga and the Kei apple growing in an orchard setting in Mpumalanga. Light intensity is obviously an important driver of photosynthesis. However, the capacity of the photosynthetic apparatus to cope with excess light differs between species.

Little is known about the light saturation levels for indigenous fruit tree species. Excess light causes photoinhibition, which affects the functioning of photosystem II and thus lowers the water use efficiency. Typical data on the light saturation for Kei apple and Marula are shown in Fig. 6.2. The low levels at which light saturation occurs for these light-adapted species is not expected and warrants further investigation.

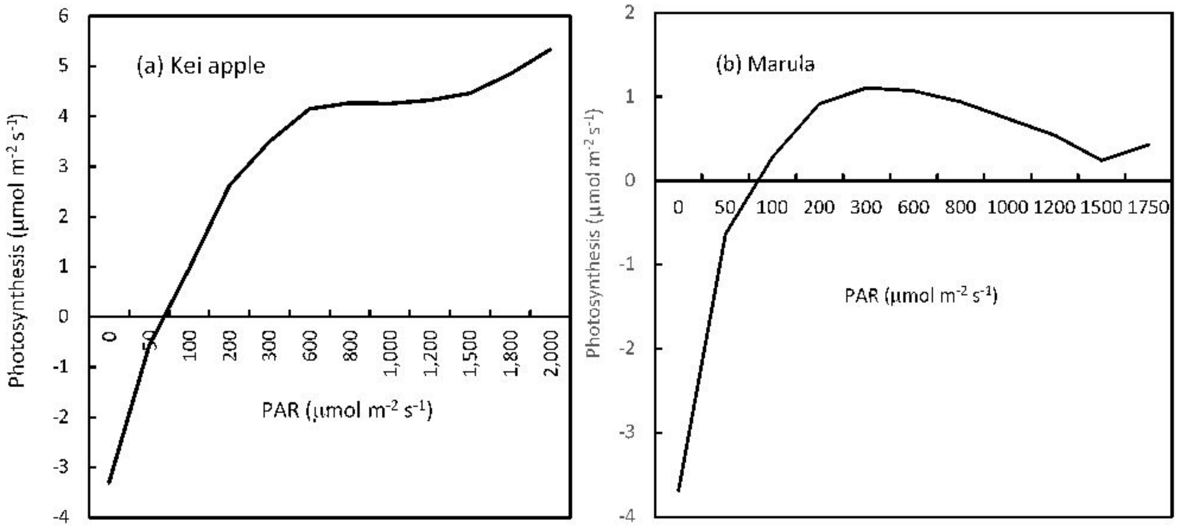


Fig. 6. 2. Light response curves for (a) Kei apple, and (b) Marula trees.

As previously stated, in this study we define water use efficiency as the ratio of CO_2 assimilation (A) to the leaf transpiration (E). This variable can also be calculated as the slope of the photosynthesis versus transpiration curve as shown in Fig. 6.3.

It is apparent in Fig. 6.3b that the WUE of Marula (3.24) is considerably greater than that of Kei apple, which is about 2.3. We are uncertain how differences in the site conditions affected the WUE values, given that Marula grew on heavy clayey soils while Kei apple grew on deep sandy soils. These figures are believable to some extent, given the vast differences in the yield of the two species.

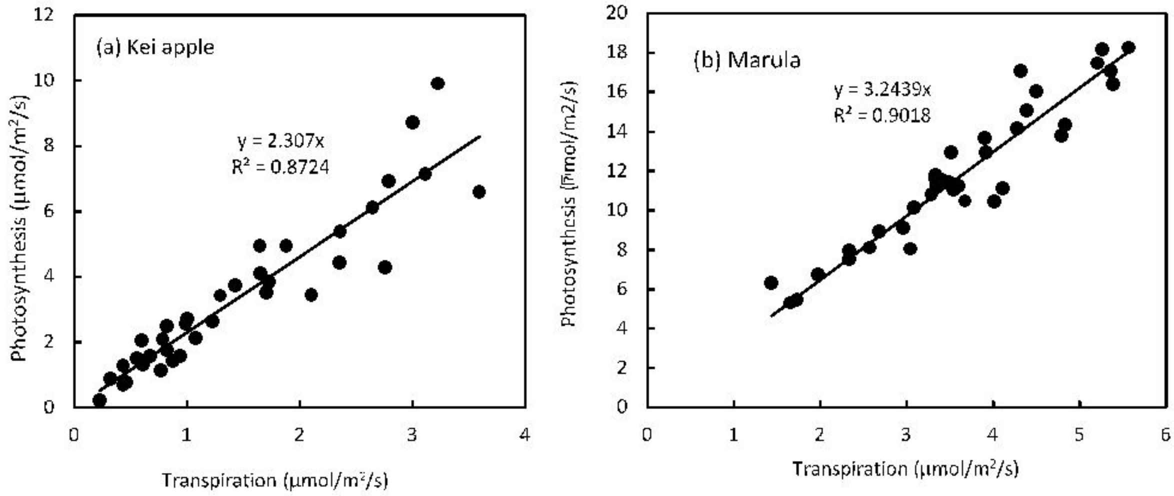


Fig. 6. 3. Water use efficiency of (a) Kei apple and (b) Marula depicted by the slope of the graphs.

6.2.4 Summary of model performance for the different indigenous tree species

The earlier chapters have shown how the model was created in the earlier stages of the project, calibrated over time and validated in the different study regions using different species. Table 6.2 summarises the parameters of the Penman-Monteith model that were applied to the different indigenous fruit tree species growing in the two provinces. The model initially created for Marula trees growing in KwaZulu-Natal gave good estimates for the Marula trees growing in Mpumalanga after subsets were applied and the model calibrated with sufficient data.

A summary of the statistics of the model fit are shown in Table 6.3. The R^2 values went up to 0.64 when the measured water use was compared with the modelled values for the Marula trees. The root mean square values went as high as ±20.3 ℓ/tree/d, with positive Nash-Sutcliffe Efficiency values recorded (Table 6.3). The RMSE appear quite large, but it is important to note that these also reflect the effect of tree size.

Table 6. 2 Parameters for the Penman-Monteith model applied to different indigenous fruit tree species in KwaZulu-Natal and Mpumalanga

Study location		KwaZulu-Natal		Mpumalanga	
Parameter	Description	S. spinosa	Marula	Marula	Kei Apple
β (-)	Describes the curvature of the f(θ) function.	0.10	1.20	0.25	0.10
g_{max} (mm s^{-1})	Maximum stomatal conductance	10.00	8.50	10	10
k_r (Wm^{-2})	Describes the curvature of the f(Rs) function	150	50	500	500
kT_p (°C)	Optimal temperature for plant growth	20	15	18.50	18.50
k_{d1} (kPa^{-1})	Describes the influence of the VPD stress factor	0.0001	0.0001	0.0001	0.0001
k_{d2} (kPa^{-1})	Describes the influence of the VPD stress factor	8	9	9	8
T_h (°C)	Maximum temperature for plant growth	41	41	41	41
T_L (°C)	Minimum temperature	5	5	5	5
θ_{FC} (cm^3/cm^3)	Volumetric soil water content at field capacity	0.083	0.083	0.27	0.10
Θ_{WP} (cm^3/cm^3)	Volumetric soil water content at the permanent wilting point	0.010	0.010	0.06	0.015

Table 6. 3 Statistical summary of the performance of the Penman-Monteith based model in predicting the daily transpiration of single Marula, S. spinosa and Kei apple trees over the period January 2017 to December 2021.

