

Quantifying the water use of apple tree orchards

by

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DECLARATION

I hereby certify that this dissertation is my own work, except where duly acknowledged. I also certify that no plagiarism was committed in writing this dissertation.

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ABSTRACT

High yielding apple orchards ($>100 \text{ t ha}^{-1}$) are becoming the norm in South Africa and it is assumed that as yields increase, transpiration rates will also increase. This raises the need for improved knowledge on water use of these orchards in relation to water availability, given the increasing pressure on scarce water resources. Accurate estimates of transpiration are therefore necessary to assess the possible link between yield and water use. A project was therefore solicited, managed and funded by the Water Research Commission and the South African Apples and Pears Producers Association to quantify the water use and water relations of high yielding apple orchards. The heat pulse velocity sap flow technique was used to monitor transpiration rates in full bearing 'Golden Delicious' and 'Cripps Pink' orchards in the Koue Bokkeveld. Measurements of water relations included stomatal conductance and predawn and midday stem water potential. Estimates of canopy size were obtained by measuring the interception of photosynthetically active radiation (PAR) and leaf area index (LAI) of trees. Weather parameters were recorded by an automatic weather station and were used to calculate reference evapotranspiration (ET_0). The transpiration rates for both 'Golden Delicious' and 'Cripps Pink' increased from spring to summer and decreased in autumn. The yield of the 'Golden Delicious' orchard was 98 t ha^{-1} , with a total of 786 mm transpired throughout the season. The yield in the 'Cripps Pink' orchard was 85 t ha^{-1} with a seasonal transpiration total of 594 mm. The higher seasonal transpiration in the 'Golden Delicious' orchard was likely a result of a higher LAI ($3.43 \text{ m}^2 \text{ m}^{-2}$) of these trees as compared to the 'Cripps Pink' trees ($2.82 \text{ m}^2 \text{ m}^{-2}$). The results show that tree water use varies according to climatic conditions and canopy size. There was no clear relationship between transpiration rates and yield in the current study. 'Golden Delicious' trees transpired more water than 'Cripps Pink' trees throughout the season; and this was a result of a bigger canopy size. These results were used as a basis for evaluating a modelling procedure of adjusting crop coefficients based on canopy height and size by Allen and Pereira (2009). Modifications to estimate transpiration crop coefficients (K_t) by Taylor et al. (2015) on citrus were used. The model overestimated the transpiration rates due to higher leaf resistance values.

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Dissertation Outline

Chapter 1 initially presents the importance of the apple industry in the South African economy, as well as a general overview of models that have been used for irrigation scheduling. The dissertation then follows with four main chapters. In chapter 2, a review of literature pertaining to tree water use is explained. This involves factors that influence tree evapotranspiration, which includes environmental and tree factors, as well as physiological responses of the trees. In addition, the manner in which orchards have been managed in relation to tree water use is also reviewed. This chapter also describes the different methods used in estimating tree water use, outlining the advantages and disadvantages of each method. Published literature specifically on apple tree water use is then evaluated. Finally, the chapter explains the different models that have been used in apple tree water use with the focus being on the FAO-56 crop coefficient approach and the Allen and Pereira (2009) method for determining crop coefficients based on tree height and canopy size. Chapter 3 covers the different transpiration measurements obtained from the apple orchards in Kromfontein. I then discuss the results obtained from the orchards in chapter 4 and transpiration coefficients are determined for the two orchards using the FAO-56 crop coefficient approach. In chapter 5, crop coefficients are determined using the Allen and Pereira (2009) method, with modifications in determining transpiration coefficients from Taylor et al. (2015). These transpiration crop coefficients were compared to the calculated transpiration rates obtained from measured transpiration and reference evapotranspiration (ET_0) in the apple orchards. Furthermore, measured transpiration rates were compared to the estimated transpiration rates using the Allen and Pereira (2009) procedure; this was done to test the tree water use model in the apple orchards at Kromfontein. Chapter 6 presents the general summary and conclusions of the study.

