DETERMINING CROP COEFFICIENTS FOR IRRIGATED FRUIT TREE CROPS USING READILY AVAILABLE DATA SOURCES

A thesis submitted to the University of the Western Cape in the fulfilment of the degree of Master of Science

by

MUNASHE MASHABATU

Department of Earth Sciences

Faculty of Natural Sciences

Supervisor:

Prof. Timothy Dube

Co-supervisor:

Prof. Nebojsa Jovanovic

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ABSTRACT

The climate variability and climate change-induced events experienced worldwide have caused a significant decrease in the rainfall volume. South Africa is considered to be one of the driest countries in the world, as it receives an average annual rainfall that is lower than the global annual average. To sustain and grow the agricultural sector, South Africa supplements the low rainfall with its freshwater resources, for irrigation purposes. This action is necessary, especially for meeting the high water requirements of the South African fruit industry, as it is one of the major exporters of fruit in the world. Research has been conducted in an attempt to accurately quantify the water requirements of various fruits, which will assist farmers to save water, to increase their productivity and to managing their irrigation water. However, a knowledge of the water use, actual water consumption rates and the factors that drive them, is minimal and inadequate, and this has had a detrimental effect on the effective management of irrigation water and water allocation by the responsible stakeholders. Therefore, the general aim of this study is to evaluate and improve the method of estimating crop coefficients for selected irrigated fruit species grown across South Africa. In order to achieve this aim, this study: (i) conducted a knowledge review of many methodologies that are used to quantify the water requirements of crops, (ii) it synthesised and compared the consumptive water use rates of selected fruit species, while discussing their implications for the management of irrigation water, and (iii) it adjusted and applied the Allen and Pereira (A&P) coefficient approach on selected fruit species. The study was divided into two sections. In the first section, the annual and monthly averages of measured crop transpiration (T_c) and evapotranspiration (ET_c) data of 'Golden Delicious' apples, 'Midknight Valencia' citrus, 'Alpine' nectarines, 'Transvalia' peaches, 'Beaumont' macadamia nuts, 'Choctaw' pecan nuts and 'Hass' avocadoes, grown in their respective orchards, were analysed and compared. In addition, the crop coefficients that were calculated by using the widely-used Food Agriculture Organisation 56th Document coefficient approach were compared, in order to demonstrate their use in the quantification of the various consumptive water-use rates. Pecans had the highest annual crop transpiration (T_c) totals (888 mm) and monthly average T_c volumes, while peach trees recorded the lowest T_c volumes. On the contrary, apples had the highest recorded annual crop evapotranspiration (ET_c) totals (1086 mm), whereas avocadoes recorded comparable annual ET_c volumes (1063 mm). However, nectarines had the highest average daily ET_c rates that ranged between 4.6 mm/d – 7.5 mm/d. Although differences in their plant physiology and the atmospheric evaporative demand contributed to the differences in their consumptive water-use rates, their canopy size and management were the overriding factors. Pecan trees had the highest Leaf Area Index (LAI) averages and significantly denser canopies, while peach trees had the lowest LAI averages. The high atmospheric evaporative demand across the seasons influenced the full crop coefficient (K_c) values of pecans and apples, although minute differences were observed in the K_c values of the two species. More precise crop water consumption rates could potentially be established if more studies were to be conducted under water-stressed conditions. These findings could then be compared to those from studies conducted in well-watered orchards. In the second section of this study, the A&P method was improved by adjusting the stomatal sensitivity function (Fr), using three methods in the literature. These methods included replacing the ratio of resistances ($r_l/100$) with (i) another ratio of resistance ($r_s/50$), (ii) r_l/α where α is a resistance parameter for the specific crop, and using a varying mean leaf resistance value that was measured or estimated throughout the season. The improved model was then used to derive the basal crop coefficients (K_{cb}) of the selected fruit species. Ideally, the improved K_{cb} values are used to derive orchard full crop coefficients (K_c) by considering the contribution of the cover crops, but this study did not derive the K_c, because there was insufficient measured ET_c data to test the model's performance. Overall, the model produced satisfactory results, where the derived K_{cb} was significantly comparable with the following measured values of the respective statistical analysis results: (i) macadamia nuts (R^2 =0.94, RMSE = 0.01, Mean of measured data = 0.44), (ii) nectarines (R^2 = 0.78, RMSE = 0.02, Mean of measured data = 0.37), (iii) peaches (R^2 = 0.80, RMSE = 0.01, Mean of measured data = 0.31), (iv) pecans (R^2 = 0.89, RMSE = 0.01, Mean of measured data = 0.22) and (v) citrus (R^2 = 0.87, RMSE = 0.03, Mean of measured data = 1.19). Moreover, the mean error showed that the A&P approach generally underestimated K_{cb} values of macadamia nuts, nectarines and peaches, while it overestimated those of pecans and citrus fruits. The study argued that the derived K_{cb} values were more of a better representation of the pecan trees than the actual measured values. However, a more detailed analysis, using the estimation of the crop transpiration (T_c), which was calculated as the product of the K_{cb} and the reference evapotranspiration (ET_o), showed that there were inconsistencies with the model when estimating the T_c during the post-harvest period. Therefore, by using the fruit tree-specific data with the A&P approach, it is possible to accurately determine the crop coefficients and to estimate the consumptive water use of the fruit orchards.

KEYWORDS

- Agriculture
- Consumptive water use
- Evapotranspiration
- Irrigation
- Canopy cover
- Leaf resistance

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

A&P	Allen and Pereira (2009) approach
EGVV	Elgin/Grabouw/Vyeboom/Villiersdorp
ET	Evapotranspiration
FAO-56	Food and Agriculture Organization, Paper No. 56
FBGD	Full-bearing Golden Delicious
FBCP	Full-bearing Cripps' Pink
HPV	Heat Pulse Velocity
HRM	Heat Ratio Method
LAI	Leaf Area Index
MAE	Mean Absolute Error
ME	Mean Error
REW	Readily Evaporable Water
RMSE	Root Mean Square Error
SFD	Sap Flux Density
T	Transpiration
TEW	Total Evaporable Water

Symbols

Cl	Percentage fraction of clay in soil (%)
E_s	Soil evaporation (mm d^{-1})
e_s	Saturation vapour pressure (kPa)
e_a	Actual vapour pressure (kPa)
E_{so}	Potential rate of evaporation from a wet soil surface (mm d^{-1})
ET_c	Actual crop evapotranspiration (mm d^{-1})
f_{PAR}	Fraction of the photosynthetically-active radiation absorbed by canopy (-)

f_c	Fraction of the ground surface covered by vegetation at midday (-)
f_{ceff}	Effective vegetation cover (-)
Fr	Stomatal sensitivity adjustment factor (-)
f_w	Fraction of the orchard floor wetted by irrigation or rain (-)
G	Soil heat flux (W m^{-2})
h	Tree height (m)
K_c	Crop coefficient (-)
K_{cfull}	Crop coefficient from a fully covered soil (-)
K_{cb}	Basal crop coefficient (-)
$K_{cbcover}$	Basal crop coefficient due to the cover crop (-)
K_{cbfull}	Basal crop coefficient of a mature well-watered orchard (-)
$K_{cbfullc}$	Maximum cover crop basal crop coefficient (-)
K_{cmin}	Minimum basal coefficient for bare soil (-)
K_{cmax}	Maximum crop coefficient for the surface under full vegetation (-)
K_d	Density coefficient (-)
K_{dc}	Density coefficient for the cover crops (-)
K_{edry}	Evaporation coefficient from dry portion of the soil (-)
K_{ewet}	Evaporation coefficient from wet portions of the soil (-)
K_{soil}	Average soil evaporation coefficient (-)
K_t	Transpiration coefficient (-)
M_L	Empirical parameter imposing an upper limit on transpiration (-)
RH_{min}	Minimum relative humidity (%)
r_l	Mean leaf resistance (s m^{-1})
R_n	Net radiation on a horizontal surface (Wm^{-2})

R_{ns}	Net radiation absorbed by the soil surface (Wm^{-2})
Sa	Percentage fraction of sand in soil (%)
SAI	Sapwood area index (m^2m^{-2})
SFi	Sap flow rate ($cm^3\ h^{-1}$)
SWC	Volumetric soil water content (cm^3cm^{-3})
T_c	Cover crop transpiration ($mm\ d^{-1}$)
T_a	Air temperature (°C)
T_{min}	Minimum air temperature (°C)
T_{max}	Maximum air temperature (°C)
t_w	Average time between independent wetting events (days)
U_2	Mean wind speed at 2 m height (ms^{-1})
VPD	Vapour pressure deficit of the air (kPa)
Ze	Effective depth of soil evaporation (m)
Zr	Effective rooting depth (m)

DECLARATION

I, Munashe Mashabatu, declare that this full dissertation, entitled '**Determining crop coefficients for irrigated fruit tree crops using readily-available data sources"**, is my work, that it has not been submitted before for any degree or examination at any other university and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Full Name: Munashe Mashabatu 17 May 2022

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DEDICATION

This thesis is dedicated to my lovely mother, Gertrude Chinodyamari Mashabatu, and my young sister, Rumbidzai Mashabatu. ***Ndinokudai mese.***

PUBLICATION

Two scientific papers were extracted from this thesis and were submitted to the Agriculture and Water Journal for publication as:

Munashe Mashabatu, Timothy Dube, Nebojsa Jovanovic, Sebinasi Dzikiti. A synthesis of the consumptive water use data of selected fruit trees collected across South Africa: Implications to irrigation management. (AGWAT-S-22-00440)

Munashe Mashabatu, Timothy Dube, Nebojsa Jovanovic, Sebinasi Dzikiti, Zanele Ntshidi. Improvement of the Allen and Pereira (2009) approach in calculating crop coefficients of selected irrigated fruit tree types using readily available data. (AGWAT-S-22-00346)

CHAPTER ONE: GENERAL INTRODUCTION

1.1 Introduction

Recent climate change-induced events have resulted in a significant decrease in the rainfall received in Africa (Hendrix & Salehyan, 2012). South Africa is ranked among the driest countries in the world, and has an average rainfall volume of 495 mm lower than the global average volume of 840 mm (Annandale et al., 2011). Dzikiti et al. (2020) reported that the agricultural sector uses 60% of the country's freshwater resources for irrigation purposes, in order to supplement its low rainfall. Irrigation activities are vital for sustaining and growing the agricultural sector, for ensuring economic growth, for food security and for restraining hunger, poverty, and unemployment changes. However, climate change and variability can cause extreme events, such as droughts, which negatively affect agriculture. There is therefore a need to create a strategy that mitigates these effects and that creates a resilient framework for farmers. Due to the water scarcity crisis in South Africa, this strategy should motivate the efficient usage of water, in order to sustain and grow the agricultural sector in the country.

Given that 98% of the country's water resources in various catchments have already been allocated (Goldblatt, 2011), there is a need to derive the irrigation water volumes from these current allocations, in order to support and improve the efficiency of agriculture. According to Dzikiti et al. (2020), approximately 45% of irrigation water is lost or wasted through various activities, including poor irrigation scheduling, pipe leakages, non-beneficial water use, etc. Therefore, there is a need to develop tools and make them available to the farmers and water managers, in order to improve their management of the available water resources (Annandale et al., 2011).

Fruit and nuts are high-value and high-water-requiring crops that are grown across South Africa. They are the country's third-most irrigated crop group and account for about 17% of the total irrigated crop groups (Dzikiti et al., 2020); therefore, they require a sufficient supply of irrigation water volumes in various catchments . Irrigated agriculture, including in the fruit industry, has an aim of applying less, but sufficient, irrigation water to meet the water requirements of crops, without necessarily decreasing their quality, yield and profits (Jovanovic et al., 2020). Past studies have quantified the consumptive water use of various fruit tree crops grown across South Africa e.g. apples (Dzikiti et al., 2018; Mobe et al., 2020), macadamia nuts

(Gush & Taylor, 2014a; Taylor, 2021), avocadoes (Taylor, 2021), citrus (Gush & Taylor, 2014a; Taylor et al., 2015), pecan nuts, peaches and nectarines (Gush & Taylor, 2014a) and wine grapes (Lategan & Howell, 2016), etc.

Various methodologies and techniques with elemental principles, accuracies, temporal and spatial scales of application, and potential problems have been used to collect and quantify the consumptive water use data. These methodologies and techniques include the following: (i) lysimeters, (ii) the soil water balance, (iii) the Bowen Ratio, (iv) eddy covariance measurements, (iv) the FAO-56 coefficient approach, and (iv) remote sensing applications etc. The FAO-56 coefficient method is a long established approach that uses climate data to determine crop coefficients (Allen et al., 1999). In this method, crop evapotranspiration (ET_c), is quantified as a product of the crop coefficient (K_c) and the reference evapotranspiration (ET_o). According to Allen et al. 1999, the ET_o is calculated from the weather data by using the adjusted Penman-Monteith equation. Past studies have used this method to quantify the consumptive water use of fruit tree crops, and they have compared the derived values with the actual measured values. Arguably, all the results have demonstrated the need to adjust these derived coefficients according to specific growing conditions (Allen and Pereira, 2009). The accurate crop coefficients obtained from this adjustment will improve the accuracy of water management in the country and guide farmers to make sound irrigation decisions.

To improve the FAO-56 coefficient approach, Allen & Pereira (2009) adjusted K_c by introducing a function of the crop height and ground cover. Allen and Pereira (2009) reported that the fractional vegetation cover, the crop height and stomatal regulation under wet conditions could be used to determine the crop coefficients. However, where this approach has been used on some irrigated orchards in the past, cases of K_{cb} overestimation have been reported for citrus (Taylor et al., 2015) and apples (Mobe et al., 2020). These studies validated the method accordingly, but it was only sufficient and relative to their respective objectives and did not necessarily make the derived K_c transferable to different environments.

1.2 Problem Statement

South Africa's water resources have been increasingly stressed by the competition between various users, the rapidly-growing population and the extreme events that are facilitated by climate change and variability. In addition, the country is one of the primary and critical exporters of a wide range of fruit species on the global market. Thus, there is a call to sustain and grow the fruit industry by improving the water use efficiency, water-saving technologies, productivity and efficient irrigation management. Research has been conducted in the country to establish the water requirements of many fruit tree crops. However, this information needs to be consolidated and used to develop tools for enhancing the on-farm water use efficiency. Most of the fruit trees grown in various orchards across the country are under extensive irrigation, to supplement the low rainfall volumes received throughout the growing season. Improving irrigation scheduling and the minimisation of water losses through leakages and non-beneficial water use, requires the derivation of accurate crop coefficients. These crop coefficients will be used to quantify crop water requirements of the selected crops. The FAO has developed guidelines for estimating crop water requirements (Allen et al., 1999) and tabulated the derived crop coefficients for most crops under standard conditions. However, the tabulated crop coefficients need to be adjusted, considering the specific growing conditions of crops, so that they are transferable between sites. In a bid to make these adjustments, past studies have used the Allen and Pereira (2009) approach which uses the crop density function to determine crop coefficients. Nevertheless, this method needs to be validated, in order to make the derived crop coefficients transferable between fields that have different soil and climate characteristics, etc. The validated Allen and Pereira (2009) method can also be used as a gap-filling tool of the identified water requirements data.

1.3 Research Questions

1. To what extent does the Allen and Pereira (2009) crop coefficient approach work for different fruit tree species?
2. What adjustments can be made to the Allen and Pereira (2009) approach to accurately derive crop coefficients for specific fruit species?
3. How can the derived crop coefficients be transferred across different fields?

1.4 General Aim

This study aims to evaluate and improve a method for deriving the crop coefficients of selected irrigated fruit tree crops grown in South Africa using information that fruit growers can easily access to improve their water resources management at a farm level.

1.5 Specific Objectives

The specific objectives are:

1. to conduct a knowledge review of various methodologies that are used to estimate crop water requirements,
2. to synthesise the consumptive water use data of fruit trees collected across South Africa, and the implications for irrigation management, and
3. to run the Allen and Pereira (2009) crop coefficient method, as published, to determine the crop coefficients for selected fruit species and to improve them, where necessary.

1.6 Research Hypotheses

1. Fruit species have different consumptive water use rates; thus, they have different crop coefficients.
2. The Allen and Pereira (2009) method needs to be validated individually per respective fruit species, in order to accurately determine their crop coefficients.
3. An improved Allen and Pereira (2009) method can be used as a gap-filling tool for the crop water requirements.

1.7 Approach

In response to the above objectives and hypotheses, the approach used in this study included identifying and selecting a wide range of fruit tree crops that are successfully grown in irrigated orchards across South Africa. The next phase included a detailed knowledge review of the available methodologies for estimating their crop water requirements in past studies. The review also identified the knowledge gaps associated with crop water requirements and discussed the state of knowledge on the crop coefficient approach. Thereafter, this study synthesised the consumptive water use data of selected fruit species grown across the country to compile all the known data collected from the respective orchards and to put the values into perspective. Finally, a comparison of the different consumptive water use rates was conducted among the selected fruit species, and their implications for irrigation water management were discussed. The following phase in the approach was quantitative, where crop coefficients were determined by using the readily-available data and then validated against the consumptive water use and weather data measurements. The validation was according to the FAO-56 guidelines (Allen et al., 1999), which were improved by Allen and Pereira (2009) and developed further by Taylor et al. (2015) and Mobe et al. (2020).

1.8 Description of Study Areas

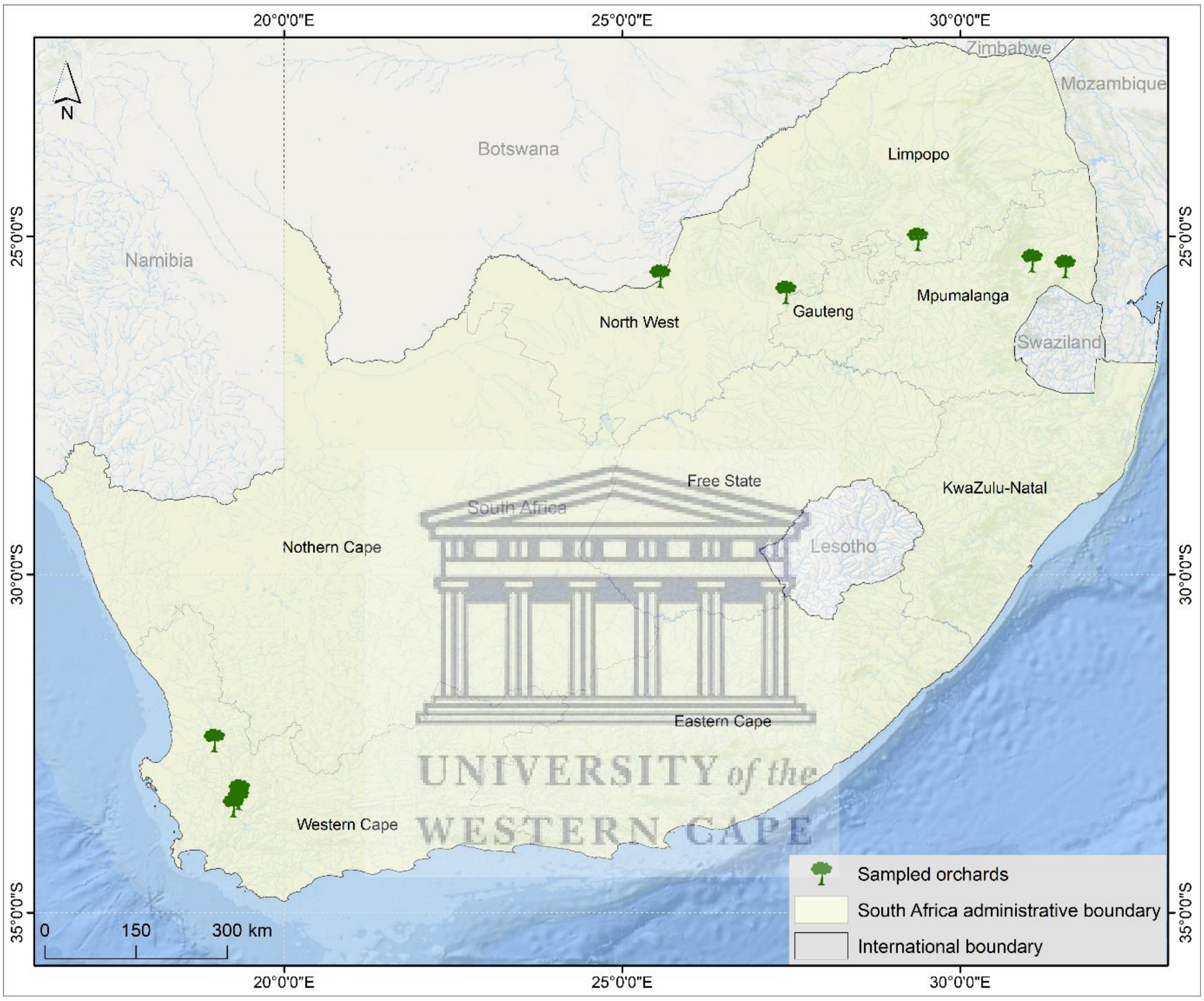

Figure 1.1 Location of sampled orchards for the selected fruit tree species across South Africa

South Africa has a tremendous diversity of fruit tree species that are grown in different geographical and climatic regions. The prioritization of the selected fruit tree species in this study was according to their geographical location, the state of knowledge on their respective consumptive water use rates, their economic importance, etc. The selection aimed at fruit trees that are grown in well-irrigated and unstressed orchards and subjected to efficient management practices. Based on background data collection and analysis, this study focused on the following species: (1) 'Beaumont' Macadamia nuts at White River and Nelspruit, both in the

Mpumalanga Province (2) ‘Hass’ avocadoes at Howick and Tzaneen, in the KwaZulu-Natal and the Limpopo Provinces, respectively, (3) Golden Delicious and Cripps’ Pink apples in the Koue Bokkeveld (KBV) and Elgin/Grabouw/Vyeboom/Villiersdop (EGVV) districts, all in the Western Cape Province (4) ‘Midknight’ Valencia and ‘Rustenburg’ Navel oranges at Malelane (Mpumalanga Province) and Citrusdal (Western Cape Province), respectively, (5) ‘Alpine’ nectarines at Wolseley, in the Western Cape Province, (6) ‘Transvalia’ peaches at Rustenburg, and (7) ‘Choctaw’ pecan nuts at Cullinan, in the Gauteng Province.

1.8.1 Macadamia nuts

The two sites used for the field data collection of macadamia nuts are located in Mpumalanga Province, South Africa. The first data-set was obtained from a ‘Beaumont’ macadamia (intergrifolia x tetraphylla hybrid) orchard located at White River (25° 21' 32.80" S, 31° 3' 34.44" E and approximately 765 meters above sea level). The area is characterised by summer rainfall, with a humid subtropical climate, average midday temperatures ranging from 20.9℃ (June) to 27.2℃ (January), and an average annual rainfall of 722 mm.

The second data-set for macadamia nuts was obtained from an orchard in a seasonally dry subtropical climate on the Schagen Valley commercial farm (25°21' 50.36" S, 30°46' 46.47"E, approximately 900 m.a.s.l), roughly 30 km from the town of Nelspruit. The area has an average annual precipitation of approximately 750 mm to 850 mm, with an annual average temperature of 23℃ (Schulze & Maharaj, 2004). The cultivar in this site was South Africa’s most predominantly-planted ‘Beaumont’ 695 (tetraphylla x integrifolia hybrid).

1.8.2 Avocadoes

The data collection for ‘Hass’ avocadoes was conducted in an orchard located in a cool, subtropical climate on the Everdon Estate, roughly 10 km from Howick (29°26’ 37’’S, 30°16’ 22’’E, 1080 m altitude), a town in the KwaZulu-Natal Province of South Africa. The area has a 17℃-20℃ mean annual temperature range, a 20℃-23℃ mean January temperature range and an annual precipitation of 860 mm. Additional water use measurements were obtained from the McNoon farm (23°43' 49.51"S, 30°8' 12.35"E) in Tzaneen in the Limpopo Province, which has a warm subtropical climate with a mean annual rainfall of 965 mm, a mean temperature of 20℃-21.5℃, and a mean January temperature of 23℃-25℃.

1.8.3 Apples

Water use information and field measurements of high-yielding apple trees were collected from orchards in two apple-growing regions in the Western Cape Province, namely, the Koue Bokkeveld (KBV) plateau region, for the 2014/15 season, and the Elgin/Grabouw/Vyeboom/Villiersdop (EGVV) region, for the 2015/16 season. While the KBV experiences very cold winters and generally hot summers, the EGVV region experiences milder winters and summers. The mean minimum daily temperatures and average maximum summer temperatures are between 8℃-9℃ and 25℃-26℃, respectively. The cultivars investigated in this site were high-yielding Golden Delicious and Cripps’ Pink/Red apples. Data for the 2014/15 season were collected from two full-bearing orchards at the Kromfontein farm with Golden Delicious (FBGD) and Cripps’ Pink (FBCP) trees.

1.8.4 Citrus

The water use data and field measurements of citrus fruits were obtained in two locations, namely, Citrusdal in the Western Cape Province, and Malelane, in the Mpumalanga Province. Both orchards were under drip irrigation. In Citrusdal, measurements were taken of the ‘Rustenburg’ Navel orange trees at the Patrysberg farm (32°27’ 15.43’’S and 18°58’ 3.58’’E, at 149 m.a.s.l). The area is characterized by winter rainfall and has an average annual rainfall of 200 mm and average minimum and maximum temperatures of 10℃ and 24℃. The Malelane experimental site, which was planted with ‘Midknight’ Valencia oranges, was on a Riverside commercial fruit and sugarcane farm (S25°26’ 39.77”, E31°33’ 02.39” and at 314 m.a.s.l) in the Mpumalanga Province.

1.8.5 Nectarines and peaches

‘Alpine’ nectarine data were collected from a commercial Ou Stasie farm near the town of Wolseley, in the Western Cape Province. The area is characterized by winter rainfall. Short-range micro-sprinklers were used for irrigation. In addition, the sap flow of ‘Alpine’ nectarines and ‘Transvalia’ peaches at Rustenburg (25°46.215’ S, 27º 20.305’ E, at 1150 meters above sea level) in the North-west Province was monitored. The area is characterized by summer rainfall; therefore, all trees in this orchard were drip irrigated.

1.8.6 Pecan nuts

The experimental orchard for ‘Choctaw’ pecans was located within the summer rainfall area of Cullinan town, in the Gauteng Province (25°35’ 20.65’’ S, 28°33’ 31.90’’ E, at 1340 meters above sea level). The study area has a subtropical climate that is characterised by long, hot summers and short cold winters, with an average annual rainfall of 673 mm (Schulze & Maharaj, 2004). The daily mean temperatures varied between 9.7℃ and 21.2℃.

1.9 Thesis Outline

Chapter One introduces the background of the study and outlines the problem statement. In addition, it describes the general aim and objectives of the study and gives a description of the study sites for the selected fruit tree species across South Africa. Lastly, the chapter provides an outline of the study.

Chapter Two identifies the irrigated fruit tree species grown across South Africa and their geographical distribution. It then highlights and discusses the irrigation scheduling methods and information on the crop water requirements of the fruit tree species. The chapter provides a critical knowledge review of the various methodologies that were used to estimate the crop water requirements and it identifies the knowledge gaps from the past studies. Recommendations are therefore made to conclude the chapter.

Chapter Three synthesises the consumptive water-use data of selected irrigated fruit tree species collected across South Africa. The field measurements of the consumptive water use of individual fruit trees are compared, and the values are put into perspective. Finally, this chapter discusses the implications of these different rates on the farmers' management of irrigation water and fruit species prioritisation.

Chapter Four applies the Allen and Pereira (2009) method, by using readily-available data to determine the crop coefficients of selected irrigated fruit tree species. In addition, the method was improved by adjusting it according to the fruit species’ different physiologies, and it was therefore used to derive accurate crop coefficients for all the selected fruit species.

Chapter Five discusses and summarises the primary findings of this study and therefore recommendations for future research.

CHAPTER TWO: LITERATURE REVIEW

2.1 Chapter Summary

Over the past few years, many studies have developed methodologies and technologies for estimating accurate crop water requirements, which are used to determine the precise crop coefficients (K_c) of irrigated orchards. Water-saving technologies and effective irrigation strategies should be implemented to reduce excess water use and to assess the water consumption in irrigated orchards, in response to the increasing water-scarcity levels. This review discusses how various approaches are used to estimate the crop coefficients, it identifies the respective knowledge gaps and makes related recommendations. For this purpose, the actual evapotranspiration (ET) is determined by using various techniques, such as lysimeters, the soil water balance, eddy covariance measurements and the Bowen ratio energy balance, as well as remote sensing applications. These techniques all have elemental principles, they are accurate, they have time and space scales, potential problems, as well as land suitability qualities. Published literature that is based on quantified investigations identifies the FAO-56 K_c approach as an efficient and trustworthy means for estimating ET_c and crop coefficients under well-watered conditions. Although the method remains the primary reference for crop water requirements, there is a need to adjust the tabulated FAO-56 crop coefficients to local conditions. This adjustment was attempted by the Allen and Pereira method, which suggests using a density function to make the crop coefficients more transferable and applicable, in order to improve irrigation management and scheduling. Further research into quantifying the crop water use could lead to updated and accurate crop coefficients, which could reduce the risk of water scarcity and saving significant amounts of water.