Site	Species	Tree no.	R^2	Slope	MAE (ℓ/d)	RMSE (ℓ/d)	NSE
KwaZulu-Natal	S. spinosa	1	0.89	1.03	2.42	3.35	0.82
		2	0.86	0.94	2.25	3.01	0.85
	Marula	1	0.74	0.89	0.92	1.43	0.71
		2	0.69	0.86	1.01	1.61	0.64
Mpumalanga	Kei Apple	1	0.40	0.72	1.87	2.30	0.21
		2	0.62	0.77	1.44	2.01	0.32
	Marula	1	0.64	1.03	3.09	3.91	0.69
		2	0.55	0.97	15.4	20.3	0.43

6.3 CONCLUSIONS

This study has reported on the water use efficiency of selected indigenous fruit tree species growing in their natural habitats and some grown in an orchard setup. This information provides insights on the performance of these species in terms of both their physiological responses to the environment in the short term and how this translates to yield in the long term. The WUE of the monitored indigenous fruit tree species was recorded to be lower than that of exotic species reported in previous studies. It was also noted that the indigenous fruit trees grown in orchard set up had higher WUE than those growing in the wild, though this could be as a result of wild animals eating the fruit in the wild before it could all be accounted for in yield studies.

CHAPTER 7: GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

7.1 GENERAL DISCUSSION

Indigenous fruit tree crops are widely reported to be naturally adapted to the local soil and climate conditions (Chirwa et al., 2007; Taylor, 2008). Therefore, they are more likely to survive environmental stresses than introduced species are. Therefore, it is not surprising that research on these so-called "orphan crops" has increasingly become important in climate change adaptation studies (Taylor, 2008; Mabhaudhi et al., 2017). Yet detailed quantitative information on how indigenous fruit tree crops interact with their environment is sparse (Dye et al., 2008; Gush and De Lange. 2015) thereby contributing to their limited utilisation. In this study, we investigated the water use patterns, and their drivers, for two fruit tree species that have a high potential for domestication and commercialisation, not only in Africa, but also elsewhere in the world. For example, some of the first commercial orchards of Marula, as an alternative fruit tree crop, were established in the Negev Desert in Israel, using plant material imported from sites with harsh growing conditions in Botswana in the 1980s (Nerd and Mizrahi., 2000). Extensive pre- and post-harvest horticultural trials have subsequently been done on Marula in Israel, but still no detailed eco-physiological data has been reported.

This study compared the water use rates of Marula and *Strychnos spinosa* (*Strychnos*), which is another widely planted fruit tree crop in backyard and school gardens and in communal farmers' fields. Despite the small difference in canopy size between the monitored plants, the annual water use of Marula trees was roughly a third of that used by *Strychnos* and there were two main reasons for this. Firstly, the daily sap flow rates of Marula were strongly influenced by soil water availability. Extended dry spells led to significant stomatal closure and subsequently to a decline in the transpiration rates of Marula, while *Strychnos* maintained high water use rates. The high transpiration rates of *Strychnos* were possibly a result of its dense and extensive network of fine roots. It is probable that the extended periods of stomatal closure for Marula led to low rates of photosynthesis culminating in low average yields (fresh mass) of only about 4.3 kg/tree. This yield was about ten times lower than that of Marula trees, also growing under sub-tropical conditions in the neighbouring Mpumalanga Province, but on heavier sandy clay loam soils (i.e. 44.9 kg/tree). On average, each *Strychnos* tree studied produced about 15.2 kg of fruit calculated as an average from 10 trees over two years. The water productivity of Marula, defined as the yield per unit volume of water transpired, was about 2.0 kg/m^3 for Marula and about 2.5 kg/m^3 for *Strychnos*.

These water productivity values are very low compared to those of irrigated commercial deciduous fruit elsewhere in South Africa. For example, Dzikiti et al (2018) and Gush et al (2019) measured values in the range 8 to 18 kg/m^3 in different apple orchards in the Western Cape Province of South Africa. According to Steduto et al (2012), the transpiration of fruit trees is correlated to their yield. Therefore, it is possible that the water productivity of the indigenous fruit tree crops could be improved with supplemental irrigation, e.g. for species like Marula whose transpiration response and possibly yield appear to be sensitive to soil water deficit in nutrient poor deep sandy soils.

The second reason for the low annual water use by Marula relates to its relatively long leafless period of over three months compared to *Strychnos* leafless period of less than a month. These differences in the water requirements of the indigenous fruit tree crops have implications on the conservation of these species. Marula for example, is classified as an endangered species in many parts of Southern and Eastern Africa (Taylor, 2008; Cemansky, 2015) due to extensive deforestation for firewood and the extensive harvesting of its products, e.g. leaves, roots and bark for medicinal purposes. Our study suggests that under conditions of severe water limitations, *Strychnos* appears to be more resilient to drought stress than Marula, likely because of its extensive root system, which can scavenge for water and nutrients. It is also possible that the transpiration stream of *Strychnos* has a lower hydraulic resistance thereby transporting water more efficiently to the evaporation sites in the leaves than Marula. However, this was not investigated in this study. Tree mortality because of drought stress is another focus of biodiversity and agroforestry programmes. Again, this was not included in this study, but this should be investigated in future studies.

Despite the differences in the water relations of Marula and *Strychnos* trees, for the first time, we demonstrate that their transpiration can be accurately modelled using a simple combination Penman-Monteith equation. However, different model parameters are required to capture the complex responses of individual species under the harsh growing conditions even for trees growing in close proximity to each other. Given the simple and readily available inputs required, the model can be used for estimating the water requirements of individual trees of these species in support of various agroforestry and biodiversity conservation programmes. This model has been applied to individual fruit trees, e.g. apple (Green et al., 2003; Green and McNaughton., 1997) and other deciduous species, e.g. poplar trees (Zhang et al., 1997), among others.

7.2 CONCLUSIONS

This study has generated useful baseline data on the ecophysiology of high priority indigenous fruit tree species that include; *S. birrea, S. Spinosa, D. caffra and V. infausta*. These species grow in large parts of the country and local experts reckon that they have a high potential for domestication and possibly commercialisation. There are currently efforts to plant the first commercial Marula orchards in South Africa and the data on its water use, and yield dynamics generated in this project will be essential for supporting such initiatives. However, the severe alternate bearing tendencies for the indigenous trees meant that more than one year's data was required per site in order to get credible data on the relationships between water use and yield. This had the effect of reducing the number of species that was assessed in this study. Our data shows that the physiology of the trees varied greatly between species. For this reason, a tree-species specific model for water use developed parameterised for each species. We hope this model will be useful for various agroforestry and indigenous plant commercialisation efforts.