CHAPTER ONE

GENERAL INTRODUCTION

Apples (*Malus domestica*) are of commercial importance in South Africa, with a total production area of 24 212 ha and a total value of production estimated at R6.3 bn during the 2015/2016 season (Hortgro, 2016). South Africa is ranked 15th in terms of world apple production, producing 792 549 tons in the 2013/2014 season (FAOstat, 2015; Hortgro, 2014). Furthermore, South Africa was 7th in world apple exports, with 374 652 tons exported in the 2013/14 season (Comtrade, 2014). This indicates that production of high quality apples is of importance in this country and it is important that this industry remains sustainable. Most apples are produced in the winter rainfall region of the Western Cape, which includes Groenland, Ceres, Villiersdorp, Koue Bokkveld, and in the Eastern Cape in the Langkloof Valley. The main apple cultivars grown in South Africa are 'Golden Delicious', 'Granny Smith', 'Royal Gala', 'Top Red' and 'Cripps' Pink' (Figure 1.1) (Hortgro Tree Census, 2016).

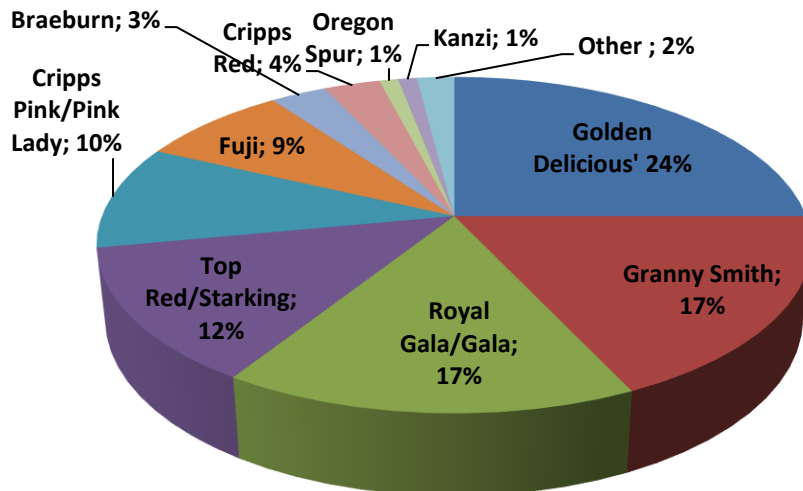


Figure 1.1 Contribution of apple cultivars to the total apple area under cultivation in South Africa (Hortgro, 2016)

As mentioned above, most of the apple production in South Africa takes place in the Western Cape, which is a winter rainfall region, where summer rainfall is low (Pretorius and Wand, 2003). Therefore, almost all apple orchards should be irrigated and to produce high quality apples, water stress should be avoided at most stages of crop growth. However, the increased competition for water resources is placing an increased pressure on an already scarce resource in this region of South Africa (Midgley and Lotze, 2011). In such a scenario, irrigation-scheduling methodologies need to be more precise to maximize water productivity (Gonzalez-Altozano and Castel, 2000), where water productivity is defined as the ratio of product obtained per unit water consumed. For this to be achieved accurate knowledge of water use of apple trees is required (Dragoni et al. 2005; Gonzalez-Talice et al. 2012). This information is also important for the issuing of water licenses. However, quantification of tree water use, under all possible scenarios, is time consuming and expensive (Jones and Tardieu, 1998) and thus models have been developed to estimate crop water use (Villalobos et al. 2013). To model effectively and accurately, it is important to understand the variables that drive tree water use, and these include climatic conditions, such as solar radiation, relative humidity, wind speed and temperature. Orchard water use is also influenced by canopy size, tree spacing and orientation, canopy structure, and soil water content (Wullschleger et al. 1998, Li et al. 2002).

Many models have been developed to determine tree water use. The FAO-56 crop coefficient model approach is one of the most widely used models worldwide, as it provides a relatively accurate, simple and convenient way to estimate ET from a variety of crops and climates (Allen et al. 1998). The Dual- K_c model (Allen et al. 1998) can consider both the transpiration and evaporation component of the crop, which are both expected to vary quite widely in different orchards. Partitioning of these components allows the determination of beneficial (transpiration) and non-beneficial (evaporation) consumptive water use. Transpiration is viewed as being beneficial as it is closely linked to productivity (Kool et al. 2014) and is therefore a key component to estimate in orchards. The transpiration crop coefficient (K_t) is the ratio of transpiration (T) to reference crop evapotranspiration (ET_o) (Kang et 2003), with values of K_t for specific orchards largely determined by the vegetation characteristics, which is largely a reflection of the ground

covered or shaded by the vegetation and the height of the crop. With this in mind, Allen and Pereira (2009) developed a method for adjusting crop coefficients for different orchards based on crop height and vegetation density and the degree of stomatal control of transpiration under wet soil conditions, which has been evaluated with good success in peach (Paço et al. 2012) and citrus (Taylor et al. 2015).