2.2 Introduction

As in other dry countries in the world, South Africa is experiencing rising water-scarcity levels, which are caused by the competition between various sectors for its limited water resources. This competition is attributed to climate change effects and both the population and economic growth. Inefficient irrigation activities and poor water management practices have equally contributed to the increasing water scarcity in the country (Dzikiti et al., 2018). There is therefore a compelling need to manage and allocate the available water resources more effectively and to minimise the non-beneficial water consumption by the agricultural sector, which depends heavily on an adequate supply of irrigated water (Jovanovic et al., 2020). South Africa receives low and inconsistent rainfall volumes; thus, crops with high water requirements, such as fruit tree species, are grown under irrigation. As a result sustainability and improvement of water use measures, irrigation scheduling, and on-farm water management practices, is needed in order to promote efficient water productivity. This will help to ensure the sustainability and growth of the agricultural industry in the country (Oweis, 2018).

The principal objective of irrigated agriculture is to administer less irrigation water volumes, but which is still sufficient to meet the crop’s water requirements, without necessarily decreasing its quality, yield and profits (Jovanovic et al., 2020). In order to achieve this, farmers need to adopt reliable techniques for estimating and quantifying their crop water requirements. However, past studies have reported that the available techniques and approaches are associated with uncertainties, which often result in both under- or over-irrigation by farmers. The validation and improvement of the techniques and approaches of these water-use models will improve irrigation scheduling and create a more efficient water management system (Gush & Taylor, 2014b).

The accurate estimation of the water requirements of fruit tree crops depends on accurate crop coefficients. However, many of the available crop coefficients were developed in other regions of the world, where the climates and local environments are different from those in South Africa. Therefore, there is a need to develop and validate techniques that quantify the actual volumes of water requirements of fruit tree crops, taking into consideration the country's local conditions and production practices.

This chapter identifies the geographical distribution of various fruit tree crops that are grown across South Africa. The different irrigation types and scheduling methods that farmers can implement are discussed in this chapter, while their advantages and disadvantages are highlighted. This chapter concludes by reviewing the various methodologies and approaches that are used to determine crop coefficients, and it identifies the state of knowledge relating to the crop coefficient approach. Then the knowledge gaps associated with these approaches are identified, which leads to a discussion and the related recommendations for further studies.

2.3 Irrigated Fruit Trees and their Geographical Distribution

Fruit and nuts are of high-value and these high-water-using crops are grown across South Africa (Fereres et al., 2003). They are the country's third-most irrigated crop group and account for about 17% of the total irrigated crop groups (Dzikiti et al., 2020). The fruit and nuts grown in South Africa can be categorized according to their morphology or climatic characteristics, and they are sub-grouped as follows: (i) tropical and subtropical crops, (ii) citrus fruits, (iii) grapes, (iv)berries, (v) pome and stone fruits, and (vi) nuts. The geographical distribution of these species across the country is strongly influenced by the climate and soils. The temperature, rainfall, humidity, radiation, etc., are some of the chief climatic factors that influence their distribution (González-Dugo et al., 2013). For instance, humidity and rainfall influence the prevalence of pests and diseases, which limit the areas that experience maximum productivity and profits for these crops. Avocadoes, mangos, bananas, pineapples, pawpaws, etc. are grown in tropical and subtropical climates in Limpopo, KwaZulu-Natal, Mpumalanga, as well as sections of the Eastern Cape Province. Tropical fruits adapt to seasonal climates without winter that are characterized by daily temperature variations that are more than annual variations in their mean daily temperature (Taylor & Gush, 2009). However, citrus fruits, such as oranges, lemons and soft citrus, are grown in nearly all the provinces across the country.

Grapes that are classified as table and wine grapes are grown in the Western Cape and sections of the Eastern Cape Province. The most-grown pome fruits in South Africa are apples, followed by peaches, nectarines and pears. Apples and pears are grown in the Cape Province due to its cold winters, which are necessary for dormancy, and its warm summers. However, there are small pome fruits in the Eastern Cape and Free State Provinces. Macadamias, the most-grown nut species in South Africa (Dzikiti et al., 2020), are grown in Limpopo, in the south of KwaZulu-Natal and in Mpumalanga. These species grow well in subtropical climates with high temperatures and a low relative humidity (Wall, 2013). Plantations of pecan species are suited to subtropical climates that are characterised by short and cold winters, and long and hot summers, such as those experienced in the Gauteng and Northwest Provinces (Gush & Taylor, 2014b).

2.4 Evapotranspiration (ET_c) Process and Factors affecting Evapotranspiration

Field crops need an adequate supply of water for transpiration and evaporation to occur. Allen et al. (1999) defined evaporation as the process when liquid water is transformed to water vapour (vaporisation) and then removed from the evaporating surface (vapour removal). Transpiration is the vaporisation of liquid water from the plant tissues to the atmosphere (Allen et al., 1999). Crops principally lose this water, in water vapour form, through their stomata. Evaporation and transpiration can occur simultaneously, and it is quite difficult to distinguish the two during this period; therefore, the combination of these two separate processes is called evapotranspiration (Mata et al., 2014). Thus, a crop's water requirements can be called evapotranspiration.

A crop's water requirements are mainly dependent on the following: (i) the weather parameters, (ii) the crop characteristics and physiology, and (iii) the environmental aspects. Air temperature, wind speed, humidity and radiation are the dominant weather parameters that affect ET. Crop type, growth, and the development stage are some of the crop characteristics that are considered when assessing the ET_c from well-watered and well-managed fields. Differences in the crop height, the crop roughness, reflection, ground cover and resistance to transpiration, result in different ET_c levels in various types of crops, under identical environmental and climatic conditions (Savva & Frenken, 2002). These environmental conditions include the poor land fertility and soil salinity. In addition, poor on-field management practices, such as the limited application of fertilizers, the failure to control diseases and pests, as well as poor soil management practices, limit effective crop development and therefore reduce the ET_c rates. The effect of soil water content on ET_c is primarily conditional on the water deficit magnitude and the soil type (Allen et al., 1999). Conversely, too much water in the soil will result in the leaching of nutrients and waterlogging, which has a detrimental effect on the root water uptake. Therefore, serious attention should be given to many different management practices that influence the factors affecting ET_c.

2.5 Water Use of Fruit Tree Crops

Water resources are scarce in South Africa, and irrigation uses more than 60% of the available water resources (Hearne & Donoso, 2005). The availability of water is vital in fruit-producing areas, including Western Cape and Mpumalanga, etc., and it is critical for it to be either allocated to its maximum or almost entirely. Poor irrigation practices by farmers, for example over-irrigation, exacerbate the crisis. The inefficient water use in the fields causes the crops to become severely water-stressed and it affects the economic yields. This calls for the implementation of accurate quantitative crop water use information and the adoption of precise irrigation scheduling technologies. These measures will allow the efficient use of the existing water resources and increase the water use efficiency (Gush & Taylor, 2014a).

According to Fundira (2003), South Africa is considered to be one of the major global fruit exporters, which has motivated numerous studies to quantify accurate water requirements of fruit species for the sustainment and growth of the local fruit industry. Fruit trees have different water requirements, and they require an adequate supply of water at different stages of their development. When the amount of rainfall is insufficient for meeting a crop's requirements, irrigation is applied to the field to supplement the rainfall and to counter the negative impact of water deficits on the yield.

Various techniques are used for measuring the consumptive water use of crops , and they will be briefly discussed later in this chapter. These techniques are grouped as follows: (i) those that measure the total evaporation, either by using an energy balance approach (e.g. scintillometry) or a soil water balance approach (e.g. soil water measurements and lysimetry), and (ii) those that measure the flux within individual plants (e.g. the heat pulse velocity technique). Past studies have used the heat pulse velocity and eddy covariance techniques to measure the consumptive water use of various fruit species, such as apples (Dzikiti et al., 2018; Mobe et al., 2020), macadamia nuts (Gush & Taylor, 2014a; Taylor, 2021), avocadoes (Taylor, 2021), citrus (Gush & Taylor, 2014a; Taylor et al., 2015), pecan nuts, peaches and nectarines (Gush & Taylor, 2014a); however, these measurements are not always accurate. For example, Alarcón et al. reported that sap flow measurements overestimated the actual transpiration volumes, post-irrigation. Further studies on the quantification of the consumptive water use of fruit trees can lead to updating the crop coefficients of various species, which will help to improve irrigation scheduling and management.

2.6 Irrigation Practices and Scheduling

The growth and production of fruit tree species depend heavily on water availability, especially those grown in arid and semi-arid climates (Broner, 1989). Since fruit and nut species are of high value and have high water requirements, they are often irrigated throughout the growing season. These species account for about 17% of the irrigated crop groups, which makes them the third-most irrigated crop in South Africa (Dzikiti et al., 2020). Therefore, it is necessary to use accurate decision-making tools that will assist with effective irrigation scheduling, in order to optimize the water efficiency, crop productivity and crop quality (Mobe, 2020). In addition, a principal aim of good irrigation scheduling practices is to maximise the significant economic benefits that are achieved by increasing the crop yield and quality, while reducing the water usage and non-beneficial water consumption (Jovanovic et al., 2020).

Dzikiti and Schachtschneider (2014) defined irrigation scheduling as deciding 'when' to irrigate and 'how much' water to apply during each irrigation event. The authors described efficient irrigation scheduling as a critical form of on-field stewardship in irrigated agriculture.

Such scheduling is critical in South Africa's fruit sector, which is entirely dependent on irrigation. However, a survey on the adoption of irrigation scheduling by Stevens (2007) revealed that only 18% of South African farmers use objective scheduling methods; this indicates that most farmers rely on their intuition to make their irrigation decisions, rather than using scientific tools or techniques. The lack of accurate irrigation scheduling guidelines and techniques is a major factor that contributes to the inadequate irrigation practices in orchards and on farms (Pereira et al., 2020). Farmers are aided to use objective techniques to quantify and effectively utilise the limited water resources to the maximum. They usually determine their irrigation water amounts by quantifying the ET of their orchards as a product of the reference ET and the crop coefficient (K_c) for a given crop, according to the standard FAO guidelines (Allen et al., 1999). While most farmers across South Africa have arguably accurate ET_o data, they do not have accurate crop coefficients to accurately determine the amount of irrigation water that they need to apply. Further research on quantifying the crop water use will lead to an updated list of these crop coefficients, and it will potentially improve the precision of irrigation scheduling, thereby reducing the risk of water wastage while saving significant amounts of water.

To achieve effective irrigation scheduling, farmers should have a comprehensive understanding of the orchard soil, the various growth stages and the crop's water requirements (Jones, 2008). When planning for irrigation, a farmer must take multiple factors into account, including the water-holding capacity of the soil, the water use, the prevailing weather conditions and quantified management decisions (Gush & Taylor, 2014b). The distribution and effective application of irrigated water should be strictly monitored, as the pressure continues to increase on the available water resources (Pereira et al., 2020). More stringent irrigation monitoring will allow for water saving, water demand management and water use efficiency (Stevens, 2007). Gush and Taylor (2014) found that approximately 1.5 million hectares of land were under irrigation in South Africa in 2007 and that an estimated 10 468 million m^3 of water per year were utilised. This demonstrates the need to apply the correct water volumes at the right time, in order to produce the maximum yield and crop quality.

The objective of efficient irrigation scheduling is to supplement the effective rainfall to meet the crop's water requirements and to restore the water deficit within the plant (Dzikiti et al., 2020). In addition, it helps to minimise the leaching of nutrients, which may harm the environment. Farmers struggle to determine when, and how much, to irrigate as they rely on their visual assessment of the plants. This affects the effective growth and yield quality of the plants. Therefore, farmers need to utilise proper irrigation scheduling techniques to avoid such scenarios, including stunted growth. In addition, changes in the status of the soil and plant water need to be monitored and eventually restored, in order to avoid the poor growth and quality of the crop.

2.6.1 Irrigation scheduling approaches

Irrigation scheduling is established on soil water measurements and calculations (Broner, 1989). There are numerous irrigation scheduling approaches (Figure 1) that farmers can adopt and use to obtain a maximum yield from the available water resources. Some of these approaches are widely-used by farmers, whilst others are used as research tools (see Figure 2.1 below).

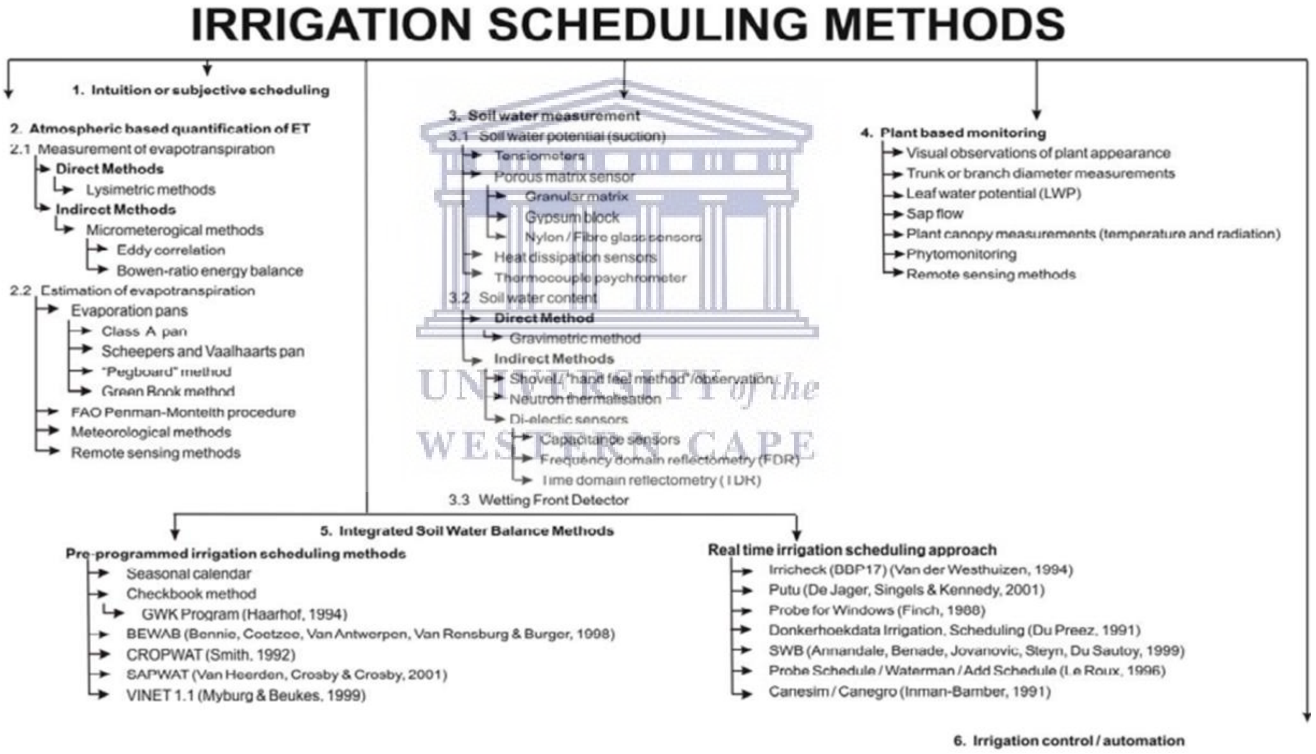

Figure 2.1 Irrigation scheduling methods that are used in South Africa (Stevens, 2007)

The intuition, or subjective, irrigation approach is developed over many years of farming experience by merely observing the soil, crop and climate variables (Broner, 1989). A farmer’s experience with a specific crop helps him to determine how much, and when, to irrigate (Stevens, 2007). Arguably, this approach is thought to be reliable and accurate, although there is no documented evidence of a quantified level of accuracy. Contrary to this approach, irrigation scheduling based on estimating the crop water requirements (ET_c) is guided by a meteorologically-compelled ET_c demand, which varies over time (Stevens, 2007). As a result, the irrigation requirements are eventually determined appropriately. However, this approach has its shortcomings, including the need for a high computational competency, which may not be readily-available to small-scale farmers (Jones, 2008).

The scheduling of irrigation events can be achieved by using the soil water measurements, which indicate the water availability within the plant (Broner, 1989). These measurements help to answer vital irrigation scheduling questions, such as how much water should be applied and when to irrigate. In addition, monitoring the soil water status is essential for enhancing irrigation and fertilizer input management (Taylor & Gush, 2009).

Plant-based monitoring can be used as a technique to determine the need for irrigation (Jones, 2008). The plant indicators that are used in this technique include the plant's appearance, the leaf water potential, the canopy temperature and the sap flow measurements (Stevens, 2007). Velez et al. (2007) argued that variations in the plant trunk, or stem diameter, provide a more conscious indication of the need for irrigation than variations in the leaf diameter, and it can therefore be used to avoid severe water stress and to control deficient irrigation activities. However, this technique is more appropriate for research purposes than for practical application in commercial farming.

Other irrigation scheduling approaches, such as the water balance methods, micrometeorological methods, remote sensing, etc., are discussed later in this chapter.

2.7 Determining Crop Evapotranspiration

Several methods have been developed by scientists to measure and estimate the evapotranspiration and water consumption of crops. It is fundamental to give an accurate account of the water balance, which includes the water applied to agricultural fields (crop water use) and the water consumed by crops through evapotranspiration (crop water consumption) (Jovanovic et al., 2020). The precise accounting of these volumes allows the accurate estimation of a crop's water requirements. Various techniques can be used to quantify crop water consumption, and these have elemental principles, accuracy, temporal and spatial scales of application, potential problems, etc. (Jovanovic et al,. 2018). They can be categorized as the gravimetric approach (lysimetry), the atmospheric approach (methods that are based on weather data and crop coefficients, and micrometeorological methods that are based on the surface energy balance and flux gradient measurements), plant measurements (sap flow and remote sensing) and soil measurements (Dzikiti et al., 2020).

2.7.1 The soil water balance method

The soil water balance method estimates ET_c as the residual term within the water balance equation (Gush & Taylor, 2014b). When it is applied to the soil, the entire equation becomes:

$$\mathrm{P} + \mathrm{I} + \mathrm{W} - ET_C - \mathrm{R} - \mathrm{D} = \pm[\Delta S] \qquad (2.1)$$

Where P is precipitation, I is irrigation, W is the upward water table contribution, R is the surface runoff, D is drainage, and ΔS is the soil water storage in the soil layer. All terms are measured in mm/s. According to Rana and Katerji (2000), it is difficult to measure all the terms in Equation 2.1 and some terms can be neglected under certain conditions and can thus be written as:

$$\mathrm{P} + \mathrm{I} - ET_c = \pm[\Delta S] \qquad (2.2)$$

However, the simplifications are unsuitable for accurate ET_c measurements, as they require accurately-estimated components (deep drainage and runoff), although this method is more applicable to catchment studies (Dzikiti et al., 2020).

2.7.2 Plant measurements

2.7.2.1 Sap flow

The water movement in the plant's xylem or sap flow may be a good indicator of transpiration over long periods. Sap flow methods monitor the flow of sap in the xylem of plants, using heat tracers and other pulsing methods (Dzikiti et al., 2018). ET_c values are obtained by measuring the sap flow along the trunk of the trees and comparing the underwater shortage to that of well-irrigated trees, by using steady heat flux and heat pulse technology (Stevens, 2007). Two distinct sap flow techniques are available, namely: (i) the sap flux technique, and (ii) the mass flux technique. Sap flow measurements are, however, particularly suitable for measuring the transpiration of trees, although the technique can also be adopted for field crops. It is vital to note that changes in transpiration are driven by various climatic factors, such as the humidity and wind, and thus sap flow changes can take place without stomatal openings changing (Taylor & Gush, 2009).

This technique has been used in various past studies to measure the sap flow rate of fruit tree species across South Africa, including the citrus species (Taylor et al., 2015), nectarines, peaches and macadamia nuts (Gush and Taylor, 2014). An advantage of the sap flow measurements is that direct measurements of the plant's water status ET_c models can be used to provide data on the plant water deficits. Like any other technique, sap flow measurements also have shortcomings, which make sap flow gauges convenient for research. These shortcomings include the sampling range of the instruments that are needed for a complete crop season, the sensor movement from plant to plant, as well as some physical problems of the instrumentation (Stevens, 2007). Both the mass flux and sap flux techniques require sampling, which causes the tissues in the trunk to degenerate die or. The technique is used mainly by researchers and progressive commercial fruit farmers.

Soil-based and micrometeorological methods can nevertheless be combined or used in conjunction with sap flow data, in order to separate the transpiration component of ET_c. In addition, approaches have been developed to upscale the sap flow measurements of individual plants to stand scale, although this remains a topic for further investigation.

2.7.3 Gravimetric measurements

2.7.3.1 Lysimetry

Lysimetry is an indirect method that quantifies ET_c and it is used as a reference for calibrating and testing other techniques that estimate ET_c indirectly (Ayars et al., 2003). This method allows the direct measurement of ET_c for those periods when there is no rain or irrigation (Stevens, 2007). The lysimeters consist of a weighing container that is buried in the field and filled with soil. The weighing lysimeter measures the soil, soil water and plant masses; therefore, temporal changes in the mass are attributed to water uptake and transpiration or evaporation (Stevens, 2007). The crops are grown in the weighing container under the same conditions as the surrounding environment. There are, however, various factors that can cause the lysimeter conditions to deviate from reality, including: (i) the imposition of a water table at the bottom of the lysimeter, (ii) the cutting of the roots by the walls of the lysimeter, and (iii) the heat conduction by the lateral walls (Stevens, 2007). In the absence of rainfall, irrigation, drainage and runoff/run-on, the change in the weight of the container is due to ET_c, assuming that the changes in vegetation mass are negligible (Dzikiti et al., 2020). Weighing lysimeters are used by scientists, mainly to estimate the real-time ET_c and for irrigation-scheduling activities (Ayars et al., 2003). However, this technique is time-consuming, and the equipment and installation costs are high, which make it even more expensive to service and maintain.

2.7.4 Atmosphere-based methods

2.7.4.1 Micrometeorological methods

Crop evapotranspiration ET_c from a vegetated surface e.g. an orchard, can be determined directly or indirectly by using micrometeorological methods. These techniques are based on the simplified surface energy balance:

$$R_n = H + \lambda E + G \qquad (2.3)$$

All terms are usually expressed in W m^{-2}, where R_n is the net radiation, which is mainly partitioned into G, λE and H. The G term represents the soil heat flux transferred into, or out of, the earth's surface, and $R_n - G$ represents the available energy. H represents the sensible heat flux, and λE is the latent heat flux (λ – latent heat of the vapourisation of water ~ 2.46 MJ kg^{-1}; E – the evaporation rate of water or the water vapour flux density in $kgm^{-2}s^{-1}$). The equation assumes that there is no advection (the horizontal transport of energy and water vapour into or out of the considered area) and applies to vertical fluxes (Jovanovic et al., 2018). The terms R_n and G are usually measured directly, by using net radiometers and soil heat flux plates, respectively (Jovanovic et al., 2018). Two examples of the widely-used micrometeorological methods include the Bowen ratio (Bowen, 1926) and eddy covariance (Dzikiti et al., 2020; Gush & Taylor, 2014), which are both used for ET_c measurements near the land surface to determine the energy, trace gases or momentum fluxes. They allow the total evaporation to be measured by placing most of the sensors in the atmosphere, and they are more portable than buried sensors (Stevens, 2007).

Evaporative heat loss occurs because the evaporation of water requires energy. Thus, as water evaporates, it withdraws heat from the leaf and eventually cools it. The ratio of the essential processes in leaf temperature regulation, i.e. sensible heat loss and evaporative heat loss, is called the Bowen Ratio (Bowen, 1926).

The Bowen ratio β is defined as:

$$\beta = \frac{H}{\lambda E} \qquad (2.4)$$

When the evaporation rate is low because of a limited water supply, the Bowen ratio tends to be high, especially in deserts, followed by semi-arid regions, temperate grasslands and forests, tropical forests and tropical regions (Krishnan et al., 2012). Plants in areas with a high Bowen ratio value conserve water and adapt to high leaf temperatures, in order to maintain a sufficient leaf-air temperature gradient (Krishnan et al., 2012). These adaptations, however, cause the slow growth of plants.

Equation 2.4 is further simplified by substituting H in Equation 2.3 to give:

$$\lambda E = \frac{Rn - G}{1 + \beta} \qquad (2.5)$$

The condition is $\beta \neq -1$. However, in reality, $\beta = -1$ may only occur when λE and H are equal but have different upward and downward directions. This usually happens in the mornings and evenings, when the flux directions are conducive to inversion.

The accuracy of the Bowen ratio, particularly under semi-arid conditions, is satisfactory although it is considered to be an indirect method. The general advantages associated with the Bowen ratio are: (i) its ability to measure the ET_c, even from vegetation surfaces that are not well-watered, (ii) the absence of surface and wind speed measurements, and (iii) the requirement for simple measurements of the temperature and vapour pressure of the air at two heights above the canopy (Stevens, 2007). The disadvantages are that: (i) the sensors are very fragile, (ii) it is massively dependent on the accurate measurements of R_n and G for precise estimates of the crop ET, (iii) it assumes that the similarity between the diffusion coefficient for heat and vapour are only acceptable between neutral and moderate unstable conditions over smooth surfaces (Allen et al., 2011).

In the eddy covariance method, fluxes of the momentum, heat and mass over occur the top canopies because of the eddies that cause air turbulence (Gebler et al., 2015). These fluxes can be determined by acquiring the air temperature (T_a) measurements and the vertical wind speed (ω) at high frequencies (10-20 Hz), and then calculating their covariance. The measurements are based on the correlation between the turbulent motion of the air and the turbulence of the constituents being transported by the turbulent motions e.g. heat or water vapour (Stevens, 2007). Therefore, sensible heat flux is estimated as:

$$H = \rho_a C_p \Sigma(\omega - \overline{\omega})(T_a - \overline{T}_a) \qquad (2.6)$$

Where ρ_a is the density of air, C_p is the specific heat capacity of air at a constant pressure, and T_a is the air temperature. The wind speed and air temperature are measured by using sonic anemometers (Dzikiti et al., 2020). The assumption of Equation 2.3 is that there is a surface energy balance closure. The covariance of the vertical wind speed and the atmospheric water vapor concentration (e) is used to perform a direct measurement of ET_c, by using the covariance method as:

$$\lambda E = \lambda \frac{M_w/M_a}{P_a} \rho_a \overline{\omega' e'} \qquad (2.7)$$

Where M_w and M_a are the water vapour and air molar masses ($gmol^{-1}$), P_a is the atmospheric pressure (kPa), ω' is the instantaneous deviation of the vertical wind speed, and e' is the vapour pressure of the air. The air density fluctuations, as well as the time delays of the sensors, spikes, noise, etc., are some of the primary sources of error with eddy covariance (Krishnan et al., 2012).

Eddy covariance is arguably the most-used micrometeorological ET_c measurement technique, due to its comparatively fast response sensors (Ibraimo, 2018). Past studies have used the technique to estimate the water consumption and crop coefficients in fruit orchards (Gush & Taylor, 2014b). According to a study by Gush and Taylor (2014), water-use data on various citrus cultivars exhibited many variations, and in most cases, they were lower than the lysimeter measurements reported in previous studies e.g. the Navel orange trees in Citrusdal, Western Cape, used slightly more water than the seasonal average of 2.0 mm, with a peak ET_c of just above 2.5 mm/d. These ET_c values are lower than those that are obtained by using lysimeters. The advantage of the eddy covariance system is that it can be used indirectly, just like the Bowen ratio, to determine the soil evaporation from a cropped field as a difference between measured crop evapotranspiration and transpiration (Krishnan et al., 2012). In addition, the system has minimal theoretical assumptions about the land surface properties, such as the aerodynamic roughness or zero plane displacement, and atmospheric stability corrections are not necessary (Stevens, 2007). This explains the importance of post-processing of eddy covariance data in ensuring that all assumptions are met. However, like any other technique, eddy covariance also has disadvantages, like being relatively expensive, taking time to install and having fragile instrumentation (Stevens, 2007).

2.7.4.2 Weather data and crop coefficients

This study defines the reference evapotranspiration, denoted as ET_o, as the evapotranspiration rate from a reference surface that is not short of water. This reference surface is a hypothetical grass reference crop with specific characteristics. Water is abundantly available at the reference surface, and soil factors do not affect it. The ET_o is defined as evapotranspiration from a disease-free, well-fertilized watered grass, which achieves optimal production under the given climatic conditions. Therefore, relating ET_o to a specific surface provides a reference to which the ET from other surfaces can be related (Allen et al., 1999). This reference ET_o depends on the weather data and therefore allows a separate ET_c to be determined for each crop and growth stage.