7.3 RECOMMENDATIONS

Several gaps remain if domestication and commercialisation of indigenous fruit trees can gain momentum in the country and elsewhere on the African continent.

1) This study covered only four species. Even for these few species, numerous questions still remain;
2) There is need for further research to understand how these species respond to different growing conditions. This study did not do an exhaustive comparison of the performance of the species in different climatic and soil conditions;
3) There is still need to select genotypes that give fruit with the best quality and yield;
4) Commercially viable means to propagate these genotypes should also be established;
5) Some species may require pollinators to perform optimally. The ratio between the fruit bearing trees and pollinators and the respective distances needs to be investigated.
6) There are also further research needs postharvest, e.g. there is need to develop postharvest handling practices for indigenous fruit.
7) There is also need to improve the range of commercially viable products that can be developed from indigenous fruit.

Lastly, this study also highlighted the complexity of accurately modelling the transpiration dynamics of Africa's highly biodiverse forests which are often needed in general circulation models, climate change, and biodiversity studies. In view of the apparent greater resilience of *Strychnos* to drought stress, agroforestry programmes in areas with poor sandy soils and low rainfall amounts could possibly derive higher production levels from this species.

REFERENCES

AKINNIFESI FK, KWESIGA F, MHANGO J, CHILANGA T, MKONDA A, KADU CAC, KADZERE I, MITHOFER D, SAKA JDK, SILESHI G, RAMADHANI T, DHLIWAYO P. 2006. Towards the development of Miombo fruit trees as commercial tree crops in southern Africa. Forests, Trees and Livelihoods 16: 103-121.

AKINNIFESI FK., LEAKEY RRB., AJAYI OC., SILESHI G., TCHOUNDJEU Z., MATAKALA P., KWESIGA FR. 2008. Indigenous fruit trees in the tropics Domestication, Utilization and Commercialization. © CAB International 2008.

ALADOS, I., FOYO-MORENO, I., ALADOS-ARBOLEDAS, L., 2012. Estimation of downwelling longwave irradiance under all-sky conditions. Int. J. Climatol. 32, 781–793.

ALLEN RG, PEREIRA LS, RAES D and SMITH M. 1998. Crop evapotranspiration. FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization (FAO), Rome, Italy.

ALTMAN, T. G. B., JACOBS P. T., 2009. Household food security status in South Africa. Agrekon Vol. 48:4

AUBREY A. (2004). Phoenix reclinata. South African National Biodiversity Institute. Available at: http://www.pza.sanbi.org/phoenix-reclinata.

BAIPHETHI, M. N., JACOBS, P. J., 2009. The contribution of subsistence farming to food security in South Africa. Agrekon Vol. 48:4

BALOYI JK AND REYNOLDS V (2004). *Ximenia caffra*. South African National Biodiversity Institute. Available at: http://www.pza.sanbi.org/ximenia-caffra.

BASTIAANSEN, W., WALTERS, R., ALLEN, R., TASUMI, M., AND TREZZA, R., 2002. Surface energy balance algorithms for land – Advanced training and users' manual. The Idaho Department of Water Resources, USA.

BEHR K. 2004. *Vangueria infausta*. Available at: http://pza.sanbi.org/vangueria-infausta Accessed on 24 July 2017.

BLURRING J. 2004. *Trichilia dregeana* South African National Biodiversity Institute. Available at: http://www.pza.sanbi.org/trichilia-dregeana

BROWNE C. 2009. The burning questions about Hluhluwe: causes and consequences of a severe wildfire. MSc thesis, University of Cape Town, South Africa.

BRUNCHI P, MORGANTI M, MANCINI M AND SIGNORINI MA. (2011). Traditional healers and laypeople: A qualitative and quantitative approach to local knowledge on medicinal plants in Muda (Mozambique). *Journal of Ethnopharmacology*. **138**:543-563.

BRUTSAERT, W. H., 1975. On a derivable formula for long-wave radiation from clear skies, Water Resour. Res. 11, 742– 744.

BURGESS, S.S.O., ADAMS, M.A., TURNER, N.C., BEVERLY, C.R., ONG, C.K., KHAN, A.A.H., BLEBY, T.M., 2001. An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. Tree Physiol. 21, 589–598.

CAROLUS B (2004a). *Carissa macrocarpa*. South African National Biodiversity Institute. Available at: http://www.pza.sanbi.org/carissa-macrocarpa.

CAROLUS B (2004b). *Syzygium cordatum. South African National Biodiversity Institute.* Available at: http://pza.sanbi.org/syzygium-cordatum Accessed on 24 July 2017.

CARRASCO, M., AND ORTEGA-FARIAS, S., 2007. Evaluation of a model to simulate net radiation over a vineyard cv. Cabernet sauvignon. Chilean J. Agric. Res. 68, 156-165.

CAWE SG, MCKENZIE B (1989) The Afromontane forests of Transkei. IV. Aspects of their exploitation potential. South African Journal of Botany 55: 45-55.

CEMANSKY R. 2015. Africa's Indigenous Fruit Trees A Blessing in Decline. Environmental Health Perspectives. 123 (12), 1-6.

CHAUVIN ND, MULANGU F., PORTO., G. 2012. Food Production and Consumption Trends in Sub-Saharan Africa: Prospects for the Transformation of the Agricultural Sector. UNDP. WP 2012-011: February 2012.

CHEN, Y., XIA, J., LIANG, S., FENG, J., FISHER, J.B., LI, X., LIX., LIU, S., MA, Z., MIYATA, A., MU, Q., SUN, L., TANG, J., WANG, K., WEN, J., XUE, Y., ZHA, T., ZHANG, L., ZHAO, T., ZHAO, L., AND YUAN, W., 2014. Comparison of satellite-based evapotranspiration models over terrestrial ecosystems in China. Remote Sens. Environ. 140, 279-293.

CHIRWA PW., BWANALI RJ., MEKE G., SAGONA W., MUNTHALI CRY., MWABUMBA L.2007. Growth and phenology of a three- to four-year-old Sclerocarya birrea international provenance trial in Malawi. Southern Hemisphere Forestry Journal. 1, 49-54.

CLEUGH, H.A., LEUNING, R., MU, Q., AND RUNNING, S.W. 2007. Regional evaporation estimates from flux tower and MODIS satellite data. Remot. Sens. Environ. 106, 285-304.

CLULOW AD, EVERSON CS, PRICE JS, JEWITT GP, SCOTT-SHAW BC (2013) Water-use dynamics of a peat swamp forest and a dune forest in Maputaland, South Africa. Hydrology and Earth System Sciences, 17 (5): 2053-2067.

COCK IE & VAN VUUREN SF, (2015). South African food and medicinal plant extracts as potential antimicrobial food agents. *Journal of Food Sc. Technology*. **52(11)**:6879-6899.