The purpose of this study was therefore to accurately estimate transpiration of mature apple orchards and relate changes in transpiration to changing weather conditions and canopy size, to assess the driving variables for water use in apples. This information was then used to evaluate the method proposed by Allen and Pereira (2009) for adjusting crop coefficients based on local weather conditions, crop height and fraction of ground shaded by the vegetation.

1.1 Hypotheses

There is a linear relationship between atmospheric evaporative demand (ET_o) and transpiration rates throughout the season in mature apple orchards.

Hourly transpiration rates are directly related to an increase in solar radiation in the morning but are reduced by increases in vapour pressure deficit (VPD) on days with high atmospheric demands.

There is a linear relationship between fortnightly transpiration crop coefficients (K_t) and canopy cover as determined by normalized difference vegetative index (NDVI) with remote sensing.

Transpiration crop coefficients (K_t) can be accurately adjusted for different mature apple orchards based on canopy height and fraction of ground shaded by the vegetation.

1.2 OBJECTIVES OF THIS STUDY

The main objectives of this study were to:

- Determine solar and photosynthetically active radiation (PAR) interception of individual apple trees throughout the research period. This was done to assess intercepted radiation and variation in canopy size throughout the season.
- Determine hourly and daily transpiration of unstressed, mature, full bearing apple trees using the heat ratio sap flux density technique, to evaluate the influence of atmospheric demand on transpiration rates throughout the season.
- Investigate hourly stomatal response in the prevailing weather conditions with the use of a leaf porometer. This was done to evaluate the response of stomata to the environmental conditions throughout the day.
- Determine transpiration crop coefficients from measured meteorological and physiological data to estimate tree water use throughout the season.

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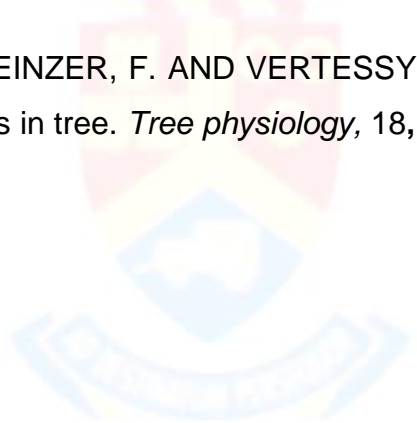
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CHAPTER TWO

LITERATURE REVIEW

2.1 Factors affecting orchard evapotranspiration

Water is lost from the orchard through surface runoff, deep percolation, evaporation from the soil surface as well as the cover crop which grows between the tree rows; and transpiration from the leaves of the crop. Of these, the biggest losses are due to evaporation and transpiration, collectively referred to as evapotranspiration (ET) (Allen et al. 1998). However, for this study, the focus will be on the transpiration component. Transpiration rates are determined by both environmental conditions and plant characteristics, which includes canopy size, crop rooting characteristics and resistances to water movement within the plant (Allen et al. 1998). In orchard situations, management options are also likely to impact transpiration rates, especially the level of irrigation and irrigation scheduling, which ultimately determine the soil water content. The way these factors regulate transpiration is well described by the Penman-Monteith equation (Monteith, 1965) as follows:

$$\lambda E = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)} \quad (1)$$

where λE is the latent heat of vaporization of water (J kg^{-1}), Δ is the slope of the saturation vapour pressure against temperature curve ($\text{Pa } ^\circ\text{C}^{-1}$), R_n is net radiation, G is the soil heat flux, ρ_a is the density of air (kg m^{-3}), c_p is the specific heat of air at constant pressure ($\text{J kg}^{-1} ^\circ\text{C}^{-1}$), $e_s - e_a$ is the vapour pressure deficit (VPD) of the air (Pa), γ is the psychrometric constant ($\text{Pa } ^\circ\text{C}^{-1}$), r_a is aerodynamic resistance and r_s is the surface or canopy resistance (s m^{-1}). The way these factors impact transpiration will be discussed below in section 2.1.1, regarding this equation.