ET is driven by various factors, including the available energy (i.e. atmospheric conditions), the availability of soil water and the vegetation characteristics. Past studies have developed methods that relate weather data to ET_o (Monteith, 1965; Priestley and Taylor, 1972), which represents the evaporative demand of the atmosphere and is driven by the climate. Consequently, ET_o, which is a climate parameter, can be computed by using weather data. Various methodologies on crop water requirements, and the procedure for calculating reference and crop evapotranspiration from meteorological data and crop coefficients, have been reviewed and updated in FAO-56 (Allen et al., 1999).

The FAO Penman-Monteith method is physically-based and explicitly incorporates aerodynamic and physiological parameters. It was developed by defining the reference crop as a hypothetical crop with an assumed height of 0.12 m, a surface resistance of 70 $sm^{-1,}$ and an albedo of 0.23, which closely resembles evaporation from an extensive surface of short green grass, at a uniform height, that is adequately watered and actively growing (Allen et al,. 2006). The method uses standard climatic data that can be measured or derived from common weather stations and then standardized, according to the time-scale of the computation.

According to Allen et al. (1999), the FAO Penman-Monteith equation is derived from the original Penman-Monteith equation (Equation 2.8), as well as the of the aerodynamic (Equation 2.9) and surface resistance (Equation 2.10) equations. The original Penman-Monteith equation is given by:

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a C_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \qquad (2.8)$$

Where R_n is the net radiation, G is the soil heat flux ($MJm^{-2}d^{-1}$), (e_s-e_a) represents the vapour pressure deficit of the air (kPa), ρ_a is the mean air density at a constant pressure, C_p is the specific heat of the air, Δ represents the slope of the saturation vapour pressure-temperature relationship ($kPaK^{-1}$), γ is the psychometric constant ($kPaK^{-1}$), and r_s and r_a are the (bulk) surface and aerodynamic resistances (sm^{-1}). This Penman-Monteith equation includes all the parameters that govern energy exchange and the corresponding latent heat flux (evapotranspiration) from uniform expanses of vegetation.

The aerodynamic resistance (r_a), which determines the transfer of heat and water vapour from the evaporating surface into the air above the canopy, is given by:

$$r_a = \frac{\ln\left[\frac{z_m - d}{z_{om}}\right] \ln\left[\frac{z_h - d}{z_{oh}}\right]}{k^2 U_z} \qquad (2.9)$$

Where r_a is the aerodynamic resistance (sm^{-1}), z_m is the height of the wind measurements (m), z_h is the height of the humidity measurements (m), d is zero plane displacement height (m), z_{cm} is the roughness length governing the momentum transfer (m), z_{ch} is the roughness length governing the transfer of heat and vapour (m), k is von Karman’s constant 0.41 (-), and u_z is the wind speed at height z (ms^{-1}).

Vapour flow resistance through the transpiring crop and evaporating soil is described by the 'bulk' surface resistance (r_s) (Daamen & Simmonds, 1996), which is given by:

$$r_s = \frac{r_1}{LAI_{active}} \tag{2.10}$$

Where r_s is the (bulk) surface resistance (sm^{-1}), r_1 is the bulk stomatal resistance of the well-illuminated leaf (sm^{-1}), and LAI_{active} is the active leaf area index [m^2 (leaf area) m^{-2} (soil surface)], which is a dimensionless quantity.

The product of Equations 2.8, 2.9 and 2.10, the FAO Penman-Monteith equation, has been parameterized for green grass vegetation cover and is highly likely to predict ET_o in a wide range of locations and climates. FAO Penman-Monteith equation is given by:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{2.11}$$

where R_n is the net radiation ($MJm^{-2}d^{-1}$), G is the soil heat flux density ($MJm^{-2}d^{-1}$), T is the mean daily air temperature (°C) at a 2.0 m height, U_2 is the wind speed (ms^{-1}) at a 2.0 m height, e_s is the saturation vapour pressure of air (kPa), e_a is the actual vapour pressure of air (kPa), Δ is the gradient of the saturation vapour pressure versus the temperature curve ($kPaK^{-1}$), and γ is the psychometric constant ($kPaK^{-1}$). Past studies have recommended that the ET_o should be calculated with the Penman-Monteith as the reference, for two reasons: (i) The sound physics, based on the energy and mass balance, accounts for the main weather variables affecting ET, such as the radiation, temperature, wind speed and humidity, and (ii) It provides the support for its extrapolation to vegetation, other than short grass and well-watered conditions, if the aerodynamic and canopy resistances are known (Jovanovic et al., 2018). The ET_o calculated from the FAO Penman-Monteith equation is used to calculate the unstressed crop coefficient by using the FAO-56 coefficient approach.

2.7.4.3 The FAO-56 crop coefficient (K_c) approach

Crop coefficient values have been tabulated for a wide range of crops (Allen et al., 1999), and they are often successfully used for a wide range of agricultural applications. The FAO-56 crop coefficient approach has been a successful and dependable means for estimating evapotranspiration (ET_c) and crop water requirements under well-watered conditions. ET_c is the amount of water required to replace the water depletion from the soil and to maintain optimal plant growth, which is termed as the crop water requirement. This approach is the most widely-used climate-based crop water requirement method, where the climatic effects on the crop water requirements are given by the reference evapotranspiration (ET_o) and the crop effects are given by the crop coefficient (K_c) (Allen et al., 1999). When using this method, the reference condition is generally the ET from a clipped, cool-season and well-watered grass ET_o. Since ET_o refers to a reference short grass, it can be translated to crop evapotranspiration (ET) under standard non-limiting conditions for crop production, or any other uniform vegetation stands, by multiplying it by the crop coefficient (K_c). K_c represents an integration of the effects of three primary characteristics that distinguish the actual crop from the reference, namely: (i) the crop height (which affects the roughness and aerodynamic resistance), (ii) the crop soil surface resistance (which is related to the leaf area fraction of the ground covered by the vegetation, the leaf age and condition, the degree of stomatal control and the soil surface wetness), and (iii) the albedo of the crop soil surface, which is influenced by the fraction of the ground covered by the vegetation and soil surface wetness (Pereira et al., 2020).

The crop coefficient K_c is therefore calculated as:

$$K_c = \frac{ET_c}{ET_o} \tag{2.12}$$

where ET and ET_o have the same units of mmd^{-1}.

K_c is ordinarily transferable between climates and regions, assuming that the ET_o accounts for almost all the variations caused by weather and climate (Allen & Pereira, 2009a). However, under specific management conditions, K_c may change. This occurs typically, depending on the frequency of irrigation/rainfall, as the soil evaporation component increases under more frequent wetting events. The effects of specific wetting events on the crop coefficient K_c values can be predicted by splitting the K_c into two separate coefficients, using the dual coefficient approach. These independent coefficients were described by Allen et al. (1999) as one for crop transpiration, i.e. the basal crop coefficient K_{cb}, and as one for soil evaporation $K_{e.}$ The single K_c coefficient is therefore substituted by:

$$K_c = K_{cb} + K_e \tag{2.13}$$

Where K_{cb} is the ratio ET_c /ET_o when transpiration occurs at a potential rate when the soil evaporation is negligible (ET_c /ET_o ~ T_c/ET_o). Therefore, K_{cb} x ET_o primarily represents the transpiration component of ET_c. K_e is the soil evaporation coefficient, which represents the evaporation component of ET_c. The soil evaporation component is maximal when the topsoil is wet from rain or following irrigation, and it is minimal (even zero) when no water remains near the soil surface. The dual crop coefficient approach is often used in real-time irrigation scheduling and for research purposes (Stevens, 2007).

According to Allen et al. (1999), the basal crop coefficient (K_{cb}), also referred to as the transpiration crop coefficient, is given by:

$$K_{cb} = \frac{T_c}{ET_o} \tag{2.14}$$

Where T is the orchard transpiration (mmd^{-1}) derived from the sap flow measurements (Nicolás et al., 2006). In tree crops, T_c can be calculated as the summation of the product of sap flux density U and the orchard Sapwood Area Index (SAI) for trees with different stem diameter classes, as follows:

$$T_c = \sum_{\mathbf{i=1}} \mathrm{SAI_i} \times \mathrm{U_i} \tag{2.15}$$

Where SAI is the m^2 of sapwood per m^2 of ground area, and U_i is the average sap flux density for a unique stem size class. The assumption in Equation 2.14 is that the crops are well watered and that the orchards do not suffer significant water stress.

However, the FAO-56 coefficient approach (Allen et al., 1999) remains the primary reference in crop water requirements because of its robustness and ease of application. Advances in research have demonstrated that crop coefficients need to be adjusted to local conditions, such as water and other stresses, as well as crop management. This is particularly true for fruit tree orchards that are managed differently e.g. different row spacing and orientation, different irrigation methods and the wetted portion of the ground, different cover crops between the rows, etc. Past studies have compared tabulated FAO-56 coefficients with the actual measured ET_c values and found that there is a need to update/adjust these crop coefficients (Allen, 2000; Paço et al., 2006). The accurate estimation of crop water requirements requires accurate crop coefficients. This tends to be the limitation of this method, as the tabulated standard FAO-56 coefficients are not always readily-transferrable between fields and regions (Allen & Pereira, 2009a; Allen 2000). Allen & Pereira (2009) attempted to address this limitation by developing a method for adjusting the crop coefficients, based on the canopy density, which will make the FAO-56 coefficient approach more transferable and applicable for improving irrigation management and scheduling.

2.7.4.4 The Allen and Pereira (A&P) approach

The K_c values for a range of irrigated crops, as tabulated by Allen et al. (1999), need to be adjusted in order to make the coefficients transferable to different sites with different climates, assuming that ET_o accounts for nearly all the variations caused by the weather and climate. Allen & Pereira (2009) formalized the FAO-56 procedure for adjusting the crop coefficient K_c (as a function of the crop height and ground cover) by using the density coefficient, K_d. They defined a density function (K_d) that expresses the energy available for transpiration in the field. Allen and Pereira (2009) reported that the crop coefficients could be determined by using the fractional vegetation cover, the crop height and the stomatal regulation under wet conditions.

Since K_{cb} depends on the vegetation amount and allows the basal crop coefficients to be transferable between sites (e.g. different orchards), the K_d was defined by Allen and Pereira (2009) as:

$$K_d = \frac{K_{cb} - K_{c\,min}}{K_{cb\,full} - K_{c\,min}} \qquad (2.16)$$

Where K_{cmin} is the minimum basal K_{cb} for bare soil (K_{cbmin} ~ 0.15 under typical agricultural conditions and K_{cbmin} ~ 0.0-0.15 for all naturally-occurring local native vegetation, depending on rainfall frequency). K_{cbfull} is the estimated basal crop coefficient under an almost full ground cover (Leaf Area Index ≥ 3.0). According to the A&P method, the density coefficient is estimated from the effective vegetable cover (f_{eff}) and the mean tree height (h) as:

$$\mathrm{K_d} = \min\left(1, \mathrm{M_L fc_{eff}}, \mathrm{fc_{eff}}^{\left(\frac{1}{1+h}\right)}\right) \qquad (2.17)$$

Where f_{ceff} is the effective fraction of ground covered or shaded by vegetation (0.01-1) near the solar noon, M_L is a multiplier on f_{ceff} that is expected to range between 1.5-2.0. In orchards, f_{ceff} can be calculated as the ratio of the tree canopy width, or ground shaded area, to an inter-row spacing of the crop at solar noon, following Allen et al. (1999). According to Allen et al. (1999), in such orchards, f_{ceff} is calculated as:

$$\mathrm{fc_{eff}} = \frac{\mathrm{fc}}{\sin\beta} \leq 1 \qquad (2.18)$$

Where f_c is the observed fraction of the soil surface covered by vegetation, as seen from directly overhead, and β is the mean elevation angle of the sun above the horizon during the period of maximum total evaporation (Gush & Taylor, 2014a). f_{ceff} is customarily calculated at solar noon, so that β is calculated as:

$$\beta = \sin^{-1}[\sin\varphi \sin\delta + \cos\varphi \cos\delta] \qquad (2.19)$$

Where φ is the latitude and δ is the solar declination in radians.

Allen and Pereira (2009) also explained that, in cases where the K_{cbfull} is not measured, it could be estimated from the weather data and crop height:

$$K_{cbfull} = Fr\left(\min(1.0 + 0.1h, 1.20) + [0.04(u_2 - 2) - 0.04(RH_{min} - 45)](\tfrac{h}{3})^{0.3}\right) \quad (2.20)$$

Where u_2 is the mean wind speed measured at a height of 2.0 m, RHmin is the minimum relative humidity (%), and h is the crop height (m). Fr is the parameter considered as a K_{cb} adjustment factor or stomatal sensitivity function, and it has a value range of 0-1. Allen and Pereira (2009) suggested the calculation of this parameter, which has values in the range 0-1 for full-cover vegetation. Assuming full-cover conditions, Fr is based on the FAO Penman-Monteith equation as:

$$Fr = \frac{\Delta+\gamma(1+0.34u_2)}{\Delta+\gamma(1+0.34u_2\frac{r_l}{100})} \quad (2.21)$$

Where Δ is the slope of the saturation vapour pressure versus the temperature curve (Pa / ℃), γ is the psychrometric constant (Pa / ℃), and r_l is the mean leaf resistance for the vegetation (s/m). The value of r_l is 100 s/m for most annual agricultural crops, which then sets Fr to 1. The value of 100 s/m in Equation 2.21 is the mean resistance for annual crops. The Allen and Pereira (2009) method overestimated the K_{cb} values by a large margin. According to Mobe et al. (2020) and Taylor et al. (2015), in some instances, this was close to 90% for apples and citrus species, respectively. Taylor et al. (2015) suggested changes to the stomatal sensitivity function (Fr) in Equation 2.21, which produced estimated K_{cb} values that were comparable with those that were measured. However, this similar adjustment did not yield satisfactory results for apples (Mobe et al., 2020).

Similarly, an alternative approach proposed by Allen and Pereira (2009) to replace the ration $r_l/100$ in Equation 2.21 with $r_s/50$ for orchards with sparse canopies, i.e. with an LAI of 3.0, also did not work for apple orchards. The constant 50 is the value of the bulk surface resistance for the grass reference. Therefore, Mobe et al. (2020) replaced the 100 s/m in Equation 2.21 with a resistance parameter α, which represents the minimum unstressed canopy resistance for apple trees. Equation 2.21 was inverted by using the measured values of the climatic variables, and the K_{cbfull} in Equation 2.20 was derived from the sap flow measurements and the mean average leaf resistance (r_l) for the orchards in the study. They finally solved the A&P equation and obtained a mean value for α of about 37 s/m, which made it more precise. The study results were independently verified by calculating the monthly transpiration totals, using the approach, as suggested by Allen et al. (1999). However, the method showed a good agreement between the A&P K_{cb} values and those obtained from sap flow sensors in an olive orchard in Portugal (Paço et al., 2019).

The cover crop K_{cb} is estimated according to the A&P method as:

$$K_{cb} = K_{cb\ cover} + K_d \left(\max \left[K_{cb\ full} - K_{cb\ cover}, \frac{K_{cb\ full} - K_{cb\ cover}}{2} \right] \right) \qquad (2.22)$$

where $K_{cb\ cover}$ is the basal crop coefficient, due to the cover crop.

If SF_i is the sap flow of a single cover crop plant measured in cm^3/h, the leaf area of which on the exposed part of the sap flow sensor is A_b, then the cover crop transpiration (T_c, in mm/h) expressed over the entire orchard surface is given by:

$$T_c = \sum_I \frac{SF_i}{A_i} \times LAI_c \qquad (2.23)$$

where LAI_c is the leaf area index for the cover crop. The maximum cover crop basal crop coefficient ($K_{cb\ fullc}$) is determined by using Equation 2.24:

$$K_{cbfullc} = \frac{T_c}{ET_o} \qquad (2.24)$$

According to Allen and Pereira (2009), the density coefficient for cover crops (K_{dc}) is derived as:

$$K_{dc} = 1 - e^{-0.7 \times LAI_c} \qquad (2.25)$$

$K_{cb\ cover}$ is determined by combining Equations 2.16, 2.24 and 2.25, assuming a K_{cmin} of about 0.15 (Allen and Pereira, 2009).

The orchard K_c can also be determined by using the density coefficient, as proposed by Allen and Pereira (2009) as:

$$K_c = K_{soil} + K_d\left(\max\left[K_{c\,full} - K_{soil}, \frac{K_{c\,full} - K_{soil}}{2}\right]\right) \qquad (2.26)$$

where K_{cfull} represents K_c from a fully-covered soil with background evaporation, and it is calculated as:

$$K_{c\,full} = \max\left(\left\{1.2 + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)](\frac{h}{3})^{0.3}\right\}, \{K_{cb} + 0.05\}\right)$$

(27)

K_{soil} in Equation 2.26 represents the average K_c from the non-vegetated surface, and it reflects the wetting frequency and soil type impacts (Mobe et al., 2020). This is determined by considering evaporation from the wet and dry portions of the orchard surface as:

$$K_{soil} = K_{e\,wet} + K_{e\,dry} \qquad (2.28)$$

Following Allen et al. (2005), K_{ewet} is calculated as:

$$K_{wet} = \frac{TEW - (TEW - REW)\exp\left(\frac{-(t_w E_{so} - REW)}{TEW - REW}\right)}{t_w ET_o} f_w \qquad (2.29)$$

where TEW is the total evaporable water representing the depth of water that can be evaporated from the surface soil layer, when the layer has initially been completely wetted. REW is the readily-evaporable water that represents the cumulative evaporation during Stage One drying (Allen et al., 1999), t_w represents the average time between independent wetting events, E_{so} is the potential evaporation rate from a wet soil surface, as described in Equation 2.32, and f_w (0-1) represents the fraction of the orchard surface that is wetted by irrigation or rain.

TEW is estimated as:

$$\mathrm{TEW} = 1000(\theta_{FC} - 0.5\theta_{WP})Z_e \qquad (2.30)$$

where θ_{FC} and $\theta_{WP,}$ with units cm^3cm^{-3}, represent the volumetric soil water content at the field capacity and the permanent wilting point, respectively, and Z_e is the effective depth of soil evaporation (Allen et al., 1999).

REW is calculated from the data obtained from the soil texture as:

$$\mathrm{REW} = 20 - 0.15(\mathrm{Sa}) \text{ for } \mathrm{Sa} \geq 80 \qquad (2.31)$$

$$\mathrm{REW} = 11 - 0.06\mathrm{C} = (\mathrm{Cl}) \text{ for } \mathrm{Cl} \geq 50$$

$$\mathrm{REW} = 8 + 0.06(\mathrm{Cl}) \text{ for } \mathrm{Sa} < 80 \text{ and } \mathrm{Cl} < 50$$

where Sa is the fraction of sand in the soil and Cl is the percentage fraction of clay in the ground (for a specific orchard). Relevant substitutions should be made for the particular soil types in the respective orchards.

The expression proposed by Allen et al. (2005), which is used to account for the presence of tree cover on soil evaporation (E_{so}), used in Equation 2.29, is shown as:

$$E_{so} = (K_{c\,max} - K_{cb})ET_o \qquad (2.32)$$

where K_{cmax} is the maximum crop coefficient for the surface under full vegetation, which is equal to K_{cfull} (Equation 2.27).

The mean canopy resistance that represents the specific fruit tree species in the A&P method can accurately predict both the K_{cb} and K_c values and the water use of fruit tree orchards, from planting to the full-bearing age. K_{cb} values that are derived by using this procedure, based on the fixed estimates of leaf resistance for citrus, did not provide reasonable water-use estimates in three citrus orchards (Taylor et al., 2015). Therefore, the mean monthly leaf resistance was considered and a good agreement with the measured values was found. However, other studies have shown a good agreement between the K_{cb} values derived using the A&P method and those obtained from the sap flow sensors (Paço et al., 2019)

2.7.4.5 Remote sensing (RS)

Of all the methods that are used to determine the ET_c and crop water requirements, satellite remote sensing is recognized as the only feasible means of providing spatially-distributed ET_c information on the land surface (Mu et al., 2011). According to Jovanovic et al. (2020), three methods have been developed to estimate ET_c from remote sensing data. These include: (i) the K_c-ET_o approach, where reflectance-based actual crop coefficients are derived from vegetation indices, (ii) Surface Energy Balance (SEB) models, which combine spectral and thermal bands data for estimating actual ET_c as an energy balance residual, and (iii) RS Penman-Monteith techniques, where biophysical parameters, such as the LAI, crop height and surface albedo, are derived from RS data to solve the Penman-Monteith model directly. In recent years, remote sensing data-sets have been used increasingly to provide large-scale spatial evapotranspiration estimates (Velpuri et al., 2013). However, the satellite sensors used by RS techniques do not detect ET_c directly; other variables are recorded and applied in complex algorithms, which then calculate ET_c (Jovanovic et al., 2018). This creates the possibility of errors, so comprehensive validation is required, for accuracy and parameterization of the algorithms.

Because the spatial heterogeneity and temporal variability in the availability of water on a vegetation surface is different for different locations, the water managers responsible for planning and allocating water resources need to know their spatial and temporal rates of ET_c (Kiptala et al., 2013). Diversified remote sensing data-sets found at different spatio-temporal scales can be used to estimate the ET_c of irrigated crops and to upscale the orchard ET. These remote sensing methods include the Multi-temporal Moderate Resolution Imaging Spectrometer (MODIS) (Velpuri et al., 2013; Kiptala et al., 2013; Anderson et al., 2011), Landsat (Senay et al., 2016), the Surface Energy Balance Algorithm for Land (SEBAL)

(Bastiaanssen et al., 1998) and the Surface Energy Balance System (SEBS) (Shoko et al., 2015).

MODIS16 ET_c data-sets have been used in previous studies to provide time-series information on the ET_c estimates (Anderson et al., 2011). However, the application of this method has its limitations, especially in small orchards, because of its low spatial resolution (~1 km), regardless of its high daily temporal resolution, which helps to pick the dynamics in ET (Mu et al., 2011). Conversely, satellites such as the GOES, provide ET_c estimates at a very high temporal scale (almost every 15 minutes), but they have a relatively coarse spatial resolution, hence the need for their integration with high spatial resolution data-sets, such as Landsat 8. Coarse-resolution satellite imagery, e.g. from GOES (Anderson et al., 2011), needs to be downscaled to a spatial scale that is compatible with the in-field water management. Some vegetation surfaces may be homogeneous, but some crops may be affected differently, depending on the water availability and water use per location. Thus, a high temporal and spatial resolution and the accuracy of remote sensing estimates are fundamental, and studies should focus on high spatial resolution remote sensing data-sets, such as Landsat, which provide accurate field-scale estimates of ET_c (30-100 m) (Anderson et al., 2011). Landsat 8 provides seasonal coverage of the global landmass at a high spatial resolution of 30 m (visible, NIR, SWIR), 100 m (thermal) and 15 m (panchromatic), which allows it to map small plots accurately (Senay et al., 2016). However, it has a low temporal resolution, i.e. 16 days to monthly. The major challenge associated with Landsat 8, as reported by Senay et al. (2016), is its ability to reliably estimate ET over clouded areas, as well as its poor temporal resolution.

2.8 Conclusion and Recommendations

Accurate methods for determining accurate crop coefficients are essential for precise water resources management. The identification and implementation of a precise method can help to restrict water use and to control the non-beneficial water consumption. Past studies on crop water use have determined ET_c by using lysimeters, by the soil water balance, by using the eddy covariance measurements and Bowen ratio energy balance or by using remote sensing applications. The literature published on quantified experimentation identifies the FAO-56 K_c approach as a dependable means for estimating ET_c and crop coefficients under well-watered conditions.

The A&P method extended the FAO-56 procedure for K_c, by estimating K_c as a function of the crop height and ground cover, in order to make the coefficients transferable to different sites and climatic conditions. Previous studies have investigated and documented the sources of uncertainty in the A&P method, in order to improve its performance. This includes a study by Mobe et al. (2020), who obtained improved K_{cb} estimates by adjusting the ratio, $r_l/100$, in the transpiration reduction factor (Fr). However, further research is required to comprehensively validate the improved A&P method for estimating the water consumption rates of various fruit tree species, which may help farmers to avoid inefficient irrigation scheduling and management throughout the season.

Majority of studies are not focussing on the transferability of crop coefficients, even though there is a vital need to identify mechanisms for extrapolating and adjusting K_c and K_{cb} values for different conditions. These mechanisms could include the development of empirically- and physically-based models, in order to prevent the repetition of experimental work for each crop species, field and season.

CHAPTER THREE: A SYNTHESIS OF THE CONSUMPTIVE WATER USE DATA OF SELECTED FRUIT TREES COLLECTED ACROSS SOUTH AFRICA: IMPLICATIONS TO IRRIGATION MANAGEMENT

3.1 Chapter Summary

The agricultural sector is one of the major water users in the world, especially in water-scarce countries like South Africa. Variations in the water consumption rate have different implications for irrigation water management. This results in farmers supplementing the rainfall with irrigation water to meet the crop water requirements and to increase the crop yield, while minimising non-beneficial water use. This study compared the annual and monthly average consumptive water-use rates and the monthly average crop coefficients of ‘Beaumont’ macadamia nuts, ‘Hass’ avocadoes, ‘Golden Delicious’ apples, ‘Midknight Valencia’ oranges, ‘Alpine’ nectarines, ‘Transvalia’ peaches and ‘Choctaw’ pecan nuts that are grown in their respective orchards. Pecans had the highest annual crop transpiration (T_c) totals (888 mm) and monthly average T_c volumes, while peach trees recorded the lowest T_c volumes. On the contrary, apples had the highest recorded annual crop evapotranspiration (ET) totals (1086 mm), whereas avocadoes recorded comparable annual ET_c volumes (1063 mm). However, nectarines had the highest average daily ET_c rates that ranged between 4.6 – 7.5 mm/d. Although the differences in plant physiology and the atmospheric evaporative demand contributed to the differences in their consumptive water-use rates, the canopy size and its management were the overriding factors. Pecan trees had the highest Leaf Area Index (LAI) averages and significantly denser canopies, while peach trees had the lowest averages. The full crop coefficient (K_c) values of pecans and apples were influenced by the high atmospheric evaporative demand across the seasons, although minute differences in their K_c values were observed. More precise crop water consumption rates can potentially be established by conducting more studies under water-stressed conditions and by comparing the findings to those obtained in well-watered orchards.

3.2 Introduction

South Africa is among many countries worldwide that are experiencing increasing water-scarcity levels. There are various reasons for this increase, including the competition for the available water resources by various sectors, which calls for the need to reinforce efficient water use and productivity. Achieving this objective will require the reduction of the excessive non-beneficial use of water, especially in the country’s agricultural sector, which uses 60% of its available water resources (Gush & Taylor, 2014a). Not only does irrigation support 25-30% of South Africa’s agriculture production, but it is also responsible for the production of 90% of high-value crops, including fruit trees (Bonthuys, 2018). Furthermore, the fruit and nut species are the country's third-most irrigated crop groups (Dzikiti et al., 2020). Therefore, the improvement of water use efficiency, irrigation scheduling and management in irrigated fruit tree orchards is therefore critical and vital for the sustainability and growth of the fruit industry (Dzikiti et al., 2017).

Agricultural water management depends on the use of precise techniques/approaches for estimating crop water requirements. The evapotranspiration (ET_c) of fruit trees is usually determined by using various techniques and strategies, including micrometeorological techniques, such as eddy covariance (Gush and Taylor, 2014; Dzikiti et al., 2017), a micro-lysimeter-derived combination of soil evaporation (E_S), and crop transpiration (T_c) (Bonachela et al., 2001), a water balance approach (Volschenk, 2017), the surface energy balance method (Dzikiti et al., 2011) and the FAO-56 crop coefficient approach (Allen et al., 1999). Various crops have unique water requirements and growth stages that require an adequate supply of water. The precise estimation of the consumptive water use of crops at these growth stages is necessary, in order to quantify the amount of irrigation water required to supplement the rainfall that is received. Ideally, the water applied to the field should not be in excess of consumptive water use of the crop (Bonthuys, 2018); however, in reality, the volume of irrigated water is usually higher than the estimated consumptive water use. The accurate estimation of the consumptive water use of various crops will improve the water use efficiency of farmers, as they will be able to provide accurate quantities of water that match the actual crop water requirements.