CORRIGAN BM, VAN WYK BE, GELDENHUYS CJ & JARDINE JM, (2011). Ethnobotanical plant uses in KwaNibela Peninsula, St Lucia, South Africa. *South African Journal of Botany*. **77**:346-359.DE WET H, NZAMA VN and VAN VUUREN SF (2012). Medicinal plants used for treatment of sexually transmitted infections by lay people in northern Maputaland, KwaZulu-Natal Province, South Africa. *South African Journal of Botany.* **78**:12-20

DE LANGE WJ, JAMES BM, MAHUMANI BK, REED LL, WISE RW, GUSH MB (2015) Economic viability and market potential. In: Gush, M.B., de Lange, W.J., Dye, P.J. and Geldenhuys C.J. (Eds). 2015. Water Use and Socio-Economic Benefit of the Biomass of Indigenous Trees: Volume 1 (Research Report). Water Research Commission, Pretoria, RSA, WRC Report 1876/1/15, Section 5.

DEPARTMENT OF AGRICULTURE FORESTRY AND FISHERIES (2011). Most common indigenous food crops of South Africa. DAFF, 2011.

DLAMINI MD (2004). *Harpephyllum caffrum* South African National Biodiversity Institute. Available at: http://www.pza.sanbi.org/harpephyllum-caffrum.

DU TOIT (2011) Food Security By Directorate Economic Services Production Economics unit. Department of Agriculture Forestry and Fisheries.

DYE PJ (2013) A review of changing perspectives on Eucalyptus water-use in South Africa. Forest Ecology and Management, 301: 51-57. DOI: 10.1016/j.foreco.2012.08.027.

DYE PJ, GUSH MB, EVERSON CS, JARMAIN C, CLULOW A, MENGISTU M, GELDENHUYS CJ, WISE R, SCHOLES RJ, ARCHIBALD S, SAVAGE MJ (2008) Water-use in relation to biomass of indigenous tree species in woodland, forest and/or plantation conditions. WRC Report No. TT361/08, Water Research Commission, Pretoria, South Africa.

DYE PJ, OLBRICH BW (1993) Estimating transpiration from 6-year-old Eucalyptus grandis trees: development of a canopy conductance model and comparison with independent sap flux measurements. Plant Cell Environment, 16: 45-53. DOI: 10.1111/j.1365-3040.1993.tb00843.x.

DYE PJ, VERSFELD D (2007) Managing the hydrological impacts of South African plantation forests: An overview. Forest Ecology and Management, 251: 121-158. DOI: 10.1016/j.foreco.2007.06.013.

DZIKITI, S., N. JOVANOVIC, RDH BUGAN, A RAMOELO, NP MAJOZI, A NICKLESS, MA CHO, DC LE MAITRE, Z NTSHIDI, HH PIENAAR. 2019. Comparison of two remote sensing models for estimating evapotranspiration: algorithm evaluation and application in seasonally arid ecosystems in South Africa. Journal of Arid Land, ttps://doi.org/10.1007/s40333-019-0098-2.

DZIKITI, S., JOVANOVIC, N.Z., BUGAN, R., ISRAEL, S., AND LE MAITRE, D.C.,2014. Measurement and modelling of evapotranspiration in three fynbos vegetation types. Water SA. 40, 189-198.

DZIKITI S, T. VOLSCHENK, S.J.E MIDGLEY, E. LÖTZE, N.J TAYLOR, M.B. GUSH, Z.

NTSHIDI, S.F ZIREBWA, Q. DOKO, M. SCHMEISSER, C. JARMAIN, W.J STEYN, H.H. PIENAAR. 2018. Estimating the water requirements of high yielding and young apple orchards in the winter rainfall areas of South Africa using a dual source evapotranspiration model. Agricultural Water Management. 208, 152-162.

EBERT AW. 2014. Potential of Underutilized Traditional Vegetables and Legume Crops to Contribute to Food and Nutritional Security, Income and More Sustainable Production Systems. Sustainability. 6: 319-335; doi:10.3390/su6010319.

EGEA, G., VERHOEF, A., VIDALE, P.L., 2011. Towards an improved and more flexible representation of water stress in coupled photosynthesis–stomatal conductance models. Agric. For. Meteorol. 151, 1370–1384.

EMANUEL PL, SHACKLETON CM, BAXTER JS (2005) Modelling the sustainable harvest of *Sclerocarya birrea* subspecies *caffra* fruits in the South African Lowveld. Forest Ecology and Management, 214: 91-103.

ERSHADI, A., MCCABE, M.F., EVANS, J.P., CHANEY, N.W., AND WOOD, E.F. 2014. Multi-site evaluation of terrestrial evaporation models using FLUXNET data. Agric. For. Meteorol. 187, 46-61.

EVERSON CS GHEZEHE SB., EVERSON TM AND J ANNANDALE J. 2012. Agroforestry systems for improved productivity through efficient use of water. WRC Report No. 1480/1/12.

GARCIA, M., SANDHOLT, I., CECCATO, P., RIDLER, M., MOUGIN, E., KERGOAT, L., MORILLAS, L., TIMOUK, F., FENSHOLT, R., AND DOMINGO, F., 2013. Actual evapotranspiration in drylands derived from in situ and satellite data: Assessing biophysical constraints. Remote Sens. Environ. 131, 103-118.

GARCIA, M., FERNÁNDEZ, N., VILLAGARCÍA L., DOMINGO, F., PUIGDEFÁBREGAS, J., AND SANDHOLT, I. 2014. Accuracy of the Temperature–Vegetation Dryness Index using MODISunder water-limited vs. energy-limited evapotranspiration conditions. Remot. Sens. Environ. 149, 100-117.

GRANIER, A., LOUSTAU, D., 1994. Measuring and modelling the transpiration of a maritime pine canopy from sap-flow data. Agric. For. Meteorol. 71, 61–81.

GREEN S., MCNAUGHTON K. 1997. Modeling effective stomatal resistance for calculating transpiration from an apple tree. Agric. For. Meteorol. 83: 1-26.

GREEN S., MCNAUGHTON K., WÜNSCHE JN., CLOTHIER B. 2003. Modeling light interception and transpiration of apple tree canopies. Agron. J. 95: 1380-1387.

GUSH MB., DZIKITI S., VAN DER LAAN M., STEYN M., MANAMATHELA S., PIENAAR HH. 2019. Field quantification of the water footprint of an apple orchard, and extrapolation to watershed scale within a winter rainfall Mediterranean climate zone. Agric. For. Meteorol. Journal. 271, 135-147.

GUSH MB (2017) The potential of *Vachellia kosiensis* as a dryland forestry species in terms of its water use, growth rates and resultant water use efficiency. Southern Forests. A Journal of Forest Science, 79 (3): 227-234.

GUSH MB, DE LANGE WJ, DYE PJ, GELDENHUYS CJ (Eds) (2015) Water Use and Socio-Economic Benefit of the Biomass of Indigenous Trees (Volume 1): Research Report. Water Research Commission Report No. 1876/1/15, WRC, Pretoria, RSA.

GUSH MB, Dye PJ (Eds) (2015) Water Use and Socio-Economic Benefit of the Biomass of Indigenous Trees (Volume 2): Site Specific Technical Report. Water Research Commission Report No. 1876/2/15, WRC, Pretoria, RSA.