2.1.1 Environmental factors

The integrated effect of several environmental factors creates the driving force for water movement out of the plant. These environmental factors include solar radiation, relative humidity or vapour pressure deficit, temperature and wind speed. Solar radiation absorbed by the leaves provides the energy to evaporate water, whilst the evaporative power of the atmosphere determines the rate of transpiration. The effects of solar radiation vary both as a function of the solar radiation available (varying with region, atmospheric conditions e.g. clouds and time of the year) and with the fraction intercepted by the canopy (Jones et al., 1985). Stomata are also triggered to open in the morning, as solar radiation increases to facilitate carbon dioxide (CO₂) uptake and therefore the start of photosynthesis. Thus, water can be lost through the stomata and transpiration can begin. On warm, dry, sunny days the water holding capacity of the air is greater than on cool, humid and cloudy days and thus, the potential driving force for transpiration will be greater on warm, dry and sunny days.

Wind can have a varying impact on transpiration, depending on the prevailing conditions. In general, the process of vapour removal from the evaporative surface depends on wind and air turbulence, which results in transfer of air at this surface (Allen et al. 1998). If the air at the evaporative surface is not replaced by drier air, the driving force for evaporation decreases. In other words, wind and turbulent air transport reduces the boundary layer resistance (r_a in equation 1) and increases transpiration. This effect is more pronounced under drier conditions than more humid conditions (Allen et al. 1998).

In many crops, there is a linear relationship between the atmospheric evaporative demand and crops under non-limiting soil water; however, in other crops this relationship is not linear (Allen et al 1998). This is largely due to numerous resistances to water movement within the plant, which differ for different crops.

2.1.2 Tree factors

Transpiration from a crop will also depend on several specific crop characteristics. These include crop type, variety and stage of development, as they influence internal resistances to water movement, crop height, surface roughness, albedo and crop root characteristics (Allen et al. 1998). Thus, different crops will transpire different amounts under the same set of climatic conditions.

As the crop develops, the ground cover, crop height, as well as leaf area will change; and the tree water use for a given crop will vary over the growing period. Canopy size is regarded as one of the most important factors that influence tree water use throughout the growing season (Giuliani et al. 1997). Canopy structure is variable in the field and causes large variability in water use from tree to tree and from orchard to orchard (Li et al. 2002). As apples are deciduous, the canopy size of apple tree orchards varies considerably throughout the season from spring to winter and will also vary throughout the life of the orchard. Gong et al. (2008) investigated the relationship between leaf area index (LAI) and crop coefficients (K_c) of apple trees and found a linear dependence of the K_c on LAI throughout the season.

The movement of water through the plant from the soil to the atmosphere is not a passive process, as plants are designed to control their water status within certain limits, in the presence of widely varying environmental conditions (Campbell and Turner 1990). The driving force for water movement through the soil-plant-atmosphere continuum is a difference in water potential between the soil and the leaves and leaves and the atmosphere (Jones and Tardieu, 1998). Transpiration rates are mainly regulated by vapour phase resistances and driving forces, so the resulting water potential is a result of the imposed transpiration rate (as dictated by atmospheric demand), rather than a determinant of the transpiration rate (Campbell and Turner 1990). However, leaf water potential does have an indirect effect on transpiration rates, since stomata tend to close when leaf water potentials become too low. Within the system, the major resistances to water movement are soil resistance, the soil-root interface, the root endodermic

resistance, the root and xylem resistance and the petiole or leaf hydraulic resistance (Campbell and Turner 1990).