Past studies have quantified the consumptive water use of various fruit trees; however, none have developed a synthesis of the consumptive water use data of irrigated fruit tree crops across South Africa. Since these crops are of high value and have their own unique water requirements, farmers need to know and understand the accurate water consumption rates of different fruit tree species across other geographical and climatic regions. A critical comparison of the different consumptive water-use rates will allow farmers to decide which fruit trees to prioritise in specific areas. With the aid of effective irrigation scheduling and management, the proper selection of fruit tree types will allow maximum yields with the limited available water resources. In a water-scarce country like South Africa, one could also investigate less water-intensive crops that are more adapted to drought. The recommendation is not that every farmer should start cultivating a specific crop, but that investigations should be carried out into crops that are known to consume smaller volumes of water, due to their physiological mechanisms of stomatal conductance, etc. Therefore, this study aims to compare the consumptive water use rates of selected fruit tree species and to discuss the implications for irrigation management, so that farmers and various stakeholders can make informed decisions on crop selection and management, as well as water management, and so that they can improve the management of their on-farm water resources.

3.3 Materials and Methods

3.3.1 Selection of fruit tree species and data

Relevant experimental data was retrieved from peer reviewed studies and reports on the water use of fruit species from 2008 to 2020. The data that was provided by Gush & Taylor (2014), Dzikiti et al. (2018) and Taylor (2021) and used in this study included weather data, water consumptive water use data (evapotranspiration and transpiration), irrigation, rainfall, and measured and observed orchard data. The prioritization of the selected fruit tree species in this study was according to their geographical location, as well as the state of knowledge on their respective consumptive water use rates, economic importance, etc. The selection was aimed at fruit trees that are grown in well-irrigated and unstressed orchards that are subjected to efficient management practices. Based on background data collection and analysis, this study focused on the following species: (1) 'Beaumont' Macadamia nuts at White River and Nelspruit, both in the Mpumalanga Province, (2) 'Hass' avocadoes at Howick and Tzaneen, in the KwaZulu-Natal and Limpopo Provinces, respectively, (3) Golden Delicious and Cripps' Pink apples in Koue Bokkeveld (KBV) and the Elgin/Grabouw/Vyeboom/Villiersdop (EGVV) districts, all in the Western Cape Province, (4) 'Midknight' Valencia and 'Rustenburg' Navel oranges at Malelane and Citrusdal in the Mpumalanga and Western Cape Provinces, respectively, (5) ‘Alpine’ nectarines at Wolseley, in the Western Cape Province, (6) ‘Transvalia’ peaches at Rustenburg, and (7) ‘Choctaw’ pecan nuts at Cullinan, in the Gauteng Province.

3.3.2 Sites and data

3.3.2.1 Macadamia nuts

Two sites were used for the field data collection of macadamia nuts, and they are both located in Mpumalanga Province, South Africa. The first data-set was obtained from a ‘Beaumont’ macadamia (intergrifolia x tetraphylla hybrid) orchard located at White River (25° 21' 32.80" S and 31° 3' 34.44" E, at approximately 765 meters above sea level). The area is characterised by summer rainfall, with a humid subtropical climate, average midday temperatures ranging from 20.9℃ (June) to 27.2℃ (January), and an average annual rainfall of 722 mm. The field measurements were carried out over two seasons, from October 2010 to October 2012.

The second data-set for macadamia nuts was obtained from an orchard located in a seasonally-dry subtropical climate on the Schagen Valley commercial farm (25°21'50.36" S, 30°46'46.47"E, at approximately 900 m.a.s.l), roughly 30 km from the town of Nelspruit. The area has an average annual precipitation of approximately 750-850 mm, with an annual average temperature of 23℃ (Schulze & Maharaj, 2004). The cultivar in this site was South Africa’s predominantly-planted ‘Beaumont’ 695 (tetraphylla x integrifolia hybrid). Water-use measurements were collected in the three orchards with varying canopy cover during the 2016/17, 2017/18 and 2018/19 seasons. The fully-irrigated, mature and full-bearing orchards were characterized as having a canopy cover exceeding 60%. Micro-sprinklers were used to irrigate all the orchards, with the irrigation being typically scheduled and the soil water content monitored once a week.

3.3.2.2 Avocadoes

Data collection for ‘Hass’ avocadoes was conducted in an orchard located in the cool, subtropical climate on the Everdon Estate, roughly 10 km from the town of Howick (29° 26’37’’S, 30°16’22’’E, 1080 m altitude) in the KwaZulu-Natal Province of South Africa. The area has a 17-20℃ mean annual temperature range, a 20-23℃ mean January temperature range, and an annual precipitation of 860 mm. Additional water-use measurements were obtained on the McNoon farm (23°43'49.51"S, 30° 8'12.35"E) near Tzaneen in the Limpopo

Province, which has a warm subtropical climate with a mean annual rainfall of 965 mm, a mean temperature of 20-21.5℃, and a mean January temperature of 23-25℃.

Water-use measurements were conducted in Howick during the 2017/18, 2018/19 and 2019/20 seasons, and the T_c measurements in Tzaneen were conducted between December 2018 and January 2020. The fully-irrigated, mature and full-bearing orchard was characterized by a canopy cover exceeding 60%. The additional data that were collected included the Leaf Area Index (LAI), the tree water status, the volumetric soil water content, as well as the yield and quality.

3.3.2.3 Apples

The water-use information and field measurements of high-yielding apple trees were collected from orchards in two apple-growing regions in the Western Cape Province, namely, the Koue Bokkeveld (KBV) plateau region for the 2014/15 season and the Elgin/Grabouw/Vyeboom/Villiersdop (EGVV) region for the 2015/16 season. While KBV experiences very cold winters and generally hot summers, EGVV experiences milder winters and summers. The mean minimum daily temperatures and average maximum summer temperatures are between 8-9℃ and 25-26℃, respectively. Cultivars investigated in this site were high-yielding Golden Delicious and Cripps' Pink/Red apples. For the 2014/15 season, data were collected from two full-bearing orchards at the Kromfontein farm, which were planted to full-bearing Golden Delicious (FBGD) and full-bearing Cripps' Pink (FBCP) apple trees. All these orchards were irrigated by using a micro-sprinkler system, with one micro-sprinkler allocated per tree.

3.3.2.4 Citrus

The water-use data and field measurements of citrus fruits were obtained in Citrusdal in the Western Cape, and Malelane in the Mpumalanga Province. Both orchards were drip-irrigated. In Citrusdal, measurements were taken for 'Rustenburg' Navel orange trees at the Patrysberg farm (32° 27' 15.43'' S and 18° 58' 3.58'' E, at 149 m.a.s.l). The area is characterized by winter rainfall and has an average annual rainfall of 200 mm and average minimum and maximum temperatures of 10℃ and 24℃. The Malelane experimental site that was planted with 'Midknight' Valencia oranges is on a Riverside commercial fruit and sugarcane farm (S25° 26' 39.77", E31° 33' 02.39", at 314 m.a.s.l) in the Mpumalanga Province. Data were collected over a period of two years, from mid-October 2011 to mid-October 2013.

Micrometeorological measurements of ET were recorded in the ‘Rustenburg Navels’ orchards on two separate occasions, from April 25 to 2 May 2011 during early winter conditions, and from 14 March to 3 April 2012 during late summer conditions. For ‘Midknight’ Valencia, ET the measurements took place during two seasonal campaigns from November 2011 to January 2012 in summer, and from June to July 2012 in winter.

3.3.2.5 Nectarines and Peaches

Field data of ‘Alpine’ nectarines were obtained at the commercial Ou Stasie farm near of Wolseley town, in the Western Cape Province. The area is characterized by winter rainfall. Short-range micro-sprinklers were used for irrigation. Data collection was done from August 2010 to June 2013. In addition, sap flow monitoring was conducted for ‘Alpine’ nectarines and ‘Transvalia’ peaches at Rustenburg (25° 46.215’ S; 27º 20.305’ E, at 1150 meters above sea level) in the North-west province. Data collection was done from August 2008 to June 2009. The area is characterized by summer rainfall; therefore, all trees in this orchard were drip irrigated.

3.3.2.6 Pecan nuts

The experimental orchard for ‘Choctaw’ pecans was located at Cullinan (25° 35’ 20.65’’ S and 28° 33’ 31.90’’ E, at 1340 meters above sea level) in the summer rainfall area of the Gauteng Province. The study area has a subtropical climate which is characterised by long and hot summers and short and cold winters, with an average annual rainfall of 673 mm (Schulze & Maharaj, 2004), and daily mean temperatures that vary between 9.7°C and 21.2°C. The field measurements were recorded over three seasons, from September 2009 to May 2012. This orchard was irrigated by using a single micro-sprinkler per tree.

Table 3.1 Additional information on the plant age, density and planting patterns for the selected fruit tree orchards

Fruit type	Age	Density	Planting pattern
Apples (FBGD)	22 years	1667 trees/ha	4 m x 1.5 m
Apples (FBCP)	9 years		
Citrus (Midknight Valencia)	16-18 years	571 trees/ha	7 m x 2.5 m
Citrus (Rustenburg Navel)	15 years	666 trees/ha	2.5 m x 6 m
Alpine Nectarine	8-10 years	1667 trees/ha	1.5 m x 4 m
Transvalia Peach	-	-	2 m x 5 m

Beaumont Macadamia	6-7 years	612 trees/ha	8 m x 4 m
Choctaw Pecan	34-37 years	142 trees/ha	9 m x 9 m
Hass Avocado	5 years	357 trees/ha	7 m x 4 m

Table 3.1 provides additional information on the plant age, density and planting patterns in all the study sites. In addition, all the selected fruit tree species had their weather variables measured continuously by using a complete automatic weather station installed in an open area that had short grass in, or close to, the respective orchards. These measured weather variables included the relative humidity, the maximum and minimum temperatures, the rainfall, as well as the wind speed and direction. The hourly values of these variables were processed into daily averages and were used to calculate ET_o by using the FAO-56 Penman-Monteith equation (Allen et al., 1999). In addition, the T_c of these trees was monitored continuously for the respective seasons, and it was measured by using the heat ratio method of the heat pulse velocity sap flow approach (Burgess et al., 2001) at hourly intervals. ET_c was measured using the open-path eddy covariance system, while E_s was measured by using micro-lysimeters. In some cases, such as with the apples, the ET_c data were corrected by using the Bowen ratio approach, as illustrated by Cammalleri et al. (2010).

3.3.3 Data selection and derivations

The measured crop transpiration (T_c) and evapotranspiration (ET_c) data for each study crop were processed and analysed for each respective season. Additional information, such as the reference evapotranspiration (ET_o), crop coefficients, rainfall and irrigated water volumes was used to consolidate the comparison of the water consumption of these irrigated fruit trees. The average monthly crop coefficients for the respective seasons were used for the comparisons.

Comparisons were also made for the calculated crop coefficients, namely, the basal (K_{cb}), evaporation (K_e) and actual crop coefficients (K_c). This study demonstrated the use of the calculated crop coefficients for estimating and/or quantifying the crop consumptive water-use rates. The FAO-56 crop coefficient approach (Allen et al., 1999) was used to calculate K_c by using the field crop water requirement and reference evapotranspiration (ET_o).

These crop coefficients and the atmospheric evaporative demand (ET_o) were therefore used as gap-filling tools for the crop water requirements (which are numerically equivalent to ET_c) by simply solving Equation 2.12 for ET to get:

$$ET_c = \mathrm{K_c} \times \mathrm{ET_o} \qquad (3.1)$$

Since most of these irrigated crop orchards are heterogeneous across the rows, and there are open spaces between rows, it is necessary to split the ET_c, as in Equation 3.1 into beneficial (T_c) and non-beneficial components, in the form of orchard floor evaporation (E_s). Equation 3.2 is therefore expressed in the discussed dual crop coefficient form as:

$$ET_c = (\mathrm{K_{cb}} + \mathrm{K_e}) \times \mathrm{ET_o} \qquad (3.2)$$

3.4 Results

3.4.1 Macadamia nuts

There were no substantial differences in the seasonal total rainfall for both seasons at the White River study site, with 887 mm being recorded in 2010/11 and 832 mm in 2011/12. However, the rainfall distribution throughout the year differed slightly. The highest monthly rainfall recorded in November, December and January for the 2010/11 season was above 150 mm. In contrast, the wettest period for the 2011/12 season occurred during January and February, while November was relatively dry. Although some rainfall was received in winter, less than 10 mm of the monthly totals was recorded. The 2016/17 season recorded the highest mean annual rainfall of 1170 mm, while the mean annual rainfall for the 2017/18 (760 mm) and 2018/19 (774 mm) seasons was lower than the mean annual rainfall for the Nelspruit region (854 mm).

The average daily transpiration that was measured at the White River orchard varied from 0.12 mm/d to 2.3 mm/d over the two seasons, while the average daily water use for the respective seasons was as follows: summer (1.58 mm/d), autumn (1.4 mm/d), winter (0.85 mm/d) and spring (1.3 mm/d). The daily average transpiration volumes for both seasons were 1.24 mm for the 2010/11 season and 1.31 mm for the 2011/12 season. In contrast, the total annual transpiration volumes were similar, with 451 mm in the 2010/11 season and 478 mm in the 2011/12 season. The total T_c per annum for the Nelspruit orchard varied between 316 mm to 340 mm during the measurement period, with the 2016/17 season recording a higher volume than the 2017/18 season. This difference is most likely attributed to the smaller canopy size of the orchard during the 2017/18 season, compared to the 2016/17 season. The average daily E_s

for the September-October 2017 and May-August 2018 period was 1.21 mm/d and 0.51 mm/d, respectively, while the estimated average daily ET_c volumes for the same respective periods were 2.09 mm and 1.04 mm. As shown by Table 3.2 below, this means that the average daily E_s contributed 58% of the average daily ET_c and 40% for the later period. More rain (37 mm) was received in the September-October period of 2017 than during the May-August 2018 period, thus less irrigated water was applied in the previous period.

Table 3.2 Estimated crop evapotranspiration (ET_c) and evaporation (E_s), with rainfall received and applied irrigation for the mature macadamia orchard at Nelspruit

Dates	N	Average E_s (mm/d)	Average ET_c (mm/d)	E_s of ET_c %	Rain (mm)	Irrigation (mm)
10 Sept - 5 Oct 2017	23	1.21	2.09	58	37	14
1 May - 7 Aug 2018	83	0.51	1.04	40	23	38

The maximum measured ET_c rates were recorded in the White River orchard in spring (5.5 mm/d), followed by summer (4.8 mm/d) and autumn (2.8 mm/d), with the lowest being recorded during the winter (1.3 mm/d). The soil evaporation measurements during these periods reached the highest soil evaporation rates in summer (0.86-1.37 mm/d), followed by autumn (0.76-1.1 mm/d), when compared to winter (0.33-0.57 mm/d).

The actual crop coefficients (K_c) for the ‘Beaumont’ macadamia orchard at White River over both seasons varied from 0.5 to 0.78, as shown by Figure 3.1 below, although more variations generally occurred during the first season (0.5 to 0.78) than in the second season (0.6 to 0.78). Figure 3.1 also shows the variation of the average basal crop coefficients (K_{cb}) across the seasons. However, these coefficients varied more in the first season (0.3 to 0.52) than in the second season. There were reasonably consistent K_c and K_{cb} values in each season, which is typical of many evergreen crops, arguably because there were less, or no, dramatic changes in the respective canopy sizes. These crop coefficients also exhibited a similar trend across the seasons. Lower soil evaporation coefficient values (K_e) (0.18 to 0.31) were observed across the season, which had the smallest variation of the three coefficients.

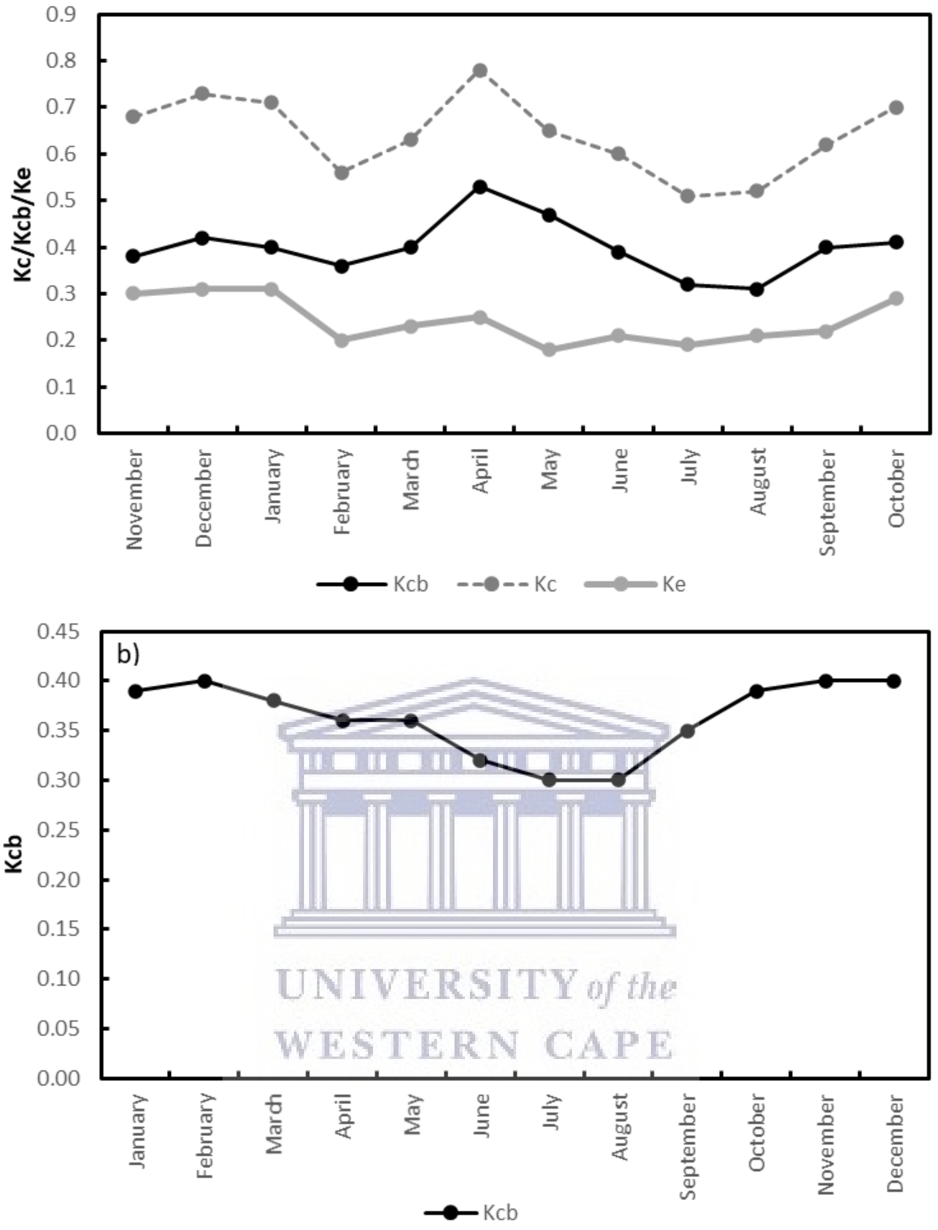

Figure 3.1 Seasonal variations in: (a) soil evaporation (K_e), basal coefficient (K_{cb}), and crop coefficients (K_c) for a full-bearing ‘Beaumont’ macadamia orchard at White River, and (b) basal (K_{cb}) for a full-bearing ‘Beaumont’ macadamia orchard at Nelspruit.

The average K_{cb} value determined over the two consecutive seasons for the Nelspruit orchard was 0.34. The K_{cb} values, which varied between 0.30 and 0.40, reached their average maximum value (0.40) in February for both seasons, due to increases in the canopy size, since the K_{cb} normalises according to the environmental conditions (Taylor, 2021). Similarly, K_{cb} also reached this maximum seasonal value in November and December, after increasing from a low in August, probably due to the decreased canopy size caused by pruning.

3.4.2 Avocadoes

The 2017/18 season recorded a significantly higher mean annual rainfall amount of 1180 mm than the 1013 mm recorded in 2018/19, and 1080 mm in the 2019/20 season. These amounts for the respective seasons were notably higher than Howick's long-term average of 860 mm. A single season of measurements was selected from another mature avocado orchard in Tzaneen, in order to have a contrasting climatic region data-set for modelling. There were considerable differences in weather conditions for Tzaneen, compared to those in Howick. The annual rainfall recorded in 2019 was 719 mm, which was well below the average rainfall amount of 1000 mm per annum.

The total T_c and ET_c for the mature orchard for the 2018/19 season were 678 mm and 752 mm, respectively, as shown in Table 3.3. In contrast, the measured orchard ET_c for the 2017/18 season was 1063 mm, which reflects the changes in the canopy size over the two seasons. The maximum recorded T_c rate was 4.32 mm/d, whilst the lowest recorded rate was 0.17 mm/d. For a more significant part of the season, the measured T_c firmly tracked ET_c, which suggests that soil evaporation (E_s) from this orchard did not constitute a significant proportion of the ET_c (Table 3.4). The trend was the same across all seasons. The orchard in Tzaneen had a seasonal T_c of 476 mm, while the daily T_c ranged from 0.06 to 2.63 mm/d.

Table 3.3 Average daily transpiration and evapotranspiration rates (mm/d) over various seasons in the mature avocado orchards in Howick (2017/18, 2018/19 and 2019/20) and Tzaneen (2018/19)

Season	**2017/2018**		**2018/2019**		**2019/2020**		**2018/19 Tzaneen**	
	T_c (mm/d)	ET_c **(mm/d)**	**T_c (mm/d)**	ET_c **(mm/d)**	**T_c (mm/d)**	ET_c **(mm/d)**	**T_c (mm/d)**	ET_c **(mm/d)**
Spring	-	3.35	1.75	2.12	-	3.12	-	-
Summer	-	3.46	2.01	2.57	-	4.28	1.75	-
Autumn	2.45	2.65	2.02	2.01	-	3.25	1.34	-
Winter	1.75	1.62	1.67	1.55	-	1.93	1.05	-
Average	2.10	2.77	1.86	2.06	-	3.15	0.98	-
Total (mm)	**-**	1063	678	752	-	-	476	-

Table 3.4 Estimated crop evapotranspiration (ET_c) and evaporation (E_s), with rainfall, and applied irrigation for the mature avocado orchard at Everdon Estate. *The irrigation sensor was reported to have failed in November 2018

Season	Average E_s (mm/d)	Average ET_c (mm/d)	E_s of ET_c (%)	Rainfall (mm)	Irrigation (mm)
Spring	0.45	2.11	20	193	35*
Summer	0.60	2.57	22	473	0
Autumn	0.35	2.26	11	566	0
Winter	0.11	1.58	6	106	130

The crop coefficients (K_c) for an 11-year-old Hass cultivar at Howick were derived from the eddy covariance data and they varied between 0.75 and 1.18. These values acknowledged the clear differences across the measured seasons. The general trend of K_c showed lower values during the winter season, recording the lowest in July (0.75). This is attributed to the lower rainfall amounts received during the season, thus lowering the volumes of T_c and E_s, which constitute ET, which influences the K_c. In addition, an apparent decline in the size of the canopy covers, due to pruning, contributed significantly. K_c increased during the spring and into the summer season, as the amount of rainfall and the canopy sizes increased.

Similarly, the K_{cb} trend in Tzaneen started declining after May and into the winter season. However, the lowest value was observed during the spring season (September) when the trees were shedding their leaves. The K_{cb} for Tzaneen varied from 0.20 to 0.43, and some missing data were observed for the October-November period. These seasonal variations in the crop coefficients are depicted in Figure 3.2.

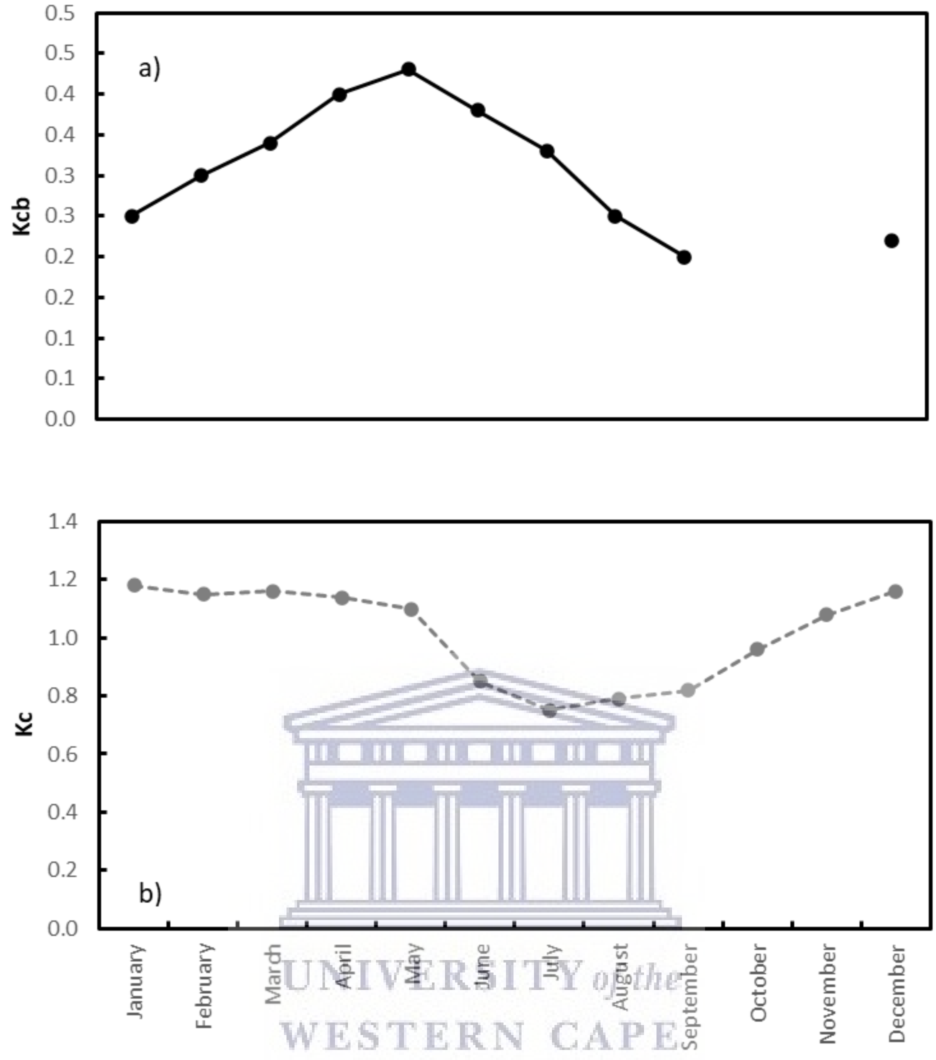

Figure 3.2 Seasonal variations in basal coefficient (K_{cb}) for a full-bearing 'Hass' avocado orchard at Tzaneen and crop coefficients (K_c) for a full-bearing 'Hass' avocado orchard at Howick

3.4.3 Apples

KBV (281 mm) received more seasonal rainfall than the amount received by EGVV (247 mm). However, the long-term annual rainfall in EGVV (>500 mm) was higher than in KBV (350-510 mm). These values show that the rainfall of the two production regions was below the average.

The sap flow rates differed significantly between the FBGD and FBCP cultivars in their respective production regions. An additional point that was noted was that there were no significant differences in the daily maximum and total seasonal T_c of FBGD in both production regions (4.8 mm and 768 mm in EGVV, and 5.0 mm and 787 in KBV), as well as the FBCP cultivars (3.9 and 655 mm in EGVV, and 1.7 and 199 mm in KBV), as shown in Table 3.5.

Table 3.5 Total water usage for the 2014/15 and 2015/16 growing seasons in KBV and EGVV, respectively, where the season starts in September, to June in the following year

	Orchard	T (mm/season)	E_s (mm/season)	ET_c (mm/season)
KBV	FBGD	787	299	1086
	FBCP	621	353	974
EGVV	FBGD	768	342	1110
	FBCP	655	247	902

The FBGD in EGVV measured a peak daily ET_c of 9.3 mm. The Shuttleworth and Wallace (1985) model was used to accurately predict transpiration for the whole season and the ET_c for mature orchards. Therefore, the modelled ET_c and its respective components showed that E_s prevailed in ET_c at the start of the season (September), before the T_c almost doubled it (October), due to the rapid increase of the leaf area after bud break. There was a persistence of this trend throughout the season. For FBGD orchards in both KBV and EGVV, the modelled seasonal ET_c totals were 1086 mm and 1110 mm, respectively, with E_s accounting for approximately 29% of the ET_c. For FBCP, the modelled seasonal ET_c total was 974 mm and 902 mm in KBV and EGVV, respectively, with E_s accounting for approximately 36% of the ET_c. It can be argued that this was due to the more open canopies of the FBCP trees, which allowed a greater magnitude of maximum solar radiation to reach the orchard floor.