GUSH MB, Dye PJ (2009) Water-use efficiency within a selection of indigenous and exotic tree species in South Africa as determined using sap flow and biomass measurements. Acta Hort. (ISHS), 846: 323-330.

GUSH MB, DYE PJ, CLULOW AD, TAYLOR NJ, EVERSON CS, DZIKITI S, NAIKEN V (2014) Application of a Heat Pulse Velocity sap flow monitoring system (heat ratio method) for measuring transpiration rates in woody plant species. In: Taylor, N.J. and Gush, M.B. (Eds). 2014. The water use of selected fruit tree orchards (Volume 1): Review of available knowledge. Water Research Commission, Pretoria, RSA, WRC Report 1770/1/14, Appendix A.

GUSH MB, TAYLOR NJ (Eds) (2014) The water use of selected fruit tree orchards (Volume 2): Technical report on measurements and modelling. Water Research Commission Report No.1770/2/14, WRC, Pretoria, RSA. (ISBN 978-1-4312-0575-2).

HANKEY A (2003). *Ficus sur*. South African National Biodiversity Institute. Available at: http://www.pza.sanbi.org/ficus-sur.

HANKEY A (2004). *Pappea capensis*. South African National Biodiversity Institute. Available at: http://www.pza.sanbi.org/pappea-capensis.

HERTOG MGL. BAS BUENO-DE-MESQUITA H, KEHILY AM, SWEETHAM PM,ELWOOD PC, KROMHOUT D. 1996. Fruit and vegetable consumption and cancer mortality in Caerphilly study. Cancer Epidemiology, Biomarkers & Prevention. 1996;5:673–7.

JARVIS, P.G., 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. Philos. Trans. R. Soc. London. B, Biol. Sci. 273, 593–610.

JIMENEZ S., FATTAHI M., BEDIS K., NASROLAHPOUR-MOGHADAM S., IRIGOYEN JJ., GOGORCENA Y. 2020. Interactional effects of climate change factors on the water status, photosynthetic rate, and metabolic regulation in peach. Frontiers in Plant Science. 11, 1-18.

KIM, H.W., HWANG, K., MU, Q., LEE, S.O., AND CHOI, M. 2012. Validation of MODIS global terrestrial evapotranspiration products in various climates and land cover types in Asia. J. Civil. Eng. 16, 229-238.

KLAPWIJK N (2002). *Podocarpus falcatus*. South African National Biodiversity Institute. Available at: http://www.pza.sanbi.org/podocarpus-falcatus.

KLAPWIJK N (2003). *Cordia caffra*. South African National Biodiversity Institute. Available at: http://www.pza.sanbi.org/cordia-caffra.

KUCICH DA., WICHT MM (2016) South African indigenous fruits – Underutilized resource for boosting daily antioxidant intake among local indigent populations? South African Journal of Clinical Nutrition, 29:4, 150-156, DOI:10.1080/16070658.2016.1219470

LADIPO, D.O., FONDOUN, J.M. AND GAGA, N. (1996) Domestication of bush mango (*Irvinglia* spp.): the exploitable intraspecific varieties in west and central Africa. In: Leakey, R.R.B., Temu, A.B., Melnyk, M. and Vantomme, P. (eds) *Domestication and Commercialization of Non-timber Products of Agroforestry Systems*. Proceedings of an International Conference held in Nairobi, Kenya, 19–23 February 1996. Food and Agriculture Organization, Rome, pp. 193–205.

LAWES MJ, OBIRI JAF, EELEY HAC (2004) The uses and value of indigenous forest resources in South Africa. In: Lawes, M.J., Eeley, H.A.C, Shackleton, C.M. & Geach, B.G.S. (eds). Indigenous forests and woodlands in South Africa: Policy, people and practice. University of KwaZulu-Natal Press, Scottsville, South Africa. P. 227-273.

LE ROUX L (2005). *Strychonos spinosa.* South African National Biodiversity Institute. Available at: http://www.sanbi.org/strychonos-spinosa.

LEUNING, R. ZHANG, Y.Q., RAJAUD, A., CLEUGH, H., AND TU, K., 2008. A simple surface conductance model to estimate regional evaporation using MODIS leaf area index and the Penman-Monteith equation. Water Res. Research. 44, 1-17.

LI T., DING., HU Y., SUN, L., JIANG C., LIU Y. 2015. Diurnal changes in photosynthesis in Sclerocarya birrea from South Africa and Israel after introduction and acclimatization in Wenshan, Yunnan Province, China. South African Journal of Botany. 100, 101-107.

LIEBENBERG F (2013). South African Agricultural production, productivity and research in the 20th century. PhD Thesis, University of Pretoria.

LU, P., YUNUSA IAM., WALKER RR. 2002. Using the Granier sap flow sensors to determine grapevine transpiration. In: Walker RR and MR Gibberd, editors. Vine and Vineyard Water Requirements: Cooperative Research Center for Viticulture 2002 Proceedings (ISBN 0-9581058-2-0); 2002:94-108.

LUBCZYNSKI MW, CHAVARRO-RINCON DC, ROSSITER DG (2017) Conductive sapwood area prediction from stem and canopy areas—allometric equations of Kalahari trees, Botswana. Ecohydrology. DOI: 10.1002/eco.1856.

MABHAUDHI T., CHIMONYO VGP. MODI AT. 2017. Status of Underutilised Crops in South Africa: Opportunities for Developing Research Capacity. Sustainability. 9, 1569; doi:10.3390/su9091569.

MAPETO T, GUSH MB, LOUW JS (2017): Single-tree water use and water-use efficiencies of selected indigenous and introduced species in the Southern Cape region of South Africa. Southern Forests, DOI: 10.2989/20702620.2016.1274861.

MAROYI A (2013). Traditional use of medicinal plants in South-central Zimbabwe: review and perspectives. Journal of Ethnobiology and Ethnomedicine. **9(31)**:1-18.

MASUPA T (2012). *Lannea discolor*. South African National Biodiversity Institute. Available at: http://www.pza.sanbi.org/lannea-discolor.

MARSHALL, M., TU, K., FUNK, C., MICHAELSEN, J., WILLIAMS, P., WILLIAMS, C., ARDO, J., BOUCHER, M., CAPPELLAERE, B., DE GRANDCOURT, A., NICKLESS, A., NOUVELLON, Y., SCHOLES, R., AND KUTSCH, W. 2013. Improving operational land surface model canopy evapotranspiration in Africa using a direct remote sensing approach. Hydrol. Earth Syst. Sci. 17, 1079-1091.

MATERECHERA, S.A., SWANEPOL, H.R., 2011. Integrating the indigenous Kei apple (Dovyalis Caffra) into a local permaculture vegetable home eco-gardening system among resource-poor households in a semi-arid environment of South Africa, in: II International Symposium on Underutilized Plant Species: Crops for the Future-Beyond Food Security 979. pp. 225–232.