To balance supply to the leaves and loss of water into the atmosphere, the plant must exert some control over the resistance to water loss from the leaves and this is achieved by the stomata. However, stomatal control over transpiration depends on the ratio between stomatal conductance and the boundary layer conductance surrounding each leaf and the canopy (Meinzer et al. 1993). When the boundary layer conductance is high relative to stomatal conductance then stomatal control of transpiration is strong and the transpiration rate will reflect the vapour pressure of the bulk air imposed at the leaf surface. The leaf area index and stomatal aperture both play a pivotal role in determining the canopy physiological conductance and hence transpiration. The climate and structure of the canopy impact the boundary or aerodynamic conductance, whilst the canopy conductance depends on the physiological behavior of the plant (Herbst 1995). The stomatal control over transpiration varies between species, with some plants exerting more stomatal control over transpiration than others (Allen and Pereira 2009). For example, citrus stomata may reopen more slowly than stomata in several temperate tree species. In arid regions, stomatal responses in apricot trees (*Prunus armeniaca*) have been observed to be highly effective in controlling transpiration and only small changes in total daily transpiration were observed over a wide range of vapour pressure deficits (Schulze et al. 1974). This is therefore an important parameter to consider when modelling transpiration of some crops, especially fruit tree species.

2.1.3 Management factors

The way orchards are managed has a large influence on ET from the orchard. Canopy cover, netting, irrigation system and the presence or absence of a cover crop all influence evaporation from the soil, but as this study focusses on transpiration, this aspect will not be discussed further. The planting system, which includes both tree arrangement in orchards (planting distances and row orientation) and training of the tree canopy by pruning and bending procedures (tree shape and height) are important factors in orchard management which will influence transpiration by impacting on the amount of solar radiation intercepted by the canopy (Willeume et al., 2004). In addition, wind velocities

can be reduced by placing windbreaks, and this will result in a decrease in evapotranspiration (Allen et al. 1998).

Crop load is also reported to influence water use per unit leaf area, in both deciduous and evergreen fruit tree species, with higher crop loads leading to increased water use (Mpelasoka et al. 2001; Martín-Vertedor et al. 2011). The seasonal water use of cropping apple and peach trees has been found to be 15-100% more than that of non-cropping trees (Jones et al. 1985). Therefore, the practice of thinning fruits from such species to improve marketable size may be a good orchard management practice to help reduce tree water use (Jones et al. 1985).

There is an increasing trend in many fruit tree industries to use high planting densities to achieve a quicker return on investment. This will increase orchard water use, especially when the trees are young and have not filled their allocated space, as compared to lower density plantings. However, as orchards get older and form a hedgerow there may be very little difference between low and higher density plantings and will largely be determined by canopy cover (Trentacoste et al. 2015).

2.2 Methods for estimating tree water use

There are several different methods for estimating tree transpiration, which include weighing lysimeters, the soil water balance and an array of sap flow methods (Pereira et al. 2011). Many of these methods require expensive equipment and substantial expertise to get reliable estimates. Some methods of estimating transpiration also require that evaporation from the soil is eliminated (e.g. weighing lysimeters) or accounted for (e.g. the soil water balance), in order to determine transpiration accurately (Smith and Allen 1996). Separating transpiration from evaporation is important for orchard water use studies as it allows an understanding of factors regulating water use from the crop, which is a key factor when trying to model plant water use (Kool et al. 2014). In addition, it also allows the separate modelling of the evaporation component. Sap flow techniques are often considered to be the most appropriate technique for determining transpiration, without altering the transpiration conditions (Smith and Allen 1996). This is due to the fact that the systems are easy to automate, the data is fairly easily interpreted, measurements

can be made on an hourly basis, they do not alter the microclimate of the plant, as whole plant chambers do, and they can estimate plant water use over extended periods of time.

2.2.1 Sap flow methods

The principle behind sap flow measurements is based on the application of heat on or within the stem to measure the water flux across a given section, at a given period, as the sap moves up the transpiration stream (Lui et al. 2012). Many methods for determining sap flow have been used and are often placed into two categories. The first being the stem heat energy balance, whereby total sap flow in the stem is determined by resolving the heat balance of a stem by continuously heating the stem, with a known or variable voltage. Although heat gauges can cover a wide range of stem diameters i.e. 2-125 mm, they are less suited for measuring the sap movement within the stem of large trees (Vandegehuchte and Steppe 2013). Thus, this method will not be discussed further, as it is not suitable for measurements of transpiration in the large trees used in this study.