The respective crop coefficients for FBGD and FBCP apples were determined from the measured T_c and E_s and the modelled ET_c values. Based on the measured T_c, the basal crop coefficients (K_{cb}) for both cultivars in both regions varied as follows: FBGD in Koue Bokkeveld (0.60 to 0.70), FBDG in Villiersdorp (0.59 to 0.82), FBCP in Koue Bokkeveld (0.42 to 0.56) and FBCP in Villiersdorp (0.52 to 0.65). Likewise, the soil evaporation coefficients (K_e) varied, with FBGD in Koue Bokkeveld (0.28 to 0.37), FBDG in Villiersdorp (0.37 to 0.48), FBCP in Koue Bokkeveld (0.27 to 0.36) and FBCP in Villiersdorp (0.25 to 0.34). For the same full-bearing orchards, the full crop coefficient (K_c) variations were FBGD in Koue Bokkeveld (0.80 to 1.18), FBDG in Villiersdorp (0.84 to 1.11), FBCP in Koue Bokkeveld (0.75

to 1.10) and FBCP in Villiersdorp (0.71 to 0.90). The seasonal variations of all these crop coefficients are depicted in Figure 3.3.

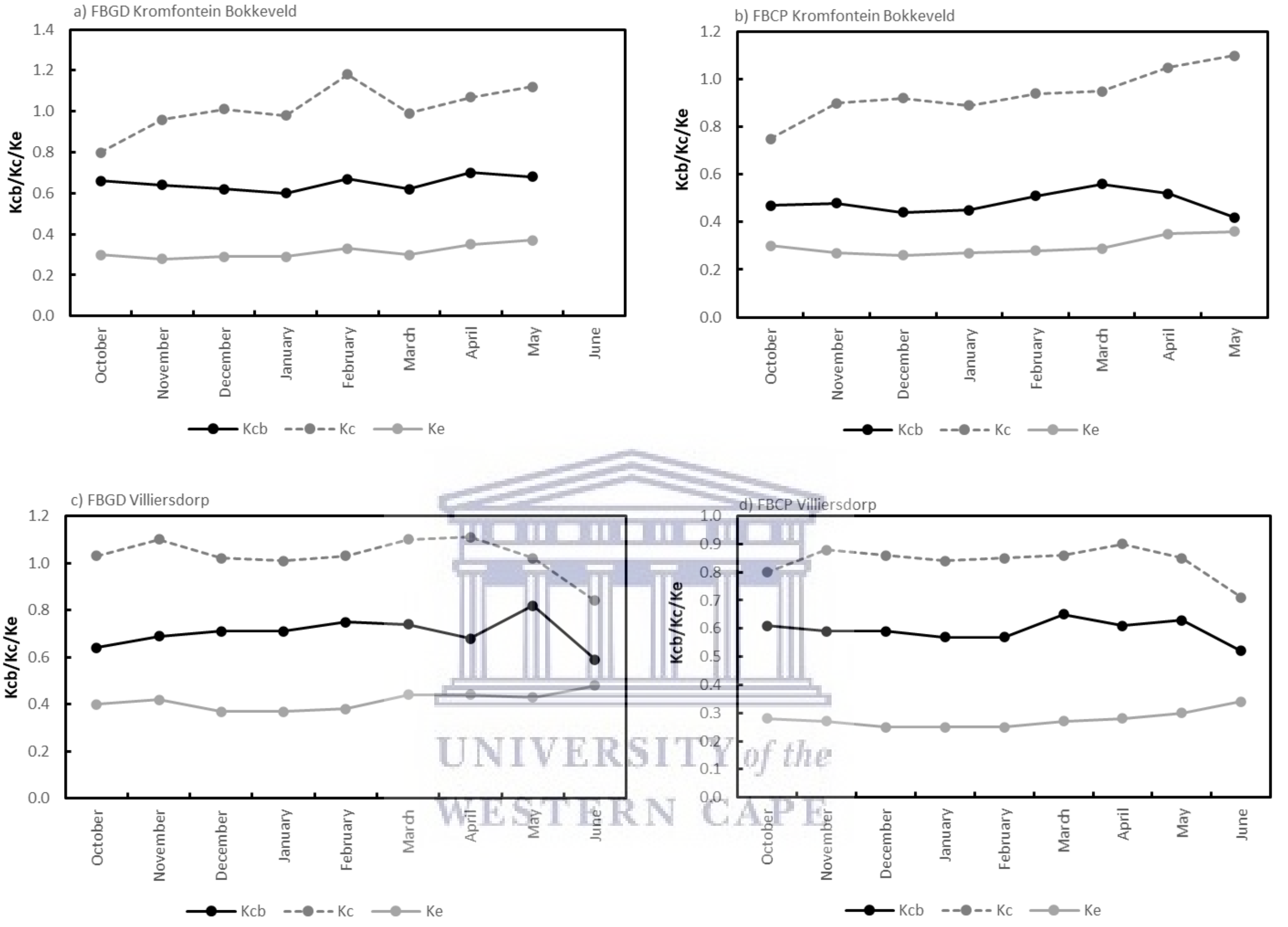

Figure 3.3 Seasonal variations in the soil evaporation (K_e), basal (K_{cb}), and crop coefficients (K_c) for full-bearing apple orchards at KBV (a, b) and EGVV (c, d) planted to 'Golden Delicious' and Cripps' Pink' apple trees

3.4.4 Citrus

In January 2012 and 2013, floods occurred after high rainfall events, in excess of 100 mm, occurred in the region where the ‘Midknight’ Valencia orchard is located. The rainfall amounts recorded in 2012 (921 mm) and 2013 (869 mm) exceeded the long-term average annual rainfall (680 mm) for the region.

The measured daily T_c of the ‘Midknight’ Valencia orchard ranged from a maximum of 2.9 mm/d to a minimum of 0.2 mm/d. The summer season measured an average daily T_c volume of 2.0 mm/d, with the autumn, winter and spring seasons measuring 1.8 mm/d, 1.4 mm/d and 1.8 mm/d, respectively. The annual T_c volumes were 654 mm for the 2011/12 season and 625 mm for the 2012/13 season. There was an increase in T_c in the hot summer months, although it was not significantly pronounced, probably because of the lack of vivid changes in the canopy size. Although the average basal coefficient (K_{cb}) for both orchards was relatively constant over the two seasons, there was a significant difference in their K_{cb} values, with the winter K_{cb} being significantly larger than the summer K_{cb}. Similarly, this increase in K_{cb} was observed in the winter months in Malelane, which has a humid and hot climate. This observation is arguably due to the higher T_c rates in this region.

The data for the 'Rustenburg' Navel orchard showed low ET_c totals, ranging from 0.77 mm to 2.79 mm for the period 25 April to 2 May 2011, which are typical for late summer and early autumn. There was a variation in these ET_c totals, which ranged from 1.39 mm to 2.76 mm during the 14 March to 3 April 2012 period. For the 'Midknight' Valencia orchard, the average ET_c measured at the site was 1.16 mm/d.

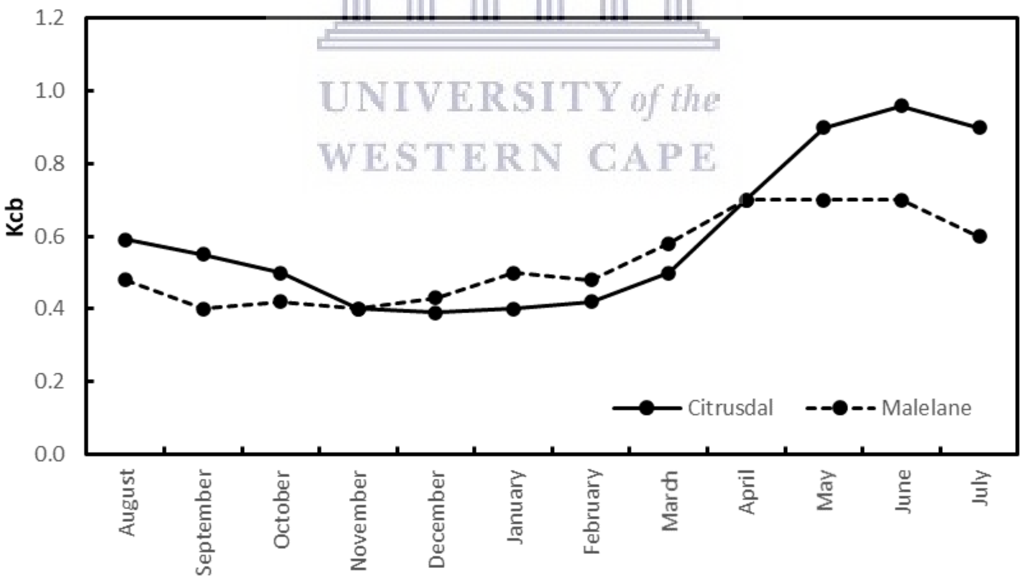

Figure 3.4 Seasonal variations in the basal crop coefficients (K_{cb}) for mature citrus orchards at Citrusdal and Malelane

The basal crop coefficients (K_{cb}) that were determined for the Citrusdal and Malelane orchards showed significant differences, particularly at the beginning and end of the season, as shown in Figure 3.4. However, this was expected, as the published crop coefficient (K_c) values from previous studies exhibited significant differences between citrus orchards (Gush and Taylor, 2014b; Taylor et al., 2015). The K_{cb} values in the two orchards varied for Malelane (0.40 - 0.70) and Citrusdal (0.40 - 0.96). The general trend of the K_{cb} showed lower values in the summer than in the winter, which is contrary to many deciduous crops. These values for both orchards were comparable during the summer season and exhibited minor variations from November up to April, with November and April recording the same K_{cb} values. Beyond April, the K_{cb} values varied significantly between Citrusdal and Malelane, and this difference was consistent throughout the winter season.

3.4.5 Nectarines and Peaches

The annual rainfall totals recorded at the Wolseley site during this period were consistent, although they increased slightly over the three years. In the 2010/11 season, the rainfall totalled 559 mm, whereas it amounted to 586 mm and 584 mm, respectively, in the 2011/12 and 2012/13 seasons. While approximately 25% of the total annual rain fell during the summer season (October-March) of the first two years, only 10% was received in the summer of the last year (2012/13), which implies that it was a drier summer season than in the previous years.

In all three seasons, the daily sap flow volumes exhibited a consistent trend. The total annual T_c was 484 mm, 496 mm, and 306 mm for 2010/11, 2011/12 and 2012/13 seasons, respectively. The first two seasons had similar annual T_c totals, with a slight increase in the second season, which was attributed to the small increases in the leaf area and the favourable weather conditions observed in the 2011/12 season.

Useful sap flow trends were also observed in the 'Transvalia' peach trees at Rustenburg. There were notable sap flow increases from spring to early summer, in response to the increasing leaf area, before a decline in autumn, as the leaves began to drop off. With regard to the total consumptive water use, a peach tree transpired 160 mm during the season, whilst the maximum daily consumptive water use volumes reached 1.24 mm/d.

The observed ET_c volumes at the 'Alpine' nectarine orchard ranged between 2.84 mm/d and 5.47 mm/d during the post-harvest period in January-February 2011. However, due to post-harvest summer pruning, there was a decrease in the LAI, which caused a decline in the T_c volumes. In August 2011, the observed ET_c volumes ranged from 0.9 mm/d to 2.0 mm/d. High total ET_c volumes, ranging from 4.6 mm/d to 7.5 mm, were recorded from November 2012, although this period was characterized by hot, dry days with no rainfall events.

The T_c and ET_c results for the ‘Alpine’ nectarine orchard were combined with the daily ET_o to derive the monthly K_{cb} and $K_{c,}$ which depict the seasonal variation in T_c and ET_c, relative to the evaporative demand. The phenological changes in the nectarine trees that influence the K_{cb} values across the respective seasons include winter dormancy through bud break (June to mid-July), full bloom (end of July), fruit set (beginning of August), fruit development (beginning of August until mid-November) up to harvesting (end of November) (Gush & Taylor, 2014a). The K_{cb} values increased from July and reached their maximum value in October (Figure 3.5), mainly because the increased LAI was influenced by the active shoot growth. However, pre-harvest summer pruning in October motivated the notable slight decrease of the K_{cb} values during the mid-October to early-December period. Because there is no demand for water by the fruit during the post-harvest period, there was a continued decrease in the K_{cb} values during the early-December to early- February period.

In addition, a decrease in the shoot growth and in the leaf area, as a result of post-harvest summer pruning, may also have contributed to the decrease in these K_{cb} values. The K_{cb} and K_c values varied from 0.40-0.60 and 0.40-0.71, respectively. The K_{cb} values increased notably from February to April, which is thought to be attributed to a post-harvest climax. Conversely, the K_{cb} values declined from April to June because of the decreased T_c volumes. The K_c values for the ‘Alpine’ nectarine cultivar also displayed a similar trend to the K_{cb} values across the seasons (Figure 3.5), although they had much higher values, due to the contribution of K_e. On the contrary, Figure 3.5 shows an almost inverse trend of the K_e values across the seasons, compared to the other crop coefficients. Because there were no recorded T_c volumes in July, K_e recorded its maximum value, which equalled K_c, as E_s was the sole contributor to ET_c.

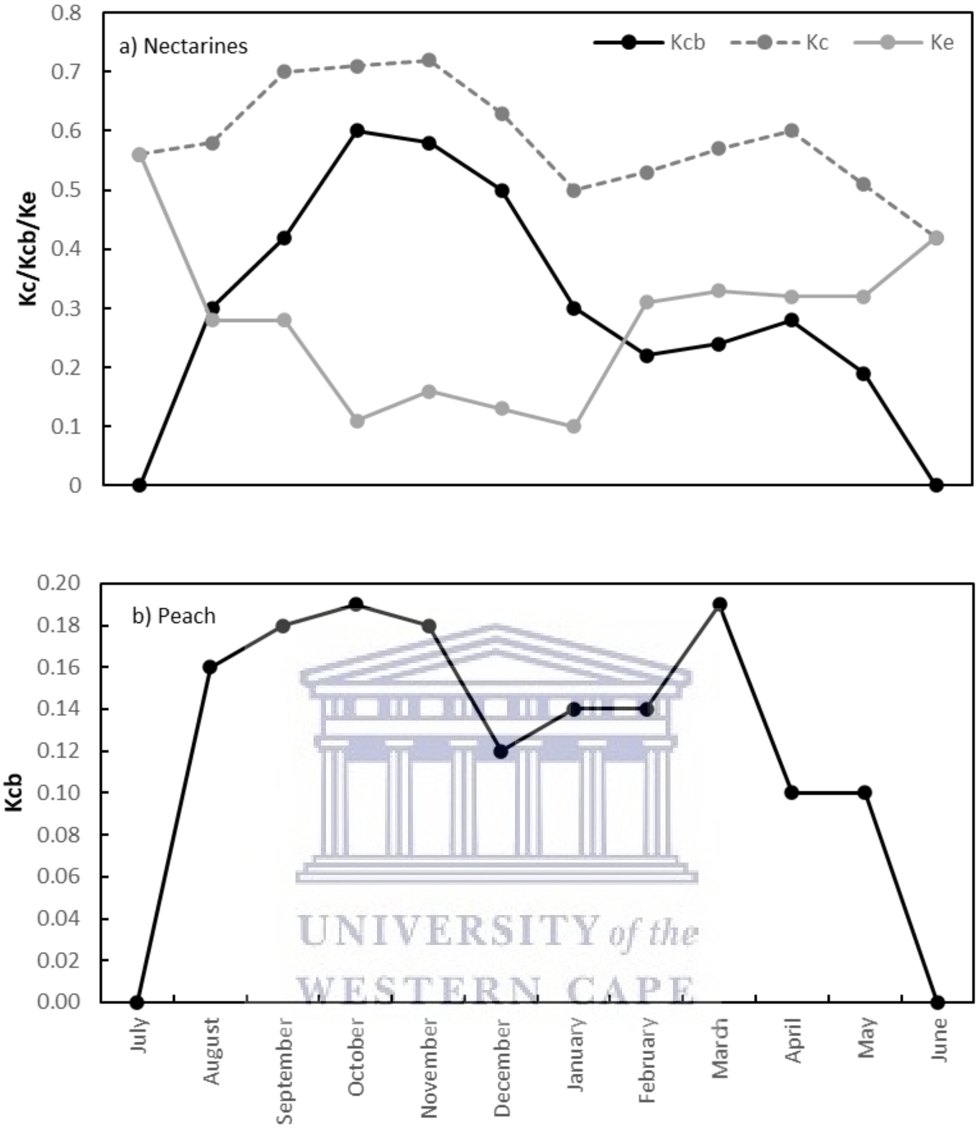

Figure 3.5 Seasonal variations in the (a) soil evaporation (K_e), basal (K_{cb}), and crop coefficients (K_c) for mature nectarine orchards at Wolseley and (b) basal crop coefficient (K_{cb}) for a mature peach orchard in Rustenburg

There was a general decrease in K_e from the winter into the spring (July to October), probably due to the fruit development on the trees, which increased the T_c and the canopy cover and could have inhibited much solar radiation from reaching the orchard floor. The low K_e values were consistent throughout the summer before they increased significantly in early January and into the autumn season.

It should be noted that insufficient data on ‘Transvalia’ peaches were available for use in this study. The seasonal variations of K_{cb} for ‘Transvalia’ peaches followed almost the same trend as that of ‘Alpine’ nectarines. K_{cb} values varied between 0 (July and June the following year) and 0.19 (October and March the next year), as shown in Figure 3.5. They increased from July and reached the maximum value in October, due to the active shoot growth and an increase in the leaf area, before starting to decline between October and the end of November, as this is a post-harvest period, when the water demand of the tree is low. Unlike nectarines, the K_{cb} values of the peaches increased notably in the summer season (from December to end-February) and reached a maximum value in March (0.19), due to the post-harvest root growth. However, the K_{cb} values declined from March to June, due to a decline in the T_c volumes associated with leaf drop, which resulted in a decrease in sap flow activities.

3.4.6 Pecan nuts

The total rainfall received per season at the Cullinan site varied substantially between the seasons, with the 2009/10 season recording 770 mm, 2010/11 receiving 520 mm, and 2011/12 receiving a total of 422 mm. The highest monthly total rainfall for the 2009/10 season was received in November (159 mm) and in April (164 mm). In contrast, in the 2010/11 season, the monthly total rainfall for November was 159 mm, 155 mm in January, and 125 mm in December of 2011/12.

During the growing season, the ‘Choctaw’ pecans had an average T_c rate that ranged from a minimum of 1.4 mm/d to a maximum of between 5.7 mm/d and 7.1 mm/d. These variations throughout the season were influenced by changes in the canopy size, which is typical of deciduous species. The average water use across the seasons was as follows: spring (3.1 mm/d), summer (3.97 mm/d) and autumn (3.51 mm/d). There were comparable seasonal T_c totals across the three seasons, namely, 2009/10 (846 mm), 2010/11 (888 mm) and 2011/12 (861 mm), with the slight variation between seasons influenced by various factors, including the canopy size and development, the soil water content and climate variability. While the daily T_c measured for February 2012 ranged between 3.1 mm/d and 5.1 mm/d, the daily measured ET_c rates ranged between 2.3 mm/d and 7.5 mm/d. These volumes implied that the T_c contributed 76% of the ET_c, thus the remaining 24% was contributed by the E_s. During this period, the measured $E_{s,}$ which ranged between 0.86 and 1.49 mm/d, had an average of 1.28 mm/d. The estimated daily E_s, using the FA0-56 model, varied between 0 mm (at the end of March to the end of April 2010) to 3.2 mm (October 2011), around the time when the rainfall and irrigation occurred in the orchard. The E_s was normally higher during the September-October period because the canopy size was smaller and the ET_o rates were high. Likewise, the seasonal E_s

totals were high in their respective seasons, namely 2009/10 (181 mm) and 2011/12 (175 mm), due to the slightly lower canopy cover. However, the 2010/11 season recorded the lowest seasonal E_s total of 72 mm.

The ET_c values varied from a minimum of 1.0 mm/d to a maximum of 6.5 mm/d, to 8.5 mm/d during the October-November period, when there was a smaller canopy cover and the ET_o values were high. The ET_c values during the winter season were negligible because there was no rainfall and no irrigation activities, and the trees were also leafless. For the other respective seasons, the daily ET_c averages were as follows: 4.05 mm/d (spring), 4.69 mm/d (summer) and 3.52 mm (autumn). While the highest seasonal ET_c totals at Cullinan occurred during the 2009/10 season (1031 mm) and the 2011/12 season (1050 mm), the lowest values occurred during the 2010/11 season. The contribution of E_s to the total ET_c across the three seasons was 18% (2009/10), 8% (2010/11) and 17% (2011/12).

The K_{cb} and K_c value trends of 'Choctaw' pecans in Cullinan varied between 0.50-1.20 and 0.70-1.20, respectively, and were reasonably constant across the different seasons. As shown in Figure 3.6, these values increased in the October-November period (at the beginning of the season) to December, when the canopy cover of the trees increased, thus there was an increase in both the T_c and ET_c. Although both the K_{cb} and K_c values declined from December to January, there was a reasonable increase after January, and they reached a maximum in April, when the pecan ET_c exceeded ET_o, due to an increase in the leaf area from the second flush of leaves. However, these values eventually decreased at the same rate towards May (at the end of the season) when the leaf drop began. Both K_{cb} and K_c reached their maximum monthly value of 1.20 in April and confirmed the expectations of a high crop coefficient for pecans.

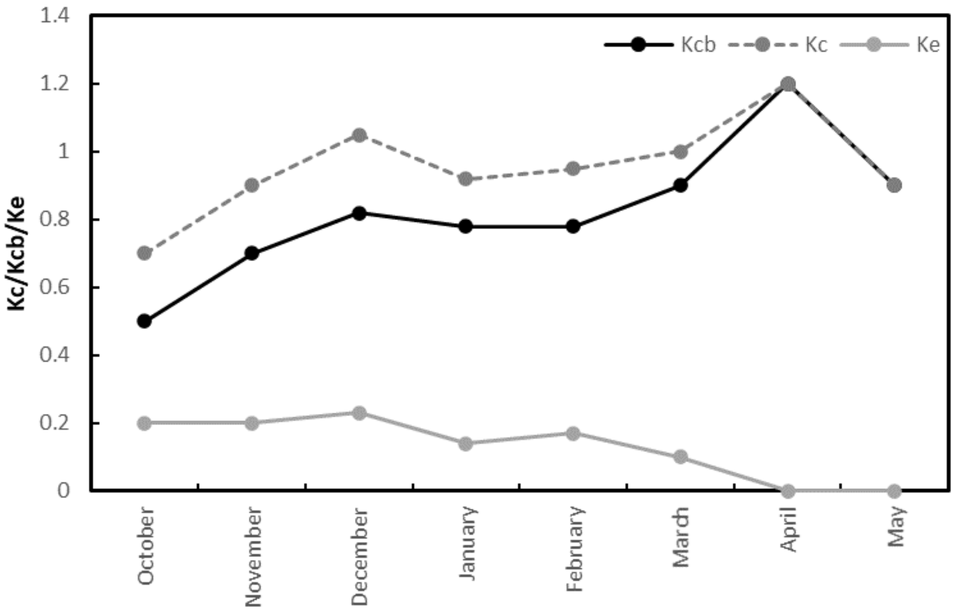

Figure 3.6 Monthly crop for mature pecan orchards at Cullinan in Gauteng

Although April and May recorded zero K_e values, there were generally slight seasonal variations of K_e (Figure 3.6). This can be attributed to the maintenance of the soil water content, due to effective irrigation by the grower. Low values of K_e throughout the season were a result of the higher root water uptake and higher rainfall interception by the pecan trees, which caused less rainfall to reach the orchard floor.

3.4.7 Comparison of consumptive water-use rates

For the orchards in this study, the amount of rainfall received, the evaporative demand and the size and characteristics of the canopy were the main factors that influenced the consumptive water use and the ET_c/ET_o ratio of macadamia nuts, avocadoes, apples, citrus, nectarines, peaches and pecan nuts. The six fruit tree species exhibited significant differences in their seasonal and annual patterns.

Primary data on the dynamics in the fractional vegetation cover and LAI to link with the dynamics of T_c and ET_c was not readily available. The graphical representation of the LAI dynamics for fruit tree species is found in the report by Gush & Taylor, (2014a). However, seasonal LAI peaks for the respective fruit species showed that pecan species had the highest LAI peak of 6.5 $mm^{-2}mm^2$, followed by macadamia nuts (5.0-6.0 $mm^{-2}mm^2$), avocados (4.0 $mm^{-2}mm^2$), citrus (3.6 $mm^{-2}mm^2$), nectarines (3.35 $mm^{-2}mm^2$) and peaches (the effective peak could not recorded due the effects of frost).

The seasonal patterns for crop transpiration (T_c) were arguably similar among apples, pecans, nectarines and citrus, mainly during the summer season, which is contrary to those of macadamia nuts and the peach species (Figure 3.7). 'Choctaw' pecans recorded the highest average monthly T_c volumes and the highest annual T_c totals of 888 mm. Likewise, full-bearing Golden Delicious apples recorded equally high average monthly and annual T_c totals of 787 mm, while 'Hass' avocadoes recorded the third-highest annual T_c totals of 678 mm.

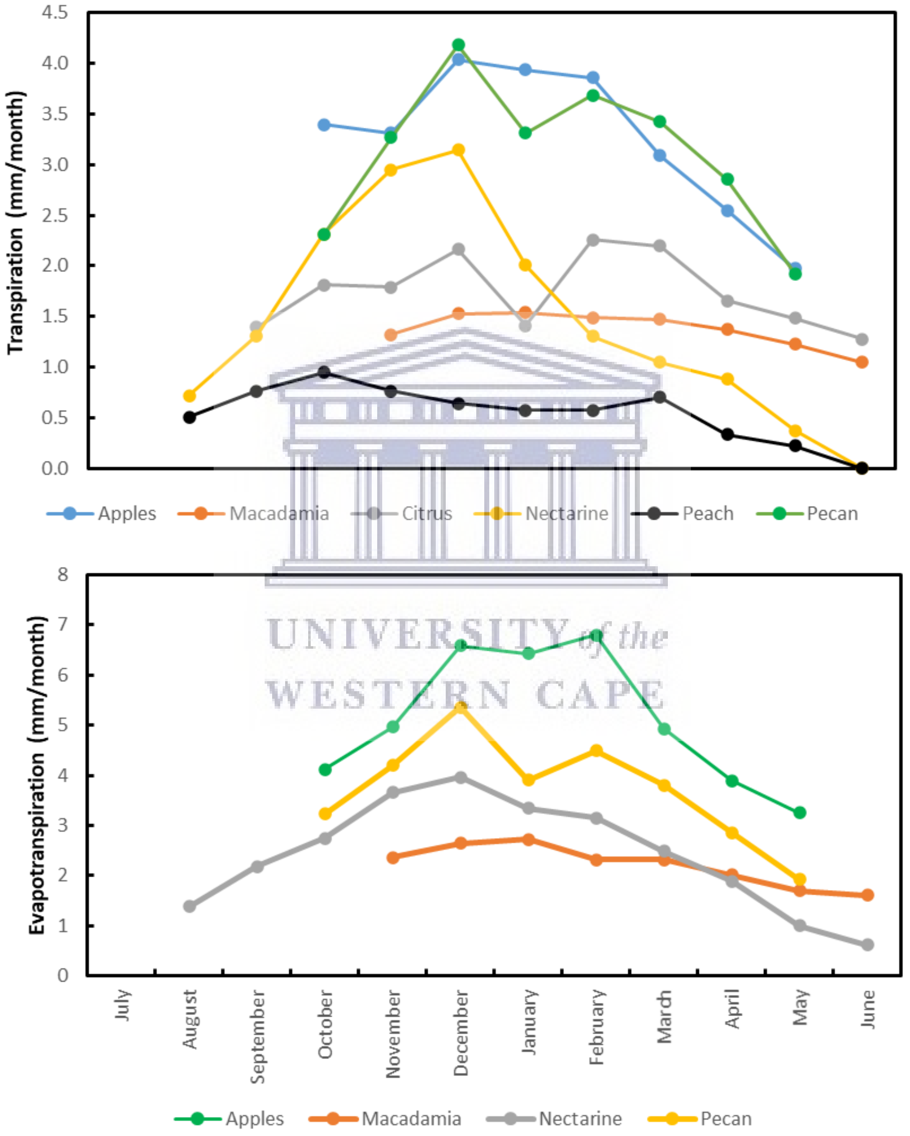

Figure 3.7 Comparison of the seasonal variations of daily crop transpiration (T_c) and evapotranspiration (ET_c) for various fruit tree species. A full-bearing Golden Delicious orchard was chosen for apples, whilst a 'Midnight' Valencia orchard was chosen for citrus

The T_c for avocadoes closely tracked the ET_c because of the very low soil evaporation (E_s). The seasonal T_c patterns of 'Midknight' Valencia oranges were comparable with those of pecans, especially with the sudden decrease in T_c during January before rising again in February, when they recorded an annual T_c of 654 mm. However, this citrus species recorded a low daily average T_c of 0.2 and 2.9 mm, like the 'Beaumont' macadamia nuts (0.12-2.3 mm). 'Alpine' nectarines arguably had similar seasonal T_c patterns to pecans and apples, although they recorded lower monthly average T_c volumes and annual T_c totals (496 mm). The seasonal T_c patterns for 'Beaumont' macadamia nuts did not vary much, especially during the summer and autumn seasons, although the values started to decrease slightly towards winter. This nut species recorded the second-lowest average monthly T_c volumes and annual T_c volumes (478 mm), which was higher than for those of 'Transvalia' peaches, with 62 mm.