MAVUNDZA EJ., MAHARAJ R, FINNIE JF, KABERA G and VAN STADEN J, (2011). An ethnobotanical survey of mosquito repellent plants in uMkhanyakude district, KwaZulu-Natal province, South Africa. *Journal of Ethnopharmacology*. **137**:1516-1520.

MAYNARD M, GUNNELL D, EMMETT P, ET AL. 2003. Fruit, vegetables, and antioxidants in childhood and risk of adult cancer: the Boyd Orr cohort. Journal of Epidemiology & Community Health 2003;57:218–25.http://dx.doi.org/10.1136/jech.57.3.218

MAZIBUKO N (2007). *Ziziphus mucronata*. South African National Biodiversity Institute. Available at: http://www.pza.sanbi.org/ziziphus-mucronata.

MBUKWA E, CHACHA M, MAJINDA RRT (2007). Phytochemical constituents of *Vangueria infausta*: their radical scavenging and antimicrobial activities. *ARKIVOC*. 104-112.

MOTLHANKA DM and MAKHABU SW (2011). Medicinal and edible wild plants of Botswana as emerging new crop opportunities. *Journal of Medicinal Plants Research*. 5(10):1836-1842.

MOTLHANKA DMT, MOTLHANKA P, AND SELEBATSO T (2008). Edible indigenous wild fruit plants of Eastern Botswana. International Journal of Poultry. **7(5)**: 457-460.

MQADI L. (2005). Production function analysis of the sensitivity of maize production to climate change in South Africa. MSc thesis, University of Pretoria.

MU, Q., ZHAO, M., AND RUNNING, S.W. 2011. Improvement to a MODIS global terrestrial evapotranspiration algorithm. Remote Sens. Environ. 115, 1781-1800.

MU, Q., HEINSCH, A.F., ZHAO, M., AND RUNNING, S.W. 2007. Development of a global evapotranspiration algorithm based on MODIS and global meteorology data. Remote Sens. Environ. 111, 519-536.

MU, Q., 2013., MODIS 1-km^2 terrestrial evapotranspiration (ET) product for the Nile Basin algorithm theoretical basis document. Numerical Terradynamic Simulation Group College of Forestry and Conservation The University of Montana, pg 1-21.

MUCINA, L., RUTHERFORD, M.C., 2006. The vegetation of South Africa, Lesotho and Swaziland. Strelizia 19. SANBI, Pretoria, pp 525-527.

MUNCH, Z., CONRAD, J.E., GIBSON, L.A., PALMER, A.R., AND HUGHES, D. 2013. Satellite earth observation as a tool to conceptual hydrological fluxes in the Sandveld, South Africa. Hydrology J. 21, 1053-1070.

MUTSHINYALO M and TSHISEVHE J (2003). *Sclerocarya birrea*. Available at: http://pza.sanbi.org/sclerocarya-birrea

NAIDOO A (2010). *Bridelia mucronata*. South African National Biodiversity Institute. Available at: http://www.pza.sanbi.org/bridelia-mucronata.

NASH, J.E., SUTCLIFFE, J. V, 1970. River flow forecasting through conceptual models part I—A discussion of principles. J. Hydrol. 10, 282–290.

NCIKI S, VUUREN S. VAN EYK A and DE WET H. (2016). Plants used to treat skin diseases in northern Maputaland, South Africa: antimicrobial activity and in vitro permeability studies. Pharmaceutical Biology. 54(11):2420-2436.

NDOU P (2003). *Dovyalis caffra*. South African National Biodiversity Institute. Available at: http://www.pza.ssanbi.org/dovyalis-caffra.

NERD A., MIZRAHI Y. 2000. Introduction of Marula, an unexploited fruit tree from Southern Africa to the Israel Negev. Israel Journal of plant Sciences. 48 (3) 217-222

NISHIDA, K., NEMANI, R., GLASSY, J.M., AND RUNNING, S.W. 2003. Development of an evapotranspiration index from Aqua/MODIS for monitoring surface moisture status. IEEE Transactions on Geoscience and remote sensing, 41 (2).

NKOSI NN, MOSTERT THC., DZIKITI S., NTULI R. 2020. Prioritization of indigenous fruit tree species with domestication and commercialization potential in KwaZulu-Natal, South Africa. Genet. Resour. Crop Evol. https://doi.org/10.1007/s10722-020-00932-5.

NOTTEN A (2004). *Rhoicissus tomentosa*. South African National Biodiversity Institute. Available at: http://www.pza.sanbi.org/rhoicissus-tomentosa.

NTSHIDI, Z., DZIKITI, S., MAZVIMAVI, D., MOBE, N.T., MKUNYANA, Y.P., 2021. Water use of selected cover crop species commonly grown in South African fruit orchards and their response to drought stress. Phys. Chem. Earth, Parts A/B/C 103070.

NTSHIDI, Z., DZIKITI, S., MAZVIMAVI, D., 2018. Water use dynamics of young and mature apple trees planted in South African orchards: A case study of the Golden Delicious and Cripps' Pink cultivars, in: Proceedings of the International Association of Hydrological Sciences. https://doi.org/10.5194/piahs-378-79-2018

OLBRICH B, OLBRICH K, DYE P, SOKO S (1996) A year-long comparison of water use efficiency of stressed and non-stressed E. grandis and P. patula: findings and management recommendations. Un-published CSIR Report FOR-DEA 958, CSIR, Pretoria.

PADULOSI S., HEYWOOD V., HUNTER D., JARVIS A. 2011. Underutilized Species and Climate Change: Current Status and Outlook. Book chapter in *Crop Adaptation to Climate Change*, First Edition. Edited by Shyam S. Yadav, Robert J. Redden, Jerry L. Hatfield, Hermann Lotze-Campen and Anthony E. Hall. John Wiley & Sons, Ltd. Published by Blackwell Publishing Ltd.

RAMPEDI TI (2010). Indigenous plants in the Limpopo Province: potential for their commercial beverage production. PhD thesis, University of South Africa.

RANKOANA SA (2016) Sustainable Use and Management of Indigenous Plant Resources: A Case of Mantheding Community in Limpopo Province, South Africa. Sustainability. 8, 221; doi:10.3390/su8030221

REINDERS FB (2013) Irrigation methods for efficient water application: 40 years of South African research excellence. Water SA, 37 (5), 765-770.

ROSE D, BOURNE L, BRADSHAW D. 2002. Food and nutrient availability in South African households. Development of a nationally representative database. Cape Town: South African Medical Research Council, Health and Development Research Group and the Burden of Disease Unit; 2002.

RUHOFF, A.L., PAZ, A.R., ARAGAO, L.E.O.C., MU, Q., MALHI, Y., COLLISCHONN, W., ROCHA, H.R., AND RUNNING, S.W. 2014. Assessment of the MODIS global evapotranspiration algorithm using eddy covariance measurements and hydrological modelling in the Rio Grande basin. Hydrol. Sci. Journ. 58. http://dx.doi.org/10.1080/02626667.2013.837578.

SHACKLETON CM, BOTHA J, EMANUEL PL (2003) Productivity and abundance of *Sclerocarya birrea* subsp. *caffra* in and around rural settlements and protected areas of the Bushbuckridge Lowveld, South Africa. Forests, Trees and Livelihoods, 13: 217-232.