The second category includes sap flux density methods, whereby the rate of sap moving through a certain stem surface is determined for a defined period. These sap flow methods measure the flow of water in the xylem either by the velocity of heat pulse carried away from the heat source in the transpiration stream or by the dissipation of heat energy in the transpiration stream away from a constantly heated probe due to convection (Allen et al., 2011). The most commonly used constant heat technique is the thermal dissipation probe (TDP) or Granier technique (Steppe 2010). The TDP method is based on the comparison in temperature between a constantly heated probe and that of an unheated probe located upstream of the heater in the xylem. The temperature difference depends on the rate of transpiration, as heat is dissipated more rapidly when the sap flux increases and therefore the smaller the temperature difference between the two thermocouples the higher the sap flux density (Steppe et al. 2010). The TDP method measures a wide range of sap flux densities ($80 \text{ cm}^3 \text{ cm}^{-2} \text{ h}^{-1}$ and more) (Vangehuchte and Steppe 2013) and has grown in popularity due to its low cost and simplicity.

Heat pulse sap flux density methods measure sap flow rates by determining the velocity of a short pulse of heat that is carried by the sap in the xylem vessels (Smith and Allen 1996). These methods include the compensation heat-pulse (CHP) method and the heat ratio (HR) method. Whilst the hardware for these two methods is the same, the way the sensors are deployed in the stem differs and therefore also the calculations of heat pulse velocity (Figure 2.1). For the CHP method one thermocouple is installed 5 mm upstream from the heating needle, whilst the other is placed 10 mm downstream from the heater (Allen et al., 2011). A heat pulse of 1-2s duration is released by the heater and carried by the flowing sap toward the mid-point between the probes; and the time is recorded at which the temperature of the upstream thermocouple is equal to the downstream thermocouple (Swanson and Whitfield 1981) Heat pulse velocity is calculated as a function of the distance between the thermocouples and the time it took to reach thermal equilibrium (Burgess et al. 2001). The advantages of the CHP method are that it requires low power requirements and the data produced is suitable for storage on a data logger. The disadvantages are that it cannot resolve reverse, low and very high flow rates ($<5 \text{ cm}^3 \text{ cm}^{-2} \text{ h}^{-1}$ and $>100 \text{ cm}^3 \text{ cm}^{-2} \text{ h}^{-1}$). In addition, accuracy depends on the correct probe spacing and alignment accuracy; and it requires calibration for each new species in which it is to be used (Edwards et al., 1996). Damage is also caused to the xylem vessels during installation, which must be accounted for through wounding corrections (Swanson and Whitfield 1981)

As mentioned above the HR method is very similar to the CHP method; however, in the HR method the two thermocouples are placed equidistant from the heat source (Figure 2.1). This method measures the ratio in temperature between the two sensors following the release of a pulse of heat (Burgess et al. 2001). The advantages of this method are that it can measure low flow rates and reverse flows and it is not susceptible to temperature changes in the sapwood. The disadvantages are that it performs poorly under high flow rates, that is, $> 45 \text{ cm}^3 \text{ cm}^{-2} \text{ h}^{-1}$ and once again; corrections need to be made for damage that occurs when holes are drilled for the installation of sensors; which cause an under-estimation of sap flux density (Burgess et al. 2001).

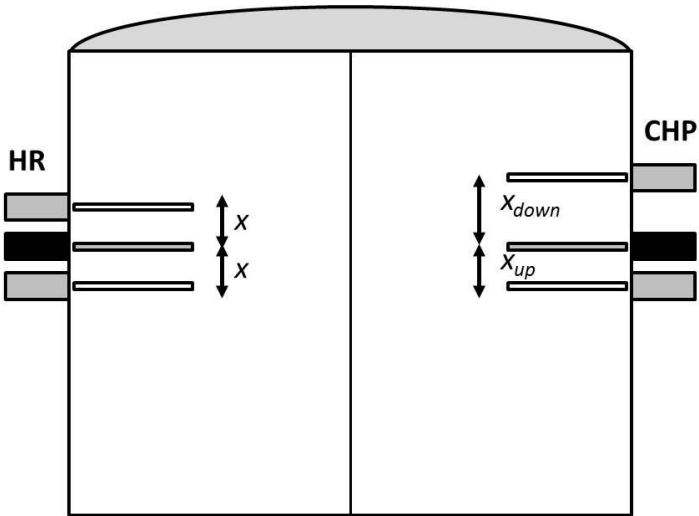


Figure 2.1 A schematic representation of the heat ratio (HR) method and compensation heat pulse method (Vandegehuchte and Steppe 2013)

These sap flow methods have been deemed to be robust and reliable in the field over extended periods of time (Diaz–Espejo and Fernández 2008). Furthermore, in a study determining transpiration in ‘Royal Empire’ apples, Dragoni et al. (2005) stated that the main advantage of the sap flow technique is that there is no disruption between the water lost from the canopy and root water uptake; and that the calculation of transpiration can be automated.