The seasonal patterns of the average monthly ET_c of apples, pecans, nectarines and macadamia nuts followed a similar trend across the growing season. The ET_c values started low in the spring season and gradually increased with time, as the summer season approached; however, they declined in January for apples, pecans and nectarines (macadamia nuts only declined in February). Notably, the ET_c values of all species declined towards the winter season (Figure 3.7). Apples recorded the highest recorded annual ET_c totals (1086 mm) among the fruit species, followed by avocadoes (1063 mm) and pecans (1050 mm). However, pecans had the maximum average daily ET_c rates, which varied between 1 to 6.5 and 8.5 mm/d across all seasons, while nectarines had the maximum daily ET_c rate recorded in November (7.5 mm/d) and January/February (5.5 mm/d), followed by macadamia nuts in the spring season (5.5 mm/d) and apples across all seasons (5.3 mm/d). Citrus trees recorded a low average daily ET_c rate of 1.2 mm/d across all seasons.

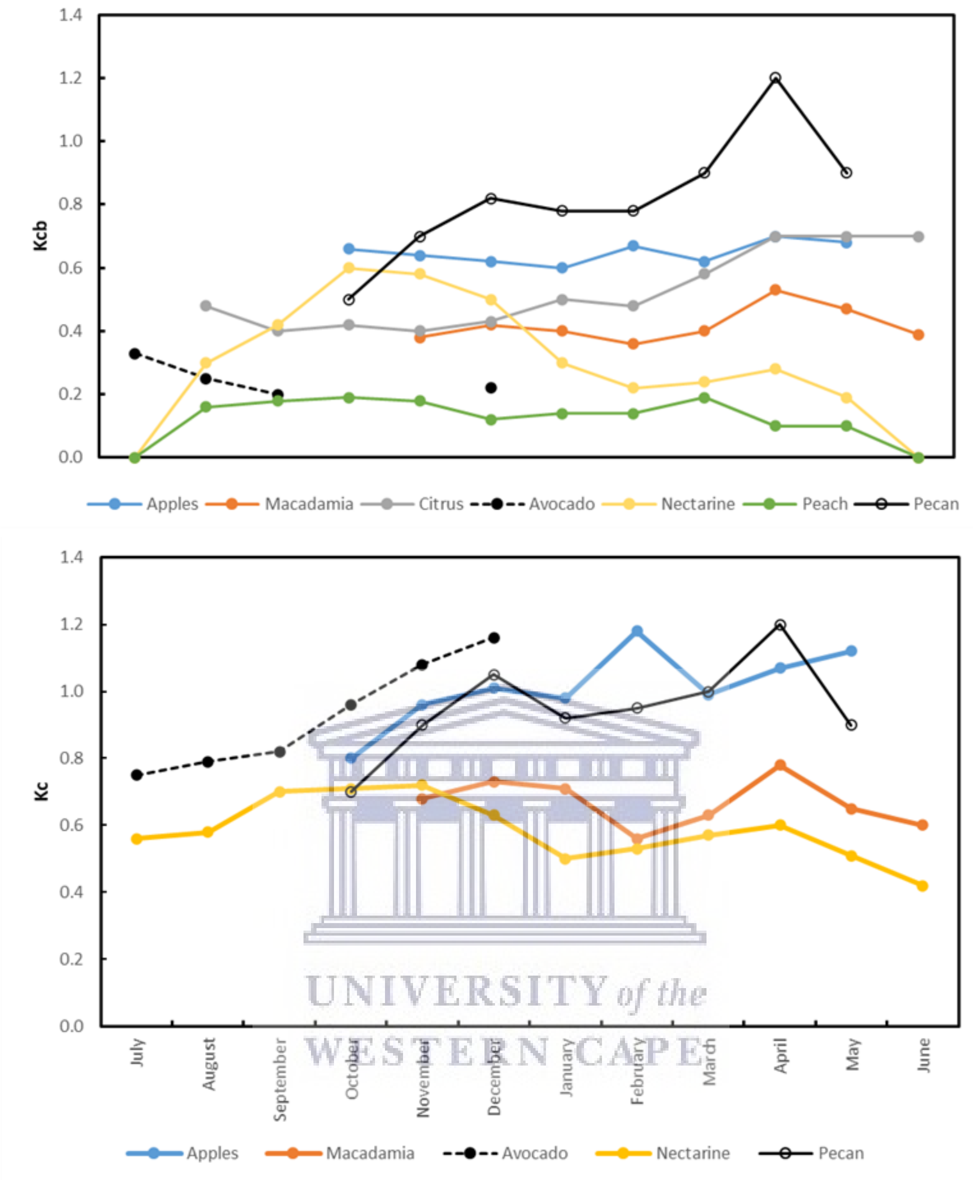

Figure 3.8 Comparison of the seasonal variations of basal crop coefficients (K_{cb}) and full-crop coefficients (K_c) for various fruit tree species. A full-bearing Golden Delicious orchard was chosen for apples, whilst 'Midnight' Valencia orchard was chosen for citrus

The average monthly patterns of the basal crop coefficients (K_{cb}) followed a similar trend across the growing seasons for almost all the fruit species. However, pecans had significantly higher values than the rest, especially during autumn. Unlike the other species, which have minimal variations in their K_{cb} values, nectarines exhibited significantly high variations and recorded zero during the winter months of June and July (Figure 3.8). Similarly, the peach species also recorded zeros during this period. The K_{cb} values of nectarines gradually decreased across the summer season before picking up in autumn. Pecan nuts recorded the highest K_{cb}

values (0.50-1.20) among the fruit species (Figure 3.8), followed by apples (0.60-0.70), citrus (0.40-0.70), nectarines (0-0.60), macadamia nuts (0.3-0.52), avocadoes (0.20-0.43) and peaches (0-0.19). On the contrary, the average monthly patterns of the full crop coefficients for the fruit tree species followed different trends across the growing seasons. As shown in Figure 3.8, they all followed their respective patterns, with pecans recording the highest K_c values (0.70-1.20), as expected, followed by apples (0.8-1.18), avocadoes (0.75-1.18), macadamia nuts (0.5-0.78) and nectarines (0.42-0.71).

The average daily evaporative demand of the study sites/area, which is represented by the reference evapotranspiration (ET_o), as shown in Table 3.6 for each month of the year. It should be noted that the evaporative demand is reflective of the energy to drive ET in general and not for a specific plant. Therefore, the ET_o reported in the table is reflective of the site/area and not necessarily on the plant. KBV (apples) had the highest evaporative demand, followed by Wolseley (nectarines), while Cullinan (pecans), Rustenburg (peaches), Malelane (citrus) and White River (macadamia nuts) had slightly different volumes.

Table 3.6 Daily averages for each month of the reference evapotranspiration (ET_o) of various irrigated study sites

	KBV	White River	Malelane	Wolseley	Rustenburg	Cullinan
August	-	-	-	2.39	3.18	-
September	-	-	3.49	3.12	4.23	-
October	5.14	-	4.32	3.86	4.99	4.61
November	5.17	3.48	4.48	5.08	4.26	4.67
December	6.51	3.63	5.04	6.29	5.34	5.10
January	6.56	3.84	2.82	6.69	4.11	4.25
February	5.76	4.13	4.71	5.94	4.09	4.72
March	4.98	3.68	3.79	4.36	3.69	3.81
April	3.64	2.59	2.37	3.15	3.31	2.38
May	2.90	2.61	2.12	1.96	2.21	2.14
June	-	2.68	1.82	1.49	2.25	-
Average ET_o	5.08	3.33	3.49	4.03	3.79	3.96

3.5 Discussion

The selected fruit tree species have high water requirements that need to be complemented by adequate rainfall volumes and supplemented by sufficient irrigation water. The crop water requirements are influenced by various factors, namely, the cultivar physiology, the phenological stages of a plant, the plant age, the density, climatic region, the geographical location, the availability of water, the size of the orchards, on-farm crop management practices, etc.

It is widely understood that the consumptive water use rates are usually significantly influenced by the cultivar, irrespective of the canopy cover. However, this study identified that canopy density and fractional vegetation cover were the overriding factors in control of the consumptive water use of the selected fruit tree crops. More specifically, the canopy development and higher root water uptake of pecans throughout the season is attributed to their high consumptive water-use rate, more than the other species. Similarly, a rapid increase in the leaf area of apple trees after bud break influenced their high T_c rates. According to Bidinger and Johansen (1988), the rate of water lost through the plant leaves reaches a peak as the crop approaches full canopy cover. The large canopy size in the apple orchard inhibited solar irradiance from penetrating the orchard floor, which resulted in high volumes of E_s. Thus, T_c became the significant flux in the orchard and contributed to 78% of the orchard's ET_c. In addition, there is a high chance of rainfall interception by the large canopies, which reduces the volume of effective rainfall reaching the orchard floor. Like apples, avocadoes had a large leaf area due to the canopy developments during the experimental period, which allowed high volumes of T_c to be recorded. This is consistent with many other fruit species, including macadamia nuts (Gush & Taylor, 2014a) and avocadoes (Mazhawu et al., 2018; Taylor, 2021). Several strict pruning events in the avocado orchards influenced the density of the canopy, the LAI measurements, and therefore, the water use of the fruit. This can probably be contributed to the higher recorded T_c rates of pecans and apples. Similarly, the decline in the T_c of macadamia nut, nectarine and peach trees after November was arguably attributed to post-harvest summer pruning and a decrease in the shoot growth activity. With regard to the peach trees, a gradual reduction in LAI, due to the leaf drop and senescence that occurred in the autumn season, contributed to these low rates. Arguably, this causes a decline in the sap flow activity of the tree and the chance of a complete cessation of the sap flow activities, once the winter season is reached. This influence of the canopy size on the crop's consumptive water use requires the farmer to carefully manage the canopy size, in order to reduce the consumptive water use rates and non-beneficial water use.

Although it appears that the physiological effects of the cultivar on consumptive water use are significantly less than those of the canopy cover in mature orchards, their notable contribution cannot be ignored. Macadamia nuts are drought-resistant or tolerant and have physiological mechanisms that allow them to adapt to a lower water availability (Gush & Taylor, 2014a).

These attributes influence the water-use rates of the species and are probably the reason for little variations in their average monthly T_c across the seasons. Like macadamia nuts, citrus trees have a greater stomatal control of T_c than most fruit species, which is attributed to the significant resistance in the transportation of water within the tree. Fruit tree crops with a high stomatal closure and drought tolerance require less seasonal water volumes than other species.

The 'Hass' avocado cultivars that received higher amounts of rainfall than other selected fruit species attracted little or no irrigation water supply, as there was adequate effective rainfall reaching the orchard floor and plant roots. Very few irrigation activities were conducted in the summer and autumn seasons because of the high rainfall amounts received at the Everdon Estate. Instead, the rainwater was sufficient to meet the crop's water requirements, and although less on-farm water resources were used in the avocado orchard, the expected crop yield was sustained. Therefore, the goal was met of boosting economic advance by increasing the crop yield, whilst reducing the costs. However, there were cases in orchards with less dense canopies, such as apples, where there was significant penetration of solar irradiance that resulted in the loss of water through E_s. This compels farmers to take measures to ensure that frequent irrigation activities are practised, in order to provide the orchard floor with a significant volume of soil water, especially during the hot and dry seasons. Although pecans had the highest T_c rates, frequent irrigation in apple orchards caused them to record the highest annual ET_c (1086 mm) and average monthly ET_c volumes. Dzikiti et al. (2018) also highlighted the fact that there was residual water in the orchard soil from the winter rains, even after the harvest. Peach trees that recorded the lowest consumptive water use rates among the selected fruit tree species were affected by waterlogging conditions because of the excessive water supply and the late frosts, which killed its flowers. Excess rainfall and/or excessive irrigation are detrimental to the growth and production of fruit, as they are a source of waterlogging and the leaching of the soil's nutrients. Other than the availability of water and a canopy cover, the rate of water loss in a crop depends on the evaporative demand of air (Bidinger & Johansen, 1988). Apple trees had the highest reference evaporative demand of air, followed by nectarines and pecans, which also explains their dominant consumptive water-use rate, compared to the other species.

Crop coefficients that account for specific orchard conditions contribute to the crop water requirements and are influenced by soil management, soil salinity, irrigation methods and irrigation scheduling. The K_{cb} values for most deciduous crops, such as apples, nectarines, pecans, peaches, etc., are higher during summer and lower in winter. However, there was evidence that citrus fruit trees exhibited quite the opposite trend. In this study, the K_{cb} values differed widely between fruit tree species, with low canopy-cover orchards (or those that experienced post-harvest pruning) appearing to experience lower crop coefficient values than high canopy-cover orchards. However, there is a need to find an approach that adjusts these coefficients for climate and vegetation, as attempted by Allen and Pereira, (2009a), for a more precise prediction of crop water use. Attempts have been made to review and update these crop coefficients for field and vegetable crops (Pereira et al., 2020; Pereira, et al., 2021), but there is still a need to find a more accurate procedure that adjusts them to the local climate and makes them easily-transferable between orchards. The sole aim is to reduce the non-beneficial water consumption by crops, in order to conserve water.

3.6 Conclusion

This synthesis and comparative study of various fruit tree crops grown in South Africa has exhibited how multiple factors influence the individual differences in their consumptive water-use rates. Although it is vital and necessary to understand the physiology of specific crops, when comparing their consumptive water use, this study established that the canopy size (leaf area) played a major role in influencing the seasonal water use of the respective orchards. Therefore, canopy management is essential for obtaining a high fruit yield and for using less water. From the assessment conducted in this study, the amount of water required by the orchard (rainfall plus irrigation water) depends on specific consumptive water use rate of crops, thus there is a need to obtain accurate estimates of their water requirements by using various approaches, including the FAO 56 crop coefficient approach.

This study established that ‘Choctaw’ pecans had the highest annual crop transpiration (T_c) rate of 888 mm, while the lowest annual T_c volumes were recorded in the ‘Transvalia’ peach orchard. The overriding factor that influenced these high T_c rates was their canopy development (canopy size) throughout the season and the higher root water uptake, compared to that of the other fruit species. Pecans had the highest LAI averages of all the crops, although there were notable cases of leaf senescence in the autumn season. A relatively low LAI influenced the low T_c rate of the peach species, due to pruning activities and the destruction of flowers by the late frost. Apple orchards contributed significantly to soil evaporation (E_s), as the incoming solar radiation could penetrate the wet orchard floor. Of all the available data, the ‘Midknight’ Valencia oranges had the lowest ET_c rates.

The conclusion of this study is framed into two significant points. Firstly, the study demonstrated the need to investigate the transferability of crop coefficients, as these may change, based on the canopy size. In addition, the crop coefficients may vary, based on the orchard planting density, the tree age, orchard management, etc. Secondly, in a water-scarce country, it is necessary to investigate less water-intensive crops that are more adapted to drought, while still achieving full production and yield. The overall choice of farmers as to which crops to select for cultivation depends mainly on the market and is thus driven by income and profits.

Overall, there is a need for further local studies on the quantification of the consumptive water use of pecans. Although attempts have been made to adjust the crop coefficients of various fruit tree species, there is also a need to formulate a relatively simple approach for adjusting and/or determining these crop coefficients and to make these measurements easily accessible to farmers. More so, future studies need to quantify the optimal water requirements of the crops being investigated. There is need to understand how much optimal water is required at agiven stage of crop development. Crop coefficients are indicative of the amount of water used, which could be far more than the optimal required for an optimal yield, depending on the type of plant. Some plants will continue to pump out water more than what they require for optimal performance.

CHAPTER FOUR: IMPROVEMENT OF THE ALLEN AND PEREIRA (2009) APPROACH FOR CALCULATING THE CROP COEFFICIENTS OF SELECTED IRRIGATED FRUIT TREE TYPES, USING READILY AVAILABLE DATA

4.1 Chapter Summary

The Food and Agriculture Organisation (FAO) 56 crop coefficient approach is the most successfully used reference method for estimating crop coefficients that assist farmers with effective irrigation management. Allen and Pereira (2009) adjusted and improved the FAO-56 approach by introducing the crop density function, which is determined from the measurements and observations of the crop height and fractional vegetation cover. This study modified the Allen and Pereira (A&P) (2009) method accordingly by adjusting the stomatal sensitivity function (Fr) using three methods suggested in the literature. These methods include replacing the ratio of resistance (r_l/100) with (i) another ratio of resistance (r_s/50), (ii) r_l/α where α is a resistance parameter for the specific crop, and (iii) using a varying mean leaf resistance value that is measured or estimated throughout the season. These were used together with specific fruit tree data, as well as the measured and observed data in orchards. The improved model was then used to derive the basal crop coefficients (K_{cb}) for the selected fruit species. Ideally, the improved K_{cb} values are used to derive the full crop coefficients (K_c) of the orchard by considering the contribution of cover crops; however, this study did not derive K_c to test the performance of the model, because there was insufficient measured crop evapotranspiration (ET_c) data. Overall, the model produced satisfactory results where the derived K_{cb} were comparable with the measured K_{cb} values with of the respective statistical analysis results, namely: (i) macadamia nuts (R^2 =0.94, RMSE = 0.01, Mean of measured data = 0.44), (ii) nectarines (R^2 = 0.78, RMSE = 0.02, Mean of measured data = 0.37), (iii) peaches (R^2 = 0.80, RMSE = 0.01, Mean of measured data = 0.31), (iv) pecans (R^2 = 0.89, RMSE = 0.01, Mean of measured data = 0.22) and (v) citrus (R^2 = 0.87, RMSE = 0.03, Mean of measured data = 1.19). Moreover, the mean error showed that the A&P approach underestimated the K_{cb} of macadamia nuts, nectarines and peaches, while it overestimated that of the pecans and citrus fruits. This study argued that the derived K_{cb} were more of a better representation of the pecan trees than the actual measured values. However, a more detailed analysis, using the estimation of the crop transpiration (T_c) calculated as the product of K_{cb} and the reference evapotranspiration (ET_o), showed that there were inconsistencies when the model estimated the T_c during the post-harvest period. Overall, the use of fruit tree-specific data, which are representative of the specific fruits in the A&P approach, has a probable chance of accurately determining the crop coefficients and estimating the consumptive water use of fruit orchards.

4.2 Introduction

An increase in the evaporative losses should be expected in South Africa over the years, due to the effects of climate change (Midgley et al., 2015). Therefore, it is critical that farmers practise efficient irrigation in order to remain sustainable. Effective guidelines are required to efficiently utilise the available weather data from a vast network of automatic weather stations located across the country more efficiently. Farmers in South Africa use the published Food and Agriculture Organisation (FAO) 56 guidelines to determine the amount of irrigation to apply to their fields by estimating the actual crop evapotranspiration (ET_c), where ET_c is quantified as a product of the crop coefficient (K_c) and the reference evapotranspiration (ET_o) (Allen et al., 1999). However, it is quite challenging to obtain accurate K_c values because the method should account for the specific orchard conditions and other factors, such as the cultivar type, crop height, canopy cover, crop spacing, soil management, etc. (Girona et al., 2011). According to Girona et al. (2011), canopy height interception is the main factor that influences the ET_c/ET_o ratio.

Attempts have been made to review and update the tabulated crop coefficients' values, in order to be more precise and so that they can be transferred between different fields with different characteristics. Allen and Pereira (2009) improved the FAO-56 crop coefficient approach (Allen et al., 1999) by introducing the crop density function, which incorporates the observations and measurements of the crop height, the Leaf Area Index or the fractional vegetation cover to estimate the crop coefficient values for a wide range of crops. Similarly, Pereira et al. (2021) reviewed and updated the tabulated K_c and K_{cb} values of vegetable crops. These updated crop coefficients can assist farmers to minimise their water use and non-beneficial water consumption and to improve their water-saving targets, while sustaining and, arguably, increasing their crop quality and yield. The FAO-56 tabulated crop coefficients are still considered to be reliable and of value, as they are in close agreement with those updated by Pereira et al. (2021). However, it is recommended that all new data on crop coefficient values be scrutinized against these recent updates and those that are tabulated in the FAO-56 document.

This study reviewed the Allen and Pereira (2009) approach and adjusted it, by using readily-available measured field data and observed crop height and fractional vegetation cover to determine the crop coefficients of selected fruit tree crops grown across South Africa. The procedure involved adjusting the method according to the fruit species, in order to obtain accurate results, as has been done in previous studies for citrus (Taylor et al., 2015) and apples (Mobe et al., 2020).

4.3 Materials and Methods

A significant volume of data was collected on the climatic variables, plant attributes, soil water content and consumptive water use (transpiration and evapotranspiration) of macadamia nuts (Gush and Taylor, 2014; Taylor, 2021), citrus, nectarines, peaches and pecan nuts (Gush & Taylor, 2014b). This study did not determine the crop coefficients for apples, as they have been extensively studied in the primary production regions of the Western Cape (Dzikiti et al., 2018, 2017; Gush & Taylor, 2014a; Mobe et al., 2020; Volschenk, 2017). In addition, this study used and modified the published Allen and Pereira (2009) approach, which is explained in Section 2.7.4, for data gap filling and the derivation of accurate crop coefficients, in order to make them transferable between different fields. The experimental crop coefficients that were used to compare with the derived crop coefficients, were derived from the actual measured crop transpiration and evapotranspiration data. This was done by using the most widely-used FAO 56 guidelines (Allen et al., 1999) discussed in Section 2.7.4.1 The basal crop coefficients (K_{cb}) were calculated by using Equation 2.14. The assumption in the equation is that there is no significant water stress in all the selected orchards.

4.3.1 Weather and soils data

Automatic weather stations equipped with data loggers and sensors to measure rainfall, solar radiation, temperature, humidity, wind speed and direction were installed in an open area and approximately 200 m from the study orchards. Measured weather variables were stored at hourly intervals. The respective hourly values were processed into daily averages used to calculate sites' daily reference evapotranspiration (ET_o) using the FAO-56 approach (Allen et al., 1999).

Soil water content at different positions and depths were measured using probes. In most cases, the probes were positioned at 10 cm, 30 cm and 60 cm depths below the surface, at three locations within the study orchards. Additional soil water content probes were installed within the tree rows to monitor soil water content in the top 10 cm of the soil profile. Specific instruments and methods used in the measurement of transpiration are found in a report written by Gush & Taylor, (2014).

4.3.2 Transpiration (T_c) data

Sap flow measurements of the study sites were taken using the heat ratio method (HRM) of the heat pulse velocity (HPV) technique. Heater probes and thermocouple pairs were inserted to various depths within the xylem sapwood of the trees to determine radial variations of Sapflow. The HPV probe were withdrawn and re-inserted to correct depths periodically, to account for stem growth, unintentional movement or accidental removal of probes. Wound correction coefficients were used to correct HPVs for sapwood wounding. Sap flux densities were finally converted to tree total Sapflow values using the calculation of the sum of the cross-sectional area for individual tree stems and the products of sap flux densities. Specific instruments and methods used in the measurement of transpiration are found in a report written by Gush & Taylor, (2014)

4.3.3 Evapotranspiration (ET_c) data

ETc was estimated using eddy covariance and micro-meteorological approaches. An Open Path Eddy Covariance (OPEC) system which comprised of a sonic anemometer for sensible heat flux, an open path infra-red gas analyser for latent heat flux were used to determine the evapotranspiration. Measurements were sampled and logged on a data logger every 30 minutes. Specific instruments and methods used in the measurement of transpiration are found in a report written by Gush & Taylor, (2014).

4.3.4 Adjustment of the Allen and Pereira approach

The literature argues that the stomatal sensitivity function (Fr) in Equation 2.21 is an overriding factor that causes the A&P approach to consistently overestimate the basal crop coefficient (K_{cb}) by a large margin, as reported for apples (Mobe et al., 2020) and citrus (Taylor et al., 2015). Therefore, these authors suggested changes in the Fr to suit the individual fruit tree species. However, Mobe et al. (2020) argued that the adjustment to Fr that was proposed for citrus did not yield satisfactory results in apple orchards. Similarly, the alternative approach, as suggested by Allen and Pereira (2009), of replacing the ration $r_l/100$ in Fr (Equation 2.21) with $r_s/50$ for orchards with sparse canopies (LAI < 3.0), did not work for apples. This is because, in the alternative ratio, r_s is the bulk surface resistance, whereas 50 is the value of the bulk surface resistance for the grass reference. Therefore, Mobe et al. (2020) replaced the 100 s/m in Equation 2.21 with a resistance parameter α, which represents the minimum unstressed canopy resistance for apple trees. Equation 2.21 was then inverted by using the measured values of climatic variables i.e. the K_{cbfull} in Equation 20 is derived from the sap flow measurements of transpiration and the mean average leaf resistance (r_l) for all twelve orchards in the study. They finally solved the A&P equation and obtained a mean value for α of about 37 s/m, which made the equation more precise.

Under the same conditions at which these two reference studies measured their r_l, Taylor et al. (2015) measured the r_l of a Rustenburg Navel orchard hourly, on five sun-exposed leaves per tree during the sunrise to sunset period, for three days or more. An average was then calculated for each measurement. The r_l that was measured varied between 419 s/m and 3146 s/m, which showed higher r_l values than the suggested 420 s/m that was being routinely discovered in citrus orchards. On the contrary, Mobe et al. (2020) measured r_l at monthly intervals on two sun-exposed leaves in the middle of the day, from around 1200 hours to 1430 hours. An average r_l value of 202 s/m was then calculated. Water stress conditions were not reported in either of the studies.

This study made the adjustments according to the fruit species, to derive the respective crop coefficients, and the results were independently verified by calculating the monthly transpiration totals, by using the approach of Allen et al. (1999). These three identified adjustments were tested and validated against each tree species in this study.

4.3.5 Statistical analysis

The daily values of the measured and derived basal crop coefficients, K_{cb}, were compared by using the coefficient of determination (R^2) given as:

$$R^2 = 1 - \frac{\mathrm{RSS}}{\mathrm{TSS}} \tag{4.1}$$

Where RSS is the sum of squares of residuals and TSS is the total sum of squares. The coefficient of determination 0 to +1, where +1 means a perfect relationship and 0 means that no relationship exists.

The Mean Error (ME), which is also known as bias, is given as:

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}(M_i - D_i) \tag{4.2}$$

Where n is the number of observations and subscript i denotes the ith observation. M_i represents the measured values and D_i the derived values. The ME considers the direction of the errors, which range from a negative to a positive infinity, with the perfect score being 0. A negative score indicates that the A&P approach is generally underestimating the values, while a positive score indicates that the A&P approach is generally overestimating the values.

The Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) were used to evaluate the performance of the A&P approach as:

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|M_i - D_i| \tag{4.3}$$

$$\mathrm{RMSE} = [\frac{1}{n}\sum_{i=1}^{n}(M_i - D_i)^2]^{0.5} \tag{4.4}$$

Where all the terms have the same description, as discussed above. The performance of the A&P approach was considered to be satisfactory when $R^2 > 0.8$ and MAE < 20%.

4.4 Results

Crop coefficients can be calculated by using readily-available data, and using the A&P approach makes it very appealing and appropriate for irrigation management and scheduling. This study calculated the basal crop coefficients (K_{cb}) by using the tree height, the fractional vegetation cover and the micrometeorological data.

4.4.1 The Macadamia orchards

Macadamia nuts are planted in the summer rainfall areas of Mpumalanga, KwaZulu-Natal, Limpopo and Gauteng. Most of the orchards located in these provinces are grown under irrigation, thus accurate crop coefficient information is required. This study tested the A&P approach on two data-sets collected by Gush and Taylor (2014) and Taylor (2021). The ratio

r_l/100 in Fr (Equation 2.21) was substituted with r_s/50, although the LAI of the orchard in White River was above 3.0, i.e. it was 5.0 throughout the whole year. This study used the mean monthly leaf resistance of 2340 s/m. This r_l value was measured by Taylor (2021) on random, fully-exposed, mature and hardened leaves that were located outside of the orchard canopy. These measurements were conducted during the day between 0900 hours and 1600 hours. No water stress was reported when these measurements were taken.