SHACKLETON CM, BOTHA J, EMANUEL PL, NDLOVU S (2002) Inventory of Marula (*Sclerocarya birrea* subsp. *caffra*) stocks and fruit yields in communal and protected areas of the Bushbuckridge Lowveld, Limpopo Province, South Africa Forestry Research Programme, Department for International Development, Report number: Project no. ZF0140/R7795.

SHACKLETON CM, DZEREFOS CM, SHACKLETON SE, MATHABELA FR (2000) The use of and trade in indigenous edible fruits in the Bushbuckridge savanna region, South Africa. . Ecology of Food and Nutrition, 39, 225-245.

SHACKLETON CM, SHACKLETON SE (2000) Direct use values of savanna resources: a case study of the Bushbuckridge Lowveld, South Africa, Journal of Tropical Forest Products, 6: 21-40.

SHACKLETON CM, SHACKLETON SE (2006) Household wealth status and natural resource use in the Kat River valley, South Africa. Ecological Economics, 57, 306-317.

SHACKLETON CM, SHACKLETON SE, BUITEN E, BIRD N (2007) The importance of dry woodlands and forests in rural livelihoods and poverty alleviation in South Africa. Forest Policy and Economics 9 (5): 558-577. DOI: 10.1016/j.forpol.2006.03.004.

STEDUTO P., HSIAO TC., FERERES E., RAES D. 2012. Crop yield response to water. FAO Irrigation and Drainage Paper 66, Rome.

STEWART, J.B., 1988. Modelling surface conductance of pine forest. Agric. For. Meteorol. 43, 19–35.

STEYN NP, NEL JH, CASEY A. 2003. Secondary data analyses of dietary surveys undertaken in South Africa to determine usual food consumption of the population. Pub Health Nutr. 2003;6(7):631–44.

SUN, Z., WANG, Q., OUYANG, Z., WATANABE, M., MATSUSHITA, B., AND FUKUSHIMA, T., 2007. Evaluation of MOD16 algorithm using MODIS and ground observational data in winter wheat field in North China Plain. Hydrol. Process. 21, 1196-1206.

SWANSON, R.H., WHITFIELD, D.W.A., 1981. A numerical analysis of heat pulse velocity theory and practice. J. Exp. Bot. 32, 221–239.

TAIZ, L., ZEIGER, E., MØLLER, I.M., MURPHY, A., 2015. Plant physiology and development. Sinauer Associates Incorporated.

TANG, R., SHAO, K., LI, Z., WU, H., TANG, B. 2015. Multiscale Validation of the 8-day MOD16 Evapotranspiration Product Using Flux Data Collected in China. IEEE Journal of selected topics in Applied Earth Observations and Remote Sensing, Vol. 8, no. 4, April 2015

TAYLOR S. 2008. The commercialisation of indigenous plant species in arid areas. Arid Areas Programme report. Centre for Development Support, University of the Free State, Republic of South Africa.

TAYLOR NJ and GUSH MB. 2014. The water use of selected fruit tree orchards (Volume 1): Review of available knowledge. Water Research Commission, Pretoria, RSA, WRC Report 1770/1/14.

TAYLOR NJ, IBRAIMO NA, ANNANDALE JG, EVERSON CS, VAHRMEIJER JT, GUSH MB (2013) Are sap flow measurements useful for determining water use of fruit orchards, when absolute values are important? Acta Hort. 991: 77-83.

TAYLOR, N.J., MAHOHOMA, W., VAHRMEIJER, J.T., GUSH, M.B., ALLEN, R.G., ANNANDALE, J.G., 2015. Crop coefficient approaches based on fixed estimates of leaf resistance are not appropriate for estimating water use of citrus. Irrig. Sci. 33, 153–166.

TENHUNEN, J.D., LANGE, O.L., PEREIRA, J.S., LÖSCH, R., CATARINO, F., 1981. Midday stomatal closure in Arbutus unedo leaves: measurements with a steady-state porometer in the Portuguese evergreen scrub, in: Components of Productivity of Mediterranean-Climate Regions Basic and Applied Aspects. Springer, pp. 61–69.

TURNER, N.C., SCHULZE, E.D., AND GOLLAN, T., 1984. The responses of stomata and leaf gas exchange to vapour pressure deficits and soil water content 1: Species comparison at high soil water contents. Oecologia. 63, 338-342.

VON BREITENBACH F (1990) National list of indigenous trees. Dendrological Foundation, Pretoria.

WHO (2004). Comparative quantification of health risks. Geneva: World Health Organisation

WILSON M (1982) The re-establishment of yellowwood forest. Veld and Flora, 68: 111-112.

WILSON AL., DOWNS CT. 2012. Fruit nutritional composition and non-nutritive traits of indigenous South African tree species. South African Journal of Botany 78: 30–36.

WISE RM, DYE PJ, GUSH MB (2011) A comparison of the bio-physical and economic water-use efficiencies of indigenous and introduced forests in South Africa. Forest Ecology and Management, 262: 906-915.

WULLSCHLEGER, S.D., KING, A.W., 2000. Radial variation in sap velocity as a function of stem diameter and sapwood thickness in yellow-poplar trees. Tree Physiol. 20, 511–518. WYNBERG R., CRIBBINS J., LEAKEY R., LOMBARD C., MANDER M., SHACKLETON S., SULLIVAN C. 2002. Knowledge on Sclerocarya birrea subsp. caffra with emphasis on its importance as a non-timber forest product in South and southern Africa: A Summary. Southern African Forestry Journal: 196, 67-78.

YAO, Y., LIANG, S., LI, X., CHEN, J., WANG, K., JIA, K; ROUPSARD, O. (2015). A satellite-based hybrid algorithm to determine the Priestley-Taylor parameter for global terrestrial latent heat flux estimation across multiple biomes. *Remote Sensing of Environment*, *165*, 216-233. DOI: 10.1016/j.rse.2015.05.013

YORK T, DE Wet H. and VAN VUUREN SF, (2011). Plants used for treating respiratory infections in rural Maputaland, KwaZulu-Natal, South Africa. *Journal of Ethnopharmacology*. **135**:696-710.

YUAN, W., LIU, S., YU, G., BONNEFOND, J., CHEN, J., DAVIS, K., DESAI, A., GOLDSTEIN, A.H., GIANELLE, D., ROSSI, F., SUYKER, A.E., AND VERMA, S. 2010. Global estimates of evapotranspiration and gross primary production based on MODIS and global meteorology data. Remote Sens. Environ. 114, 1416-1431.

ZHANG, Y.Q., CHIEW, F.H.S., ZHANG, L., LEUNING, R., AND CLEUGH, H.A. 2008. Estimating catchment evaporation and runoff using MODIS leaf area index and the Penman-Monteith equation. Water Resour. Res. 44, W10420, doi:10.1029/2007WR006563.