In this current study, however, the heat ratio method was used to measure the sap flow rates due to previous success using this technique in apple trees (Gush and Taylor 2014) and considerable expertise within the broader project team. In the heat ratio method heat pulse velocity is calculated per Marshall (1958) as:

$$V_h = \frac{k}{x} \ln \left(\frac{v_1}{v_2} \right) 3600 \quad (2)$$

where V_h is the heat pulse velocity (cm h^{-1}), k is the thermal diffusivity wood, assigned a nominal value of $2.5 \times 10^{-3} \text{ cm}^2 \text{ s}^{-1}$ (Marshall 1958), x (cm) is the distance between the heater and either thermocouple, and v_1 and v_2 are the increases in temperature after the heat pulse has been released (from initial temperatures).

Burgess et al. (2001) developed a numerical model to determine appropriate wound correction coefficients, which correct for the damage caused during sensor implantation. To correct heat pulse velocity measured with heat ratio method three coefficients b , c and d are used in the following equation:

$$V'_h = bV_h + cV_h^2 + dV_h^3 \quad (3)$$

where V'_h is the corrected heat pulse velocity and the correction coefficients corresponding to wound width (z) are calculated as:

$$b = 6.6155z^2 + 3.332z + 0.9236 \quad (4)$$

$$c = -0.149z^2 + 0.0381z - 0.0036 \quad (5)$$

$$d = 0.0335z^2 - 0.0095z + 0.0008 \quad (6)$$

Sap flux density (SFD) can be calculated as follows (Burgess et al. 2001):

$$SFD = \frac{V'_h \rho_b (C_w + M_c C_s)}{\rho_s C_s} \quad (7)$$

Where, V'_h is the wound corrected heat pulse velocity, ρ_b is the basic density of wood, C_w the specific heat capacity of the wood matrix (1200 J kg⁻¹ °C⁻¹ at 20°C), C_s is the specific heat density of sap (water, 4182 J kg⁻¹ °C⁻¹ at 20°C), M_c is the water content of sapwood and ρ_s is the density of water. Volumetric sap flow is subsequently calculated from the product of sap velocity and conducting sapwood area. Gross wood cross-sectional area is calculated from under the bark radius and heartwood is discounted by observing visual discoloration of wood or staining conducting sapwood with safranin.

2.3 Apple tree water use

Apple water use will vary throughout a single season, according to the phenological cycle and throughout the life of the orchard, according to canopy size. Figure 2.2 illustrates the different stages in the growth cycle of pome fruits. Throughout the early part of the season water use will increase with shoot growth, until shoot growth stops in the latter part of the season, which is often January in the Southern Hemisphere (Landsberg and Jones 1981).

The next stage is the fruit cell expansion stage whereby the fruit cells begin to fill with water and sugars; and rapid fruit growth is observed. Tree water use increases during this period and thus, irrigation should be applied at maximum rates. At the end of the fruit cell expansion stage, the fruit are mature and harvested. At this stage, there is a reduction in tree water use and the leaves begin to fall for many apple tree cultivars. When leaf fall occurs, generally the tree will use very little water due to the reduced leaf area and reduced photosynthesis as the tree enters dormancy during winter (Boland et al. 2002). Additional factors affecting transpiration volumes from an orchard which are determined by weighing lysimeter may include cultivar, rootstock, training system and planting density (Naor et al. 2008).