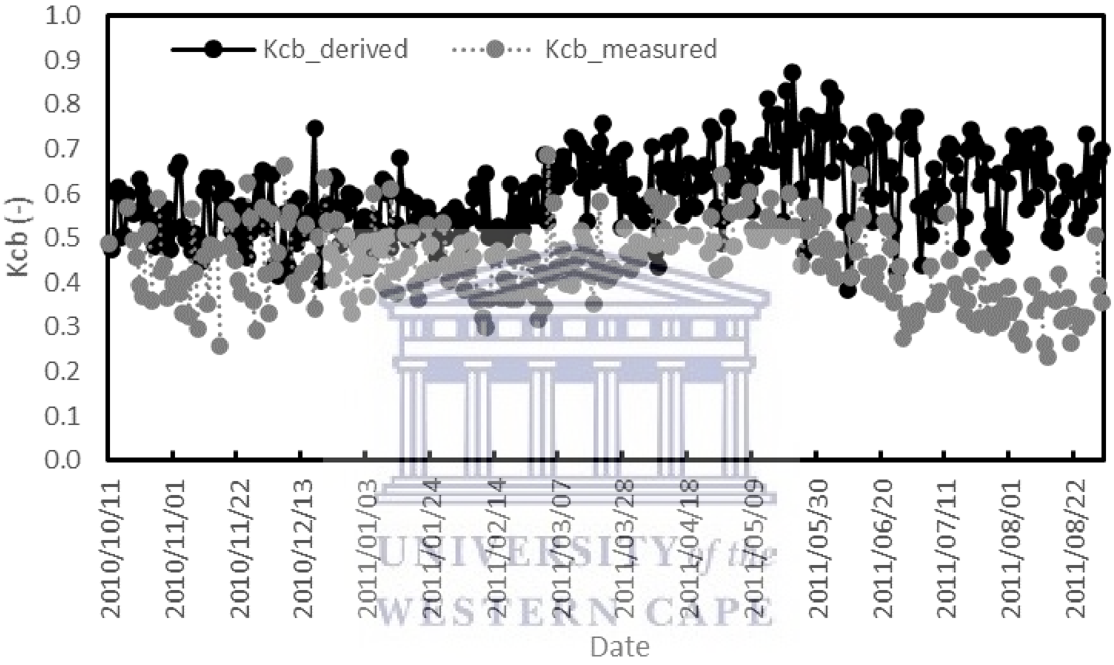

Figure 4.1 Comparison of the derived vs measured basal crop coefficients for macadamia nuts in the Mpumalanga Province

The order of magnitude of the derived K_{cb} for the macadamia orchard in Mpumalanga was comparable with the measured values (Figure 4.1). The same method was used on the second macadamia orchard in Nelspruit (Figure 4.4) and it yielded comparable results. The modelled monthly transpiration for the mature macadamia orchard in Mpumalanga performed very well, as the predicted values were close to the actual monthly measured values (Figure 4.2). Overall, the obtained results of derived K_{cb} values were satisfactory, with an R^2 of 0.94, an ME of -0.23, and an MAE of 24%. Moreso, the RMSE and the mean of measured data were 0.01 and 0.44 respectively. The mean error pointed to an overall underestimation of the A&P approach in deriving the K_{cb} values.

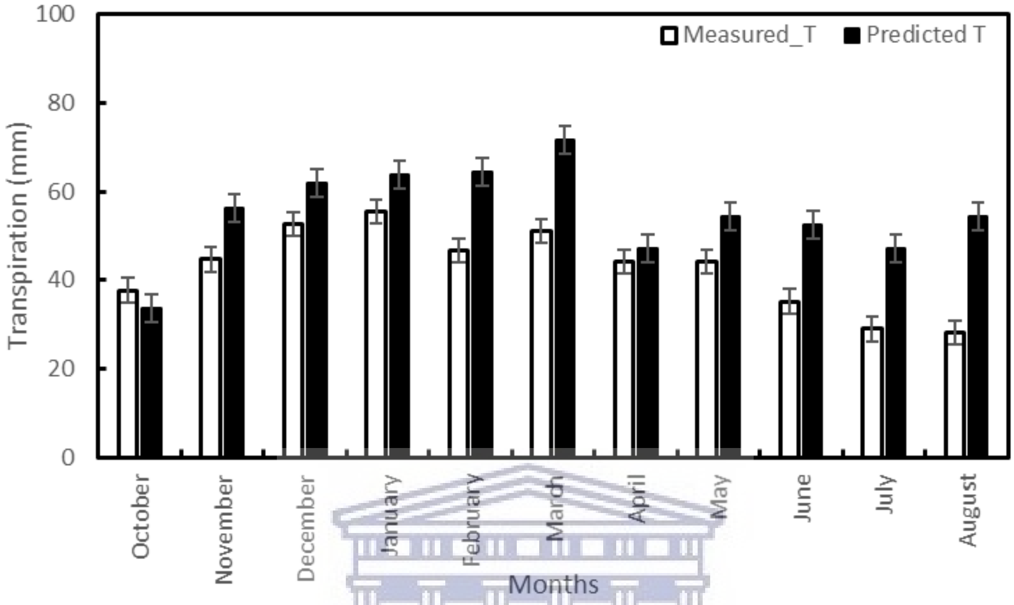

Figure 4.2 Comparison of the measured and modelled monthly transpiration for a mature macadamia orchard at White River

The ET at this orchard was measured over a short period, due to equipment constraints. Although there were insufficient measured ET_c data, the measured K_c concurred fairly with the K_c values (Figure 4.3) in spring. However, the case was slightly different during the winter season, when the K_c values were substantially lower than the predicted K_c values. Therefore, more measured ET_c data are needed, in order to confirm the trends.

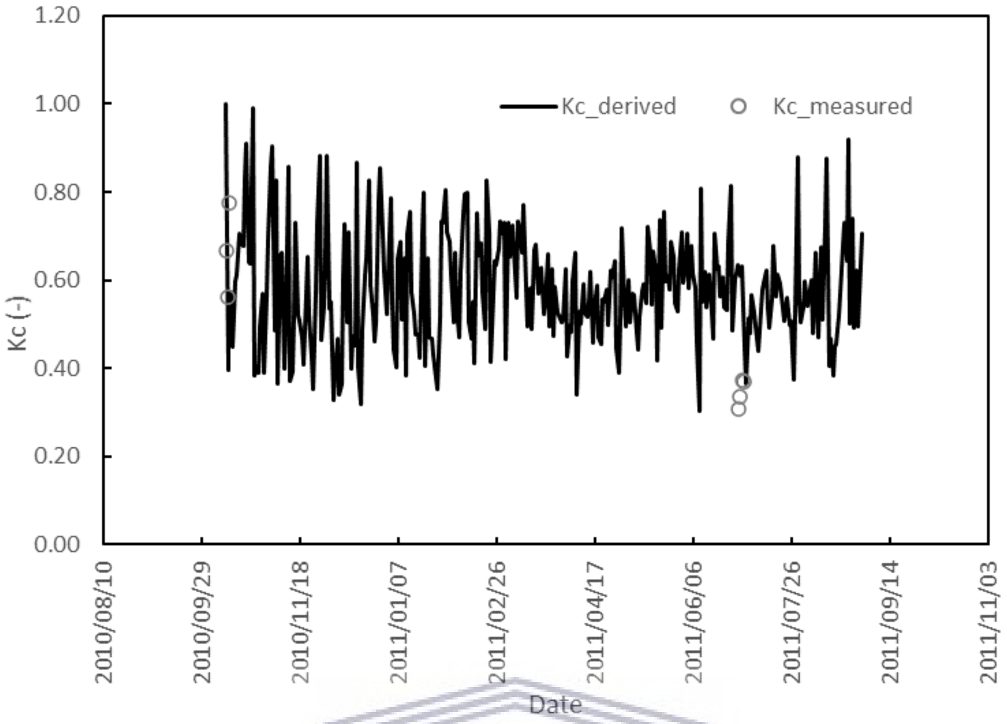

Figure 4.3 Measured and predicted crop factors for a mature macadamia orchard at White River

Similar to the prediction of K_{cb} for the macadamia orchard in White River, the K_{cb} for the macadamia orchard in Nelspruit was predicted well, as depicted in Figure 4.4. Likewise, the comparison between the measured and predicted crop coefficients (Figure 4.5) did not show a clear trend, because the daily values of the measured data were insufficient for producing weekly values.

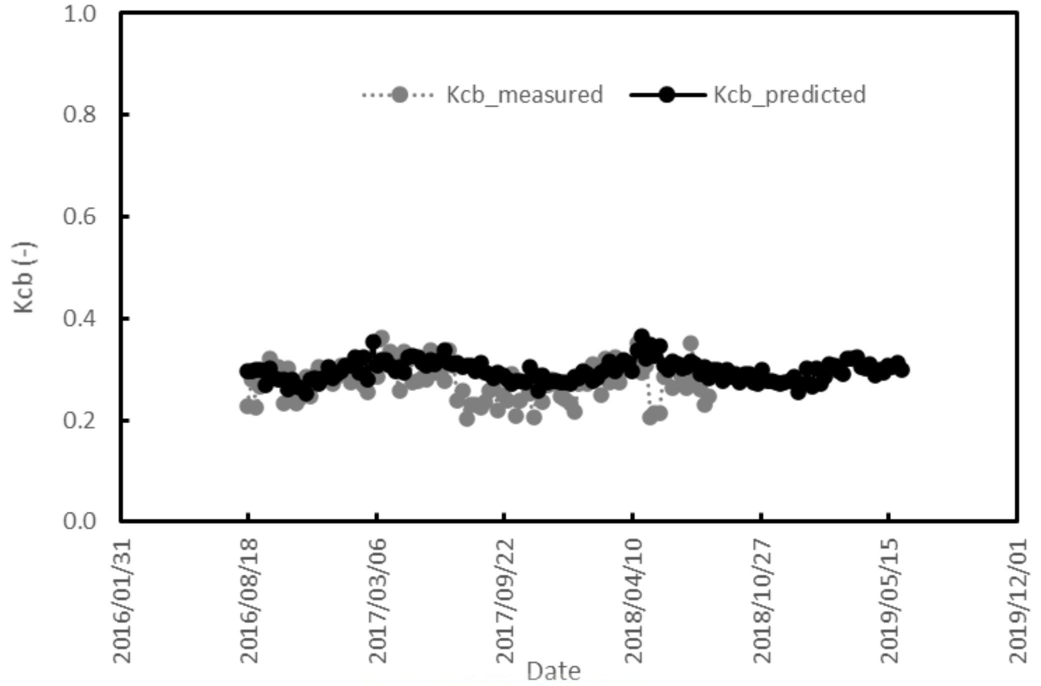

Figure 4.4 Comparison of the measured and derived basal crop factors for a mature macadamia orchard in Nelspruit

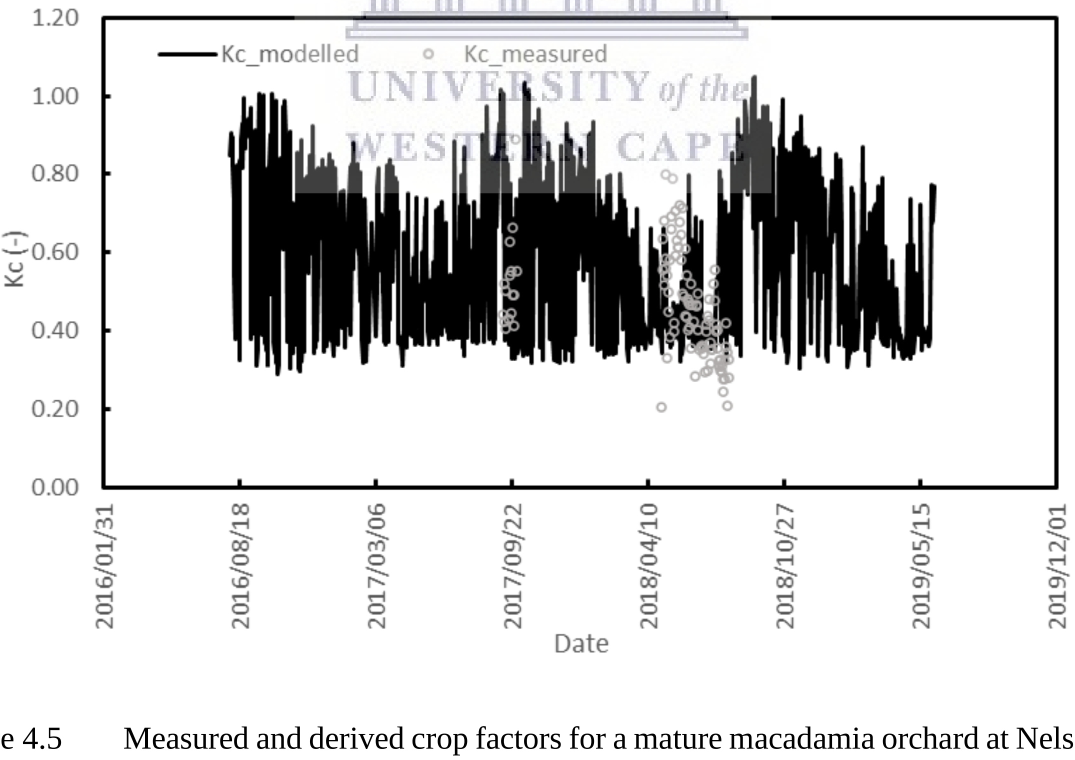

Figure 4.5 Measured and derived crop factors for a mature macadamia orchard at Nelspruit

Notable differences between the measured and derived crop coefficients shown in Figure 4.4 occurred when the crop ET_c values were low, which concurred with the White River data.

4.4.2 The Alpine nectarine orchard

Data for a mature 'Alpine' nectarine orchard were collected in Wolseley, in the Western Cape (Gush and Taylor., 2014). Data similar to those reported for macadamia nuts were measured, although data for this specific orchard were collected over two years. As with the macadamia nuts, this study replaced the $r_l/100$ ratio with $r_s/50$. However, the LAI for nectarines was less than 3.0 for most of the growing season. Therefore, a constant value of the leaf resistance (r_l) of 600 s/m, obtained by Paudel et al. (2015), was used throughout the season. The bulk surface resistance was calculated, as described in Equation 2.10. Paudel et al. (2015) measured the leaf conductance three times in July, August and September (2012) on fully-developed leaves that were exposed to sunlight in a normally-irrigated plot. No water stress was reported when these measurements were taken. Linear interpolation was used between the measurement dates to obtain the daily values of the tree LAI that was used in Equation 2.16.

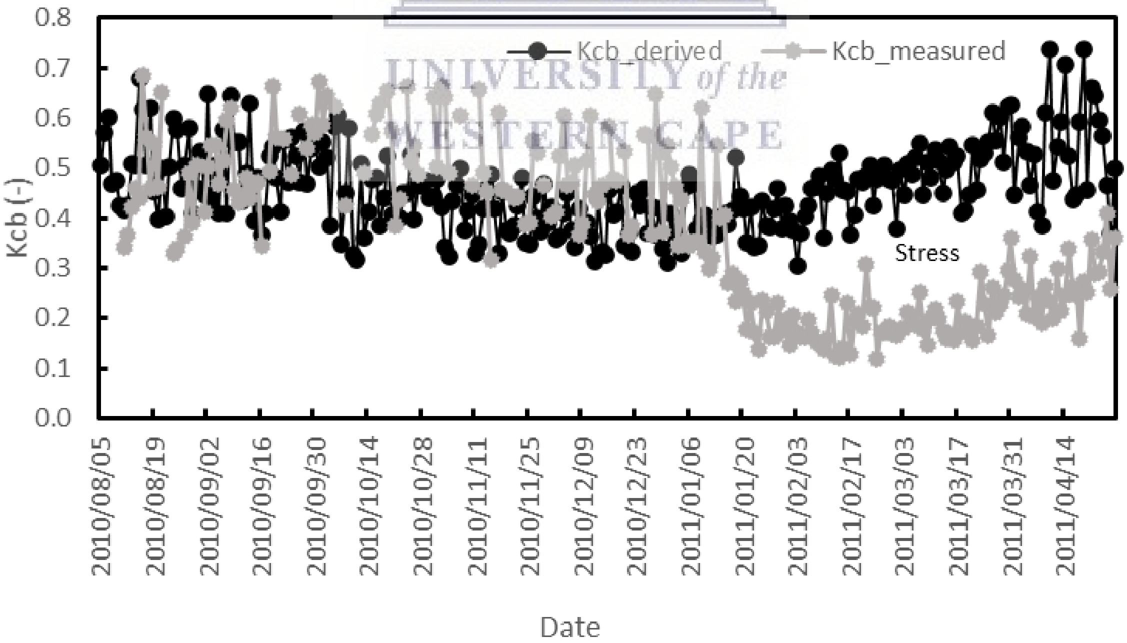

Figure 4.6 Measured and derived weekly basal crop factors for a nectarine orchard at Wolseley

Figure 4.6 shows the daily K_{cb} values for the nectarine orchard. The derived K_{cb} values had the same order of magnitude as the measured values in the August-November and April-May growing seasons. On the contrary, the two sets of values of K_{cb} were not comparable during the December-March period. The derived K_{cb} was consistently higher during this post-harvest period because irrigation activities were withheld, for reasons that were not communicated. The farmer resumed watering the trees from late March until the end of April. Therefore, the grey area, where Figure 4.6 shows lower measured K_{cb} values, indicates the effects of water stress. It should be noted that the gap-filling approach proposed in this study is applicable for unstressed crops. Therefore, this study argues that if the water stress were to be removed, then the derived K_{cb} values would be comparable to the measured values. Overall, the obtained results of derived K_{cb} values were moderately satisfactory, with an R^2 of 0.80 (Table 4.1), an ME of -0.15, and an MAE of 20%. Moreso, the RMSE and the mean of measured data were 0.01 and 0.37 respectively. The mean error pointed to an overall overestimation of the A&P approach when deriving the K_{cb} values.

It was quite difficult, or rather impossible, to objectively assess the performance of the A&P method on ET_c for this nectarine orchard, as there were only 13 days-worth of measured crop ET_c data. This is evident in Figure 4.7, which compares the measured and derived crop factors of this orchard.

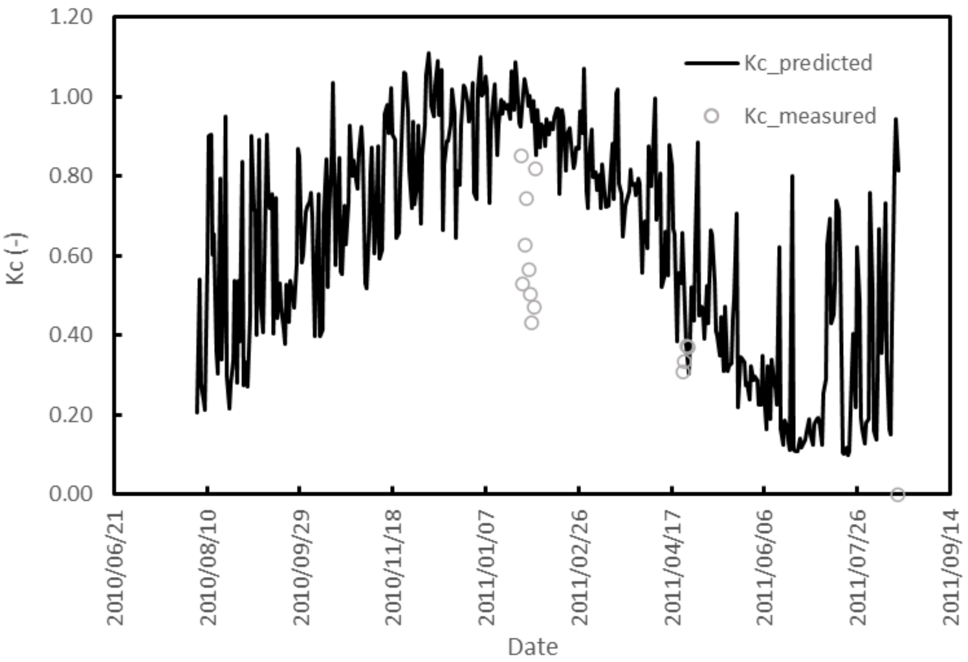

Figure 4.7 Comparison of the measured and derived crop coefficients (Kc) for a mature 'Alpine' nectarine orchard at Wolseley

Modelled monthly transpiration for the mature nectarine orchard in Wolseley performed reasonably well during the August - September period as the predicted values were close to the actual measured monthly measured values (Figure 4.8). Contrarily, the model overestimated the transpiration values during the period of water stress. Overall, this study concludes that the A&P procedure can be applied and developed for nectarine orchards, by replacing the r_l/100 ratio with r_s/50. In addition, it should be noted that this study used the dual crop coefficient equation (Allen et al., 1999).

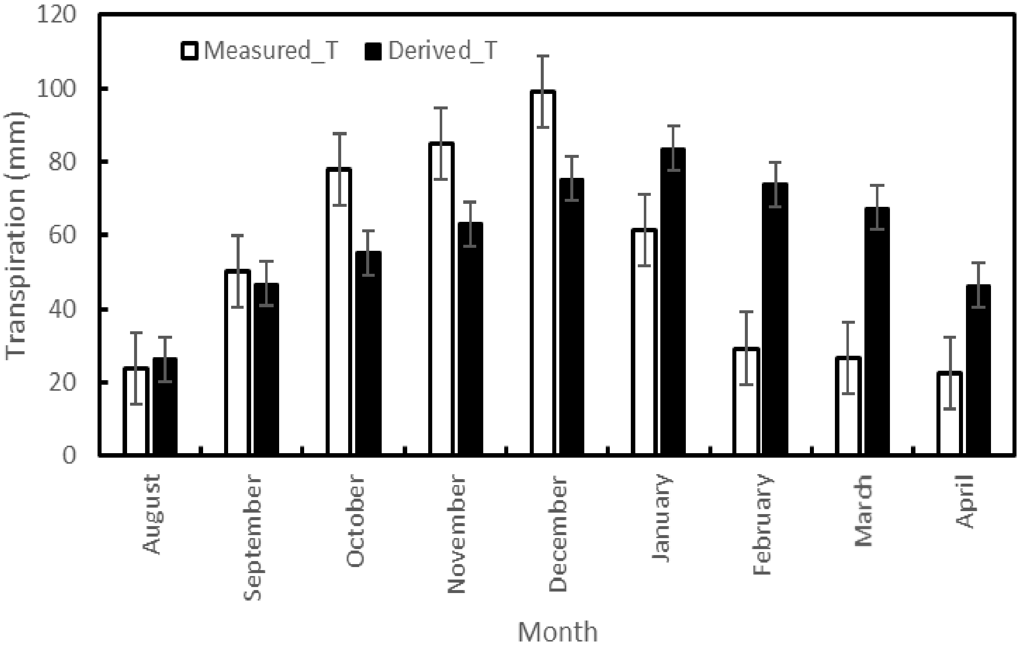

Figure 4.8 Comparison of the measured and modelled monthly transpiration for a mature nectarine orchard at Wolseley

4.4.3 The peach orchard

A significant volume of consumptive water use (T_c) data was collected from a peach orchard in Rustenburg. However, insufficient evapotranspiration data were available for this study, thus it failed to determine the K_c for this species. The available data included the orchard's microclimate, tree transpiration, growth and soil water content, among other things. The A&P approach was applied, as recommended for peaches, and as expected, the typical results showed that the approach overestimated the basal crop coefficients. This study utilised the suggestions of Mobe et al. (2020) to make changes to the stomatal sensitivity function (Fr) in Equation 2.21, and obtained the α value of 59.7 s/m, which produced a much better fit than the alternative adjustments that have been discussed earlier. A constant value of 600 s/m was used throughout the season. Although (2009) suggested using a leaf resistance value of 430 s/m for pome fruits, which yielded less accurate results than the 600 s/m value suggested for nectarines by Paudel et al. (2015b).

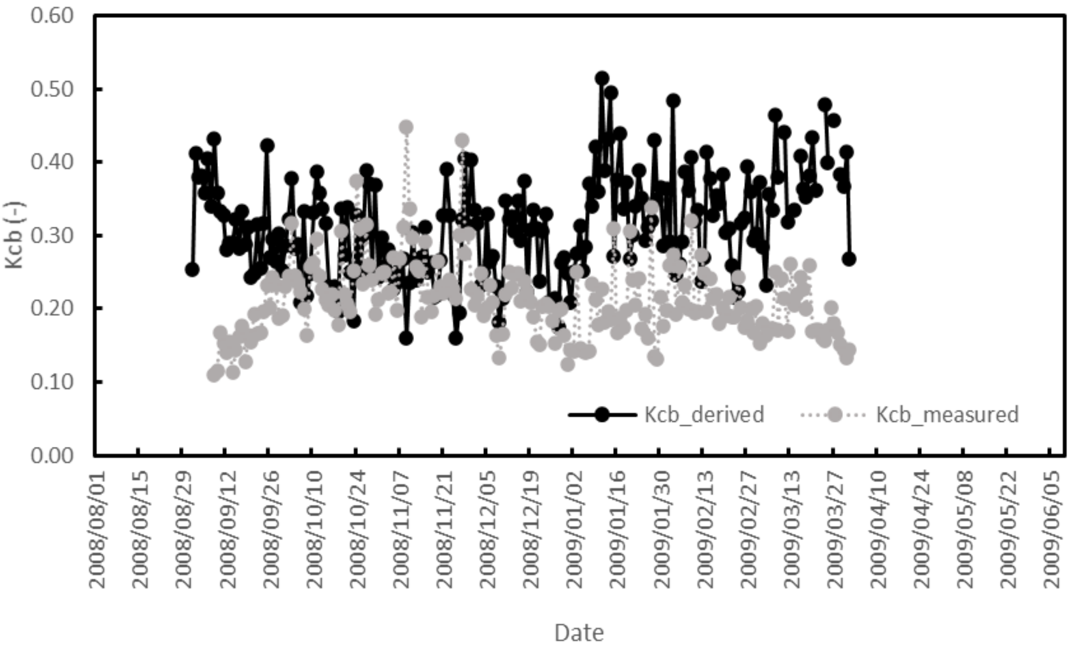

Figure 4.9 Comparison of the derived vs measured basal crop coefficients for peaches in Rustenburg

The daily derived K_{cb} values were closer to the daily measured K_{cb} values (Figure 4.9). The obtained results were verified by calculating the monthly T_c totals and using the crop coefficient approach, as suggested by Allen et al. (1999), which shows satisfactory results for the September-November growing season (Figure 4.10). However, the T_c results were not entirely comparable during the December-March period, which can arguably be attributed to the post-harvest pruning, which would have decreased the LAI.

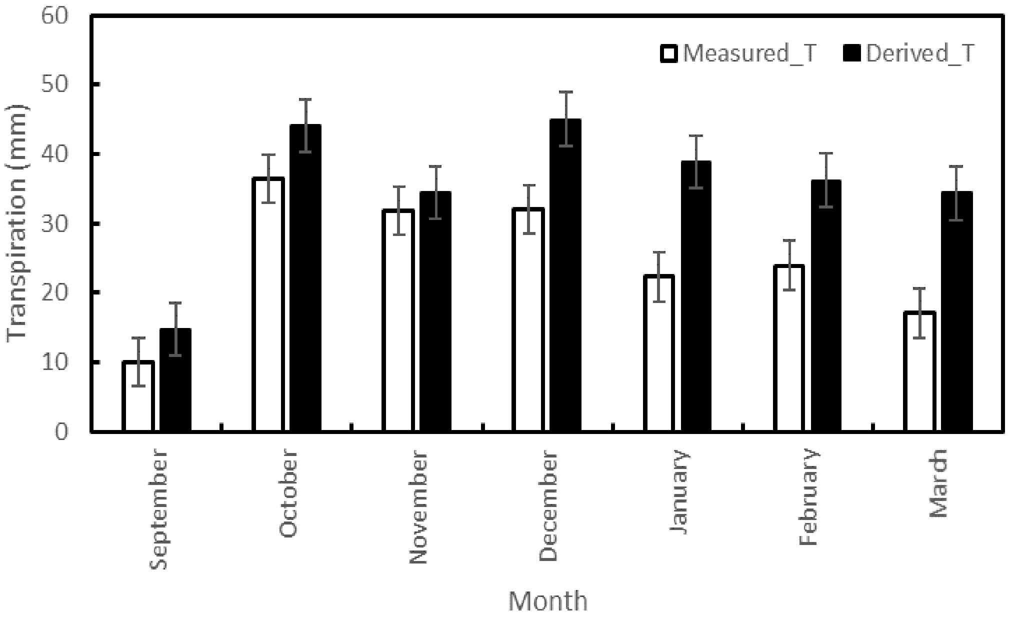

Figure 4.10 Comparison of the measured and modelled monthly transpiration for a mature peach orchard in Rustenburg

Overall, the results of the derived K_{cb} values were satisfactory, with an R^2 of 0.89 (Table 4.1), an ME of 0.08, and an MAE of 11%. Moreso, the RMSE and the mean of measured data were 0.01 and 0.31 respectively. The mean error pointed to an overall overestimation of the A&P approach in deriving the K_{cb} values.