ZHANG, Y., LEUNING, R., HUTLEY, L., BERINGER, J., MCHUGH, I., AND WALKER, J.P. 2010. Using long-term water balances to parameterize surface conductances and calculate evaporation at 0.05° spatial resolution. Water Resour. Res. 46, 1-14.

ZHANG, H., SIMMONDS, L.P., MORISON, J.I.L., AND PAYNE, D., 1997. Estimation of transpiration by single trees: comparison of sap flow measurements with a combination equation. Agric. For. Meteorol. 87, 155 – 169.

ZWEIFEL, R., BÖHM, J.P., HÄSLER, R., 2002. Midday stomatal closure in Norway spruce—reactions in the upper and lower crown. Tree Physiol. 22, 1125–1136.

CAPACITY BUILDING

STAFF DEVELOPMENT

Both institutional and individual capacity building were done. Institutional capacity was done through training of staff in the Department of Botany at the University of Zululand. The following people were trained: Dr Nontuthuko Ntuli (lecturer), Mr Prince Sokhela, and Ms Zoliswa Mbhele, who are technicians. Training covered included basic data logging principles, uploading and downloading routines for data and programmes, setting up automatic weather stations, installing and troubleshooting heat pulse velocity sap flow systems.

COMMUNITY DEVELOPMENT

The stakeholder engagement that was held at the beginning of the project also involved members of the community who learnt more about the value of the indigenous fruit trees and shared their own knowledge.

INSTITUTIONAL DEVELOPMENT

University of Zululand staff were trained in this project as detailed under the stuff development section. Students on course for graduation – four MSc students were trained on the project. One has completed her study, while the other three are expected to graduate by the end of 2022.

KNOWLEDGE DISSEMINATION & TECHNOLOGY TRANSFER

SCIENTIFIC ARTICLES

Nkosi NN, Mostert T., Dzikiti S., Ntuli NR. (2020). Prioritization of indigenous fruit tree species with domestication and commercialization potential in KwaZulu-Natal, South Africa, Genetic Resources and Crop Evolution Journal.

Dzikiti S., Ntuli NR., Nkosi NN, Ntshidi Z et al. (2022). Water use dynamics of two co-occurring indigenous fruit tree species growing on deep sandy soils in northern Zululand, South Africa. South African Journal of Botany.

Ntshidi Z., Dzikiti S., Mobe NT. (2022). Water use efficiency of indigenous fruit trees in South Africa. Conference paper 6th International Congress on Water, Waste and Energy Management, Rome, Italy.

POPULAR ARTICLES

No popular articles have been published on this work.

SELECTED PRESENTATIONS

Four conference presentations were delivered by students and researchers, and these are summarised as follows:

Dzikiti S, Ntuli R, Nkosi NN et al. 2019. Water use of indigenous fruit tree crops: A case study for Marula and Strychnos in Northern Zululand.

This was an oral presentation made at the 22nd Indigenous Plant Use Forum Conference at Tshipise, a Forever Resort, in Limpopo from 08-12 July 2019.

Nkosi NN, Mostert T, Dzikiti S., Ntuli NR. 2020. Phenology and yield studies of Strychnos Spinosa in Northern Zululand.

This was an oral presentation made by a student on the project (Ms Noluthando Nkosi) at the South African Association of Botanists conference held from 6-10 January 2020 in Bloemfontein.

Dzikiti S., Ntuli R, Nkosi NN et al. 2020. Water productivity of selected indigenous fruit tree crops in South Africa.

This was an oral presentation made at the Combined Congress in Bloemfontein from 20-23 January 2020.

Ntshidi Z., Dzikiti S., Mobe NT. 2022. Water use efficiency of indigenous fruit trees in South Africa.

This was an oral presentation made at the 6th International Congress on Water, Waste and Energy Management, held in Rome, Italy from 20-22 July 2022.

TECHNOLOGY TRANSFER

There was no new technology created in this project, only modification of an already well-known model.

APPENDIX A

PHENOLOGICAL STAGES OF *S. BIRREA* OBSERVED FROM MAY 2018 TO FEBRUARY 2019 AT BONAMANZI GAME PARK

Growth stage	May				Jun				July				Aug				Sept				Oct				Nov				Dec				Jan				Feb			
Leaf fall and leafless period			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																								
Leaf flush																	🟩	🟩	🟩	🟩																				
Leaf development																		🟩	🟩	🟩	🟩	🟩	🟩																	
Flowering (Male trees)																					🟩	🟩																		
Flowering (Female trees)																							🟩	🟩																
Fruiting																									🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩								
Fruit maturation																																	🟩	🟩	🟩	🟩				
Fruit drop																																					🟩			

APPENDIX B

PHENOLOGICAL STAGES OF *S. SPINOSA* OBSERVED FROM MAY 2018 TO MAY 2019 AT BONAMANZI GAME PARK

Growth stage	May				Jun				July				Aug				Sept				Oct				Nov				Dec				Jan				Feb				Mar				April				May			
Leaf fall	🟩	🟩	🟩	🟩	🟩	🟩	🟩																																													
Dormancy								🟩	🟩	🟩																																										
Flowering											🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																																		
Leaf development												🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																																	
Fruiting																				🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩			
Fruit harvest																																																		🟩		

APPENDIX C

PHENOLOGICAL CALENDAR OF *VANGUERIA INFAUSTA*

Period	Months	Growth stages																										
		Leaf abscission			Dormancy			Leaf initiation			Leaf maturity			Flower formation			Flower Dropping			Fruit formation			Fruit maturity			Fruit ripening		
Season 1 (2020/2021)	August				🟨	🟨	🟨																					
	September				🟨					🟨						🟨												
	October							🟨	🟨	🟨				🟨	🟨	🟨			🟨									
	November							🟨	🟨				🟨				🟨	🟨		🟨	🟨	🟨						
	December										🟨	🟨	🟨							🟨	🟨	🟨						
	January										🟨	🟨	🟨										🟨	🟨	🟨			
	February										🟨	🟨	🟨													🟨	🟨	🟨
	March		🟨	🟨							🟨	🟨	🟨															
	April	🟨	🟨	🟨																								
	May	🟨	🟨	🟨																								
	June				🟨	🟨	🟨																					
	July				🟨	🟨	🟨																					

APPENDIX D

PHENOLOGICAL CALENDAR OF *DOVYALIS CAFFRA*

Period	Months	Growth stages																										
		Leaf abscission			Dormancy			Leaf initiation			Leaf maturity			Flower formation			Flower Dropping			Fruit formation			Fruit maturity			Fruit ripening		
Season 1 (2020/2021)	August			🟪				🟪	🟪	🟪						🟪												
	September	🟪	🟪					🟪	🟪	🟪				🟪	🟪	🟪			🟪			🟪						
	October							🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟪	🟪						
	November							🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟪	🟪			🟪			
	December							🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟪	🟪			🟪
	January							🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥				🟪	🟪	🟪
	February							🟪	🟪	🟪																		
	March							🟪	🟪	🟪																		
	April										🟪	🟪	🟪															
	May										🟪	🟪	🟪															
	June										🟪	🟪	🟪															
	July										🟪	🟪	🟪															