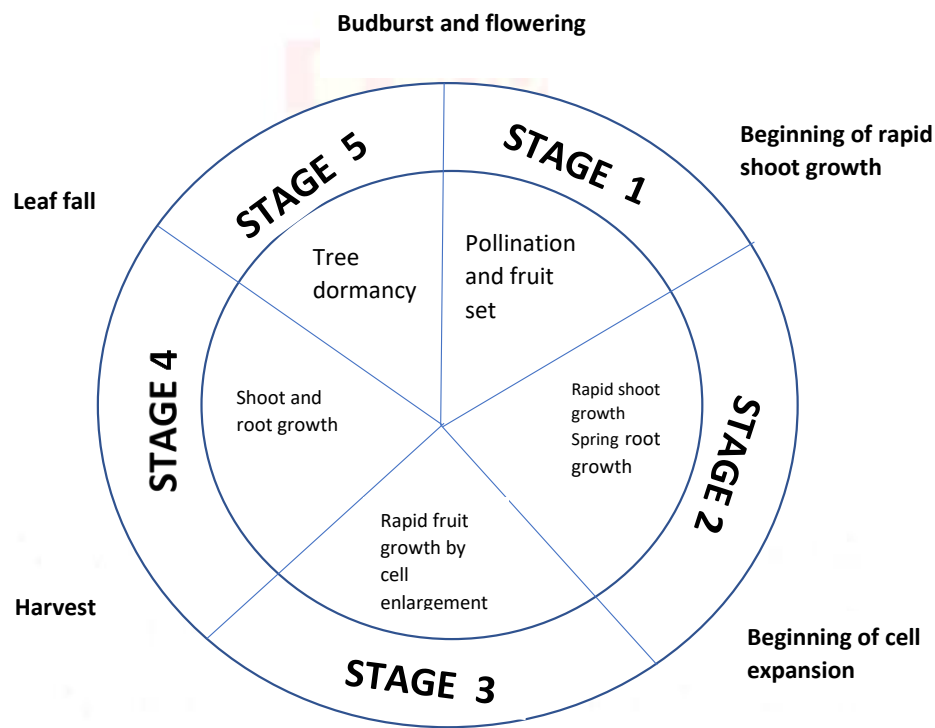


Figure 2.2. The growth cycle of pome fruit tree (adapted from Boland et al. 2002).

Published literature in Table 2.1 below shows that water requirements for apple trees vary depending on the different tree spacings, measurement techniques and physiological factors experienced by the trees. These factors provide an explanation on the different results concerning annual, monthly and daily water requirements in apple trees in different regions. Techniques used to measure the transpiration component mainly involved the

sap flow technique and for evapotranspiration, both sap flow and lysimetry. The average daily transpiration rate of apple trees has been reported to range between 2.3 mm day⁻¹ and 4.6 mm day⁻¹, with maximum rates reaching 6 mm day⁻¹ (Table 2.1). These maximum daily transpiration rates are often important in the design of the farmers' irrigation system as they must meet the peak demand of the trees in summer. To observe the influence of plant density on tree water use, the published data in Table 2.1 was analyzed in all the different studies. Gong et al (2007) reported that eight-year-old apple trees transpired an average of 2.3 mm day⁻¹ with estimated maximum rates of 6.1-6.5 mm day⁻¹. The component measured was evapotranspiration and the estimation method employed was the sap flow method and microlysimetry. The row spacing of the orchard was highly dense at 3 m x 3.2 m. In comparison, Villalobos et al. (2013) measured the water use of nine-year-old 'Golden Smoothie' trees at a less dense row spacing of 4 m x 1.6 m and the maximum transpiration rate was 5 mm.day⁻¹. The differences were 1) the component measured and 2) the water use on an area basis. Higher rates of transpiration in the study by Gong et al. (2007) may have been attributed to both evaporation and transpiration being measured, whilst Villalobos et al. (2013) only measured the transpiration rates. In terms of plant spacing, the orchard in the study by Villalobos et al. (2013) had a low planting density and this may have influenced the low transpiration rates. It is also important to mention that the canopy volume as determined by LAI may have had a contribution in the transpiration rates on both studies. The maximum LAI in Villalobos et al. (2013) was 2.5 m m⁻², whereas in the study by Gong et al. (2007) it was 3.2 m m⁻². In addition to the above-mentioned studies, Liu et al (2012) drew similar results in comparison to Villalobos et al. (2013), with 'Golden Delicious' apple trees transpiring maximum estimates of 4.5 mm day⁻¹ at a row spacing of 4 m x 6 m (Table 2.1). Although the planting density in the study by Liu et al. (2012) was much lower than the study done by Villalobos et