4.4.4 The pecan orchard

The limited knowledge on the consumptive water-use rate of pecan nuts grown in their production regions across South Africa, calls for the need to determine accurate crop coefficients. Past studies identified the tree age, height, spacing pruning strategies and irrigation design as the overriding factors that influence the consumptive water use of pecans, with the cultivar and climate also being mentioned (Ibraimo et al., 2016; Ibraimo, 2018).

This study obtained the relevant pecan orchard observations, measurements and weather data from Cullinan, in the Gauteng Province. The A&P approach was adjusted by replacing the ratio r_l/100 with r_s/50. Although other studies recommended the use of varying r_l values, since rl is subjected to change due to climate variations (Jarvis, 1976), this study obtained r_s by dividing the constant r_l value of 780 s/m with a varying LAI that was measured throughout the season. The value 780 s/m was obtained by inverting Equation 2.21 and using the measured climatic variables and K_{cbfull} (calculated from measured K_{cb} values). This adjustment provided a good relationship between the derived K_{cb} and the measured K_{cb} values. The results showed the same order of magnitude between the derived K_{cb} values and the measured K_{cb} values during the October-December period, as shown in Figure 4.11. However, the adjusted A&P approach overestimated the orchard K_{cb} significantly, which can probably be attributed to the occurrence of vegetative flushes, or structural canopy changes, around this period (Ibraimo et al., 2016).

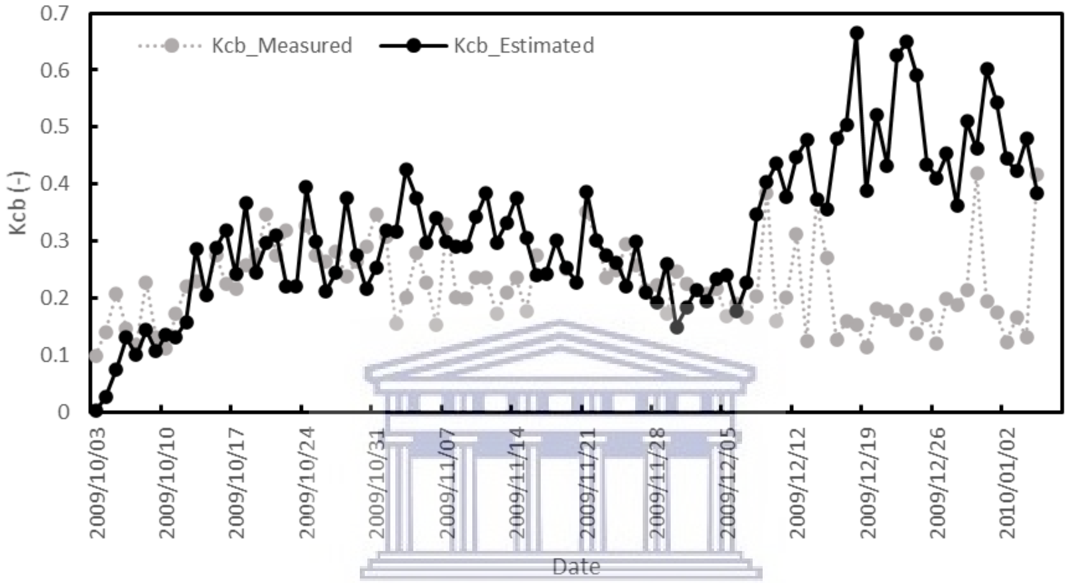

Figure 4.11 Comparison of the derived vs measured basal crop coefficients for pecan nuts in Cullinan

Although there was this overestimation of K_{cb} during this period, the A&P approach generally underestimated the K_{cb} with an ME of -0.13. Regardless of the discrepancy in the estimation of basal crop coefficients during the December-January period, the model's overall accuracy was moderately satisfactory, with an R^2 of 0.78, an MAE of 16 % and an ME of -0.13 (Table 4.1). The RMSE and the mean of measured data were 0.02 and 0.22 respectively. Nevertheless, the mean error pointed to an overall underestimation of the A&P approach in deriving the K_{cb} values.

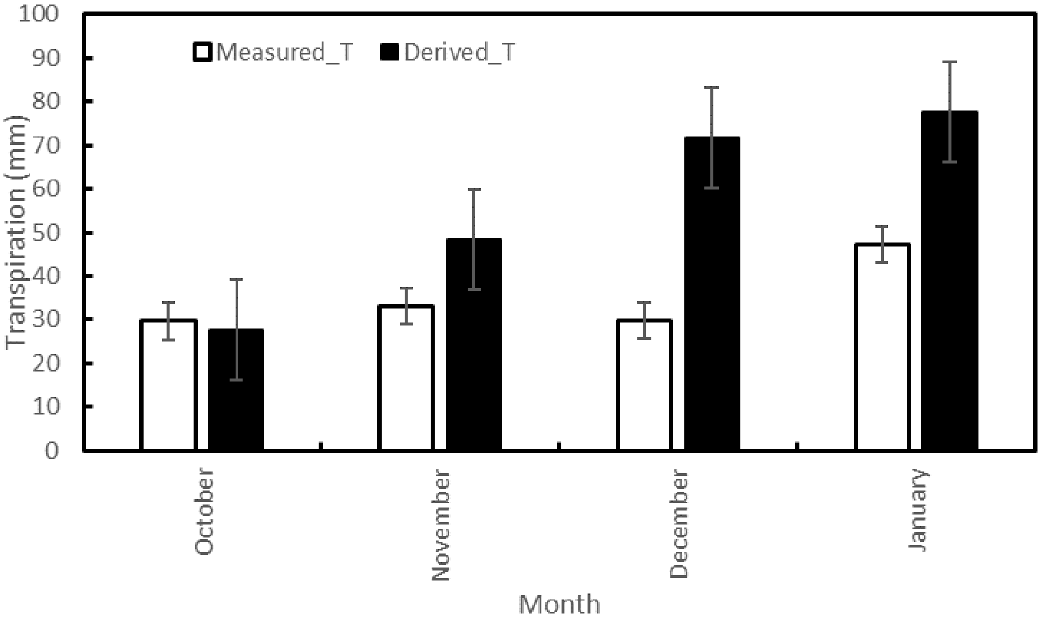

Figure 4.12 Comparison of the measured and modelled monthly transpiration for a mature pecan orchard at Cullinan

A more detailed analysis of the performance of the A&P method was undertaken by estimating the total monthly pecan T_c (Figure 4.12). Contrary to the estimation of K_{cb}, there is a significant magnitude of overestimation of the T_c by the model, which shows the influence of the evaporative demand on the transpiration rate of pecan nuts.

4.4.5 The citrus orchard

Past studies on the citrus species have demonstrated that their consumptive water use varies with the respective cultivars (Dzikiti et al., 2011; Gush and Taylor, 2014b). While consumptive water use information is significant to farmers in their respective production regions, it is not invariably transferable to other regions in South Africa, or for different seasons. Crop coefficients from different citrus-growing orchards in different regions yield different crop coefficients, since the stomatal control of transpiration is an important factor that determines the different consumptive water-use rates between the cultivars (Taylor et al., 2015). For example, cultivars such as Bahianinha navels have stronger stomatal control of T_c than Valencias. Therefore, it is probable that the parameterization of the A&P approach for different citrus cultivars may be different.

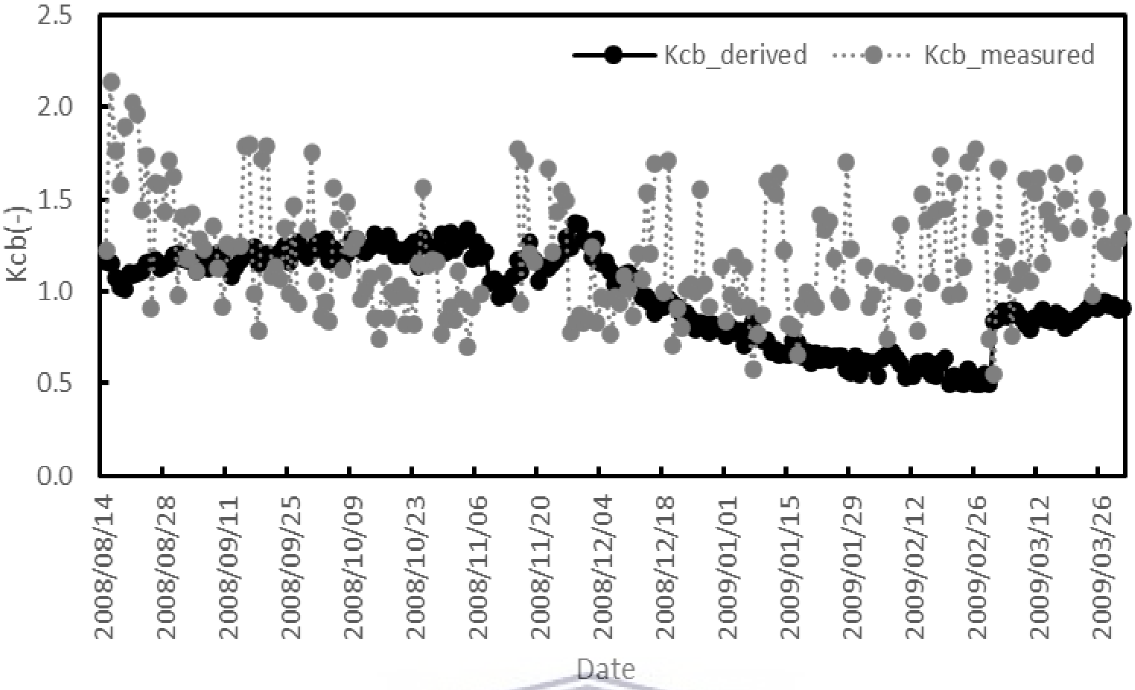

Figure 4.13 Comparison of the derived vs measured basal crop coefficients for citrus in Groblersdal

This study ran the A&P method for the mature Delta Valencia orchard in Groblersdal, and it used an approach similar to that used by Mobe et al. (2020), which was discussed earlier, although with an additional variable leaf resistance. The basal crop factors derived by using this calculation are shown in Figure 4.13 above. A study by Taylor et al. (2015) showed that the fixed parameters of citrus trees reported by Allen and Pereira (2009) are not able to generate an accurate K_{cb} for citrus orchards. The r_l value of 420 s/m, that was suggested by Allen and Pereira (2009), was proven to be too low for the citrus trees, especially during the summer months, when there is a high Vapour Pressure Deficit (VPD). Thus, this study used linear interpolation between the measured dates for the r_l variation, and between dates without physiological justification, although a constant mean leaf resistance is desirable. The idea of using a varying leaf resistance was proposed by Taylor et al. (2015), and the approach needs to be investigated further for citrus orchards.

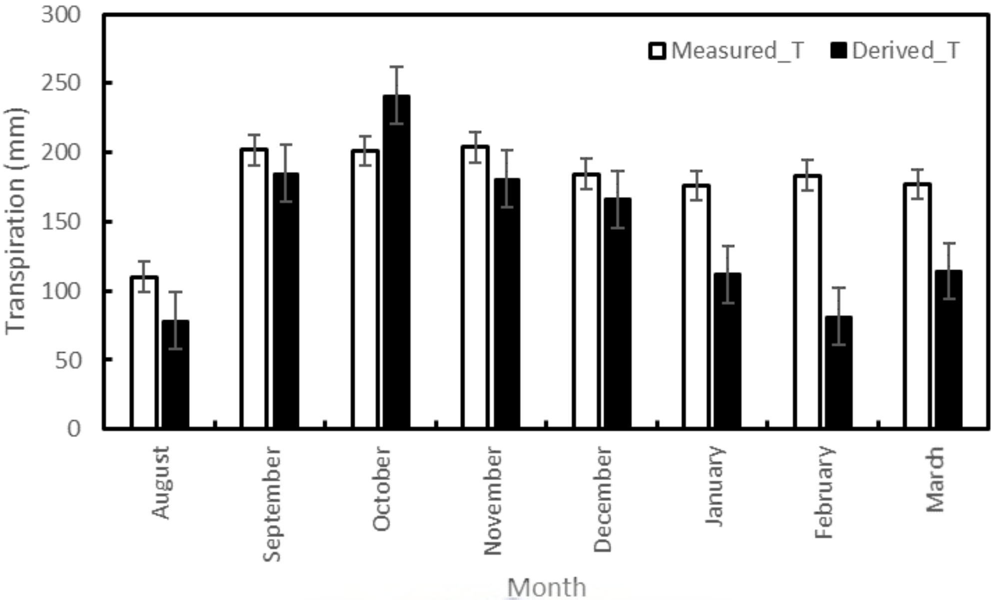

Figure 4.14 Comparison of the measured and modelled monthly transpiration for a mature citrus orchard at Groblersdal

The approach used in this study for the Delta Valencia orchard produced reasonably satisfactory results. The derived K_{cb} values had a comparable order of magnitude during a significant period of the growing season (Figure 4.13). However, the adjusted A&P approach underestimated the K_{cb} values in January-March. Further work is required to improve the parameterisation of the A&P approach, considering the complexity of the varying r_l throughout the growing season. Overall, the results of the derived K_{cb} values were reasonably satisfactory, with an R^2 of 0.87 (Table 4.1) and an ME of 0.09. The RMSE and the mean of measured data were 0.03 and 1.19 respectively. The mean error pointed to an overall overestimation of the A&P approach when deriving the K_{cb} values. The approach produced comparable T_c values closer to the measured T_c values (Figure 4.14). Derived T_c values were obtained from the product of the derived K_{cb} and ET_o obtained from the AWS near the study site.

4.4.6 Results summary

The selected fruit tree species included in this study have different physiological characteristics that allow them to respond differently to climatic variables and that influence their consumptive water use rates, hence the performance of the A&P approach in determining their respective crop coefficients. Table 4.1 below summarises the performance of the A&P approach in determining basal crop coefficients for the selected fruit trees.

Table 4.1 Summary of parameters used in the derivation of K_{cb} using the A&P approach, the obtained range of derived K_{cb}, average K_{cb} values in the respective study periods, and statistical analysis data on the model's performance

Fruit Species	f_c (%)	r_l (s/m)	h (m)	Period (months, years)	N	K_{cb} Derived (-)	K_{cb} Average Derived (-)	ME	MAE	RMSE	R^2
Macadamia nuts	98	2340	5.0	Oct - Aug, 10/11	325	0.38 - 0.87	0.60	-0.23	0.24	0.01	0.94
Pecans	89	780	13.0	Sep - Mar, 09/10	95	0.10 - 0.66	0.35	-0.13	0.16	0.02	0.78
Nectarines	70	600	3.2	Aug - Apr, 10/11	266	0.30 - 0.74	0.46	-0.15	0.20	0.01	0.80
Peaches	49	600	3.5	Aug - Apr, 08/09	206	0.11 - 0.44	0.21	0.08	0.11	0.01	0.89
Citrus	60	300 - 1000	5.0	Aug - Jun, 08/09	230	0.49 - 1.37	0.97	0.09	0.44	0.03	0.87

f_c is the fractional cover, r_l is the leaf resistance, h is the tree height, N represents number of observations, ME is the mean error, MAE is the mean absolute error, RMSE is the root mean square error and R^2 is the coefficient of determination

Macadamia nuts had the highest value of calculated f_c, and the measured r_l recorded a high average K_{cb} value of 0.60, which was second only to that of citrus (0.97). Although the A&P method underestimated the macadamia K_{cb} values by a bias of 0.23, it had a very strong coefficient of determination value of 0.94, which was higher than that of the other selected species. For peach trees, which had the lowest derived K_{cb} range of 0.11 to 0.44, and an average K_{cb} value of 0.21, for the study period, the model's performance was satisfactory, with a slight overestimation bias (ME = 0.08), an RMSE of 0.01 and a strong coefficient of determination value of 0.89. The low K_{cb} values were expected, considering the low f_c values. This study used the same constant r_l value of 600 s/m.

Contrary to the rest of the selected fruit species, this study used varying r_l values that ranged from 300 s/m to 1000 s/m. Although citrus trees had varying r_l values that were gap-filled by using interpolation, the model produced satisfactory results, with a slight overestimation of the K_{cb} values and a strong R^2 value of 0.87. Statistically, the A&P approach underestimated the basal crop coefficients for macadamia nuts, pecan nuts and nectarines, while it overestimated the K_{cb} values for peaches and citrus trees.

4.5 Discussion

Previous studies have used the FAO-56 crop coefficient approach (Allen et al., 1999) to estimate the crop water requirements used by farmers to reduce consumptive water use on their farms and to assist them with irrigation water management (Jovanovic et al., 2020). However, obtaining accurate crop water requirements needs accurate crop coefficients that are transferable between the sites and growing regions (Allen, 2000), which is a limitation of this approach. Therefore, Allen and Pereira (2009) improved the FAO-56 crop coefficient approach by suggesting a method that determines crop coefficients using readily available field observation and measurement data such as the fractional vegetation cover and the crop height. This was achieved by introducing the density coefficient function.

The A&P approach has been evaluated and validated in the past years so as to yield accurate crop coefficients of various crops (Taylor et al., 2015; Mobe et al., 2020). However, authors have reported a comparable magnitude between the derived and measured crop coefficients, and a general over-estimation of these crop coefficients for the respective fruit species i.e. citrus (Taylor et al., 2015) and apple orchards (Mobe et al., 2020) was noted. A similar observed source of uncertainty with the A&P method was its stomata sensitivity function (Fr) in Equation 2.21. Both studies suggested that adjustments should be made to Fr to suit the specific crops. The leaf resistance (r_l) value is the sensitive variable that influences the performance. There have been arguments on whether to use constant or varying values of r_l, given the differences in the physiology of the crops. Taylor et al. (2015) proposed using a variable r_l value instead of a fixed one, since citrus trees possess a strong stomatal control (Dzikiti et al., 2011). The author claimed that there was a strong relationship between the r_l of citrus and ET_o, which suggests that the r_l increases strongly with the increasing evaporative demand. However, this approach did not work in an apple study by Mobe et al. (2020) because of the differences in their physiology. Moreover, replacing the $r_l/100$ ratio in the stomatal sensitivity function (Fr) with $r_s/50$, as suggested by Allen and Pereira (2009), did not yield satisfactory results for apples. Therefore, (2020) replaced the 100 s/m with a calculated mean resistance parameter of 37 s/m for apple trees, which made the A&P approach more precise. These three alternative adjustments were used throughout this study for the selected fruit species.

In a macadamia nut orchard in White River, replacing the $r_l/100$ ratio with $r_s/50$ yielded satisfactory results, where a mean monthly r_l value of 2340 s/m was measured by Taylor (2021). Although this substitution was the best fit for macadamia nuts, its LAI was greater than 3.0, which is contrary to the conditions published by Allen and Pereira. According to Taylor (2021), the T_c of macadamia nuts is considered to be a supply-controlled system because of its strong stomatal control that responds to increases in the atmospheric evaporative demand. The canopy size and atmospheric evaporative demand are the major driving variables of the T_c of macadamia nuts. Similar to macadamia nuts, the $r_l/100$ ratio for the nectarine orchard was replaced with $r_s/50$ and yielded satisfactory results in most parts of the growing season, although a value of 600 s/m was used. However, unlike macadamia nuts, which are less sensitive to water stress in their phenological stages (Taylor, 2021), nectarines are heavily affected by a water supply deficiency (Gush & Taylor, 2014a). The farmer responded to waterlogging conditions in the nectarine orchard in Wolseley by reducing the irrigation volumes, which resulted in lower T_c rates and caused the A&P method to overestimate the K_{cb} during this period. The overestimation of the crop coefficients by the A&P approach is expected, as it does not respond accurately during water stress conditions. It is recommended that farmers investigate orchard drainage and irrigation systems to avoid such scenarios, as nectarines are sensitive to water stress and waterlogging conditions.

The study used a constant leaf resistance value of 600 s/m on peaches, as suggested by Paudel et al. (2015b), which is contrary to the 430 s/m value published by Allen and Pereira,(2009) for pome fruits. Moreso, this study used an approach suggested by Mobe et al. (2020) and obtained a α value (minimum unstressed canopy resistance for peach trees) of 59.7 s/m, which produced a much better fit than the other alternative adjustments discussed earlier. Summer pruning practices and leaf abscission, in response to the fruit harvest, are the major contributors to the decline in the sap flow activities of peaches (Gush & Taylor, 2014a), and hence the consumptive water use of the plant, which depends on light interception, among various other factors (Ayars et al., 2003). The wider row spacing in the Rustenburg orchard contributed to the low peach T_c and it contributed to the low K_{cb} values measured in the orchard, causing a slight overestimation of K_{cb} by the modified A&P approach. Detailed research is recommended to critically investigate the physiological factors that affect the consumptive water use of peaches, post-harvest.

The A&P approach was adjusted for pecan nuts by replacing the ratio $r_l/100$ with $r_s/50$, using a constant value of 780 s/m, and by varying the LAI measured throughout the season. The use of a constant r_l value for pecans produced a good fit between the derived and measured K_{cb} values, although other studies recommended the use of varying r_l values, since r_l is subjected to change, due to the climate variations (Jarvis, 1976). The atmospheric evaporative demand has a strong influence in determining the consumptive water use of pecan nuts. Low consumptive water use values in the December-January period were attributed to a decline in the atmospheric evaporative demand, thus reducing the measured crop T_c. The results obtained in this study show a huge overestimation of the K_{cb} values by the A&P model. This is attributed to the pecan species having irregular cropping and the occurrence of vegetative flushes, or canopy structure changes, that occur during this period (Ibraimo et al., 2016). However, this study argues that the derived K_{cb} trend represents the basal crop coefficients better for the pecan species. High basal crop coefficients are common for pecan nuts, since mature pecans use large volumes of water, relative to other species. The consumptive water-use rate is high in pecan orchards due to the dense canopies, the large leaf area, especially after bud break, the low canopy resistance and the large surface resistance (Sammis et al., 2004; Ibraimo et al., 2016). Pecan trees experience numerous shoot growth cycles in a single season and have a high stomatal conductance, which result in higher T_c rates. This study recommends assessing the occurrence of changes in the pecan canopy structure and vegetative flushes throughout the growing season. It is essential to understand the factors that affect the consumptive water use of pecan nuts.

The r_l value of 420 s/m, as suggested by Allen and Pereira (2009), proved to be too low for the citrus trees, especially during the summer months, with a high VPD. Leaf resistances higher than the published 420 s/m are occasionally found for citrus trees (Dzikiti et al., 2008). Taylor et al. (2015) showed that the reported fixed parameters of citrus trees could not accurately generate K_{cb} for the citrus orchards. This study used varying r_l values, ranging between 300 s/m and 1000 s/m, that were interpolated between measured dates. The suggestion of using a variable leaf resistance, as proposed by Taylor et al. (2015), needs to be investigated further for citrus orchards. Citrus trees have greater stomatal control of the T_c than various other fruit species, which is attributed to their resistance to water transportation within the tree (Hall et al., 1975). These need to be regulated efficiently, in order to minimise uncertainty. The high resistances in the Groblersdal orchard were due to the accumulation of plant carbohydrates in the leaves. Research is needed to determine the effects of leaf resistances on the consumptive water-use of citrus trees.

4.6 Conclusions

A multitude of methodologies for determining accurate crop coefficients have been developed over the years, and the Allen and Pereira, (2009) approach, which improved the widely-used

FAO-56 crop coefficient approach, has produced satisfactory results in many studies. However, the A&P method needs to be adjusted, by understanding the physiology of specific crops. More specifically, this study demonstrated that different crops have a different stomatal resistance and conductance, and these have been proven to be the significant factors that influence the performance of the A&P method through the stomatal sensitivity function (Fr). It was found that the A&P approach performs better when the specific reference leaf resistance is used for each fruit tree, rather than using the published grass reference (100 s/m) that is used for all crops. More accurate measured and observed orchard data, such as the fractional vegetation cover, the tree height, the bulk canopy resistance and the climate data are essential for the satisfactory performance of the model in deriving the accurate crop coefficients that are used for irrigation water management. This study used three adjustment approaches on the stomatal sensitivity function, including those suggested by Allen and Pereira (2009), Taylor et al. (2015) and Mobe et al. (2020) for the selected fruit tree species. All five species responded differently to these adjustments, and still more work is required in order to improve the model's performance further, particularly for the nectarine, pecan and citrus trees that were overestimated during the post-harvest period. An observation made in this study on the post-harvest performance of the model on the nectarine orchard is that it is difficult for the model to derive accurate basal crop coefficients for a crop that is experiencing water stress conditions, since the irrigation water had been withdrawn during this period. For pecan nuts, irregular cropping and the occurrence of vegetative flushes or canopy structure changes are the probable causes of the measured K_{cb} trends, and hence, the overestimation by the model. Lastly, high and varying resistances in the citrus orchards influenced the model's performance, as these determine the consumptive water use of these species. The use of varying, yet accurate, leaf resistances for citrus trees is highly recommended. Overall, crop-specific data and precise orchard measurements are necessary in order to improve the accuracy of the A&P approach. Below is a summary of the parameters that were used in the derivation of K_{cb} and the statistical analysis that was undertaken for the selected fruit species on the performance of the model.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

South Africa's water resources have been under increasing stress, due to competition between the users, the growing population and the effects of climate change. The fruit-growing industry is one of the water users in the agriculture sector that has been most affected by the increasing water-scarcity levels. Therefore, there is a need to develop water-saving technologies by effectively managing irrigation water and by minimising water use and non-beneficial water consumption. The consumptive water-use rates of a wide range of fruit species are variable and they are affected by factors, such as weather changes, climate variability and on-farm management practices. This study used the Allen and Pereira (2009) approach to derive crop coefficients of selected irrigated macadamia nuts, pecan nuts, nectarines, peaches and citrus species grown across South Africa.

This study synthesised the consumptive water-use data that was collected from across South Africa and discussed their implications for irrigation water management. The annual and monthly average water-use rates and crop coefficients of the selected fruit tree species were compared. As expected, pecan nuts had the highest annual T_c and monthly average T_c volumes, due to their physiology, which allows them to use large volumes of water. Surprisingly, apples and avocadoes had higher ET_c volumes than pecans. Although the physiological differences and responses to the atmospheric evaporative demand contributed to the consumptive water-use rates, the canopy size and management were the overriding factors. The outcomes of the synthesis demonstrated the usefulness and importance of canopy management for obtaining a maximum yield, and it plays a significant role in influencing the consumptive water of fruit trees.

As discussed in the literature review, this study identified the Allen and Pereira (2009) approach as an appropriate tool for deriving the accurate crop coefficients of field crops. Chapter Four observed the need to adjust the A&P method by using crop-specific and orchard-measured and observed data. It was understood that fruit species have different physiological characteristics, such as their leaf resistance and stomatal conductance, which respond differently to weather-induced factors like the Vapour Pressure Deficit and the atmospheric evaporative demand. Therefore, this study modified the A&P approach according to each selected fruit tree, by adjusting the stomatal sensitivity function. The adjustments suggested by Allen and Pereira (2009), Taylor et al. (2015) and Mobe et al. (2020) produced satisfactory results for determining the basal crop coefficients of the fruit species. However, deriving these crop coefficients during the post-harvest period proved to be complex, especially in species such as nectarines, pecan nuts and citrus, which are sensitive to water stress, have irregular physiological changes and have large varying leaf resistance values, respectively. These results demonstrated the effect that water stress conditions, and using a mean leaf resistance value, particularly the ones published by, have on the model's performance.

5.2 Recommendations

Over the years, research has been conducted to estimate the accurate crop coefficients and consumptive water use of various crops grown in the world, by using a multitude of published methodologies. All these attempts have been made to assist farmers to achieve maximum production (yield) by using less water, in order to save it. In addition, accurate crop coefficients will assist farmers to minimise their water use and non-beneficial water consumption, and to improve their management of irrigation water. This study reviewed the methodologies for determining crop coefficients and highlighted the importance of understanding their underlying principles, accuracy and potential problems.

Even though the A&P approach has proved to be dependable in numerous studies, this study demonstrated the need to modify it by adjusting the stomatal sensitivity function, which has been identified as the source of the uncertainties in the model’s performance. Although the improved A&P method yielded satisfactory results in deriving the basal crop coefficients for the respective irrigated fruit orchards, further extensive research is required to validate the improved model. An area of interest is to carefully and sufficiently scrutinize all the model’s input data, including the climate data and all the measured and observed field data. Many studies have failed to provide sufficient evidence on the consumptive water-use data (T_c and ET_c). Likewise, the measured K_c and K_{cb} values should be absolved of the biases caused by the measuring equipment and data handling, etc. and they must be scrutinised according to the published FAO-56 values.

Finally, this study identified the canopy size as being a significant factor that influences the consumptive water-use rates of various irrigated orchards. Canopy management is consequently critical for regulating these rates and for achieving the overall goal of saving water.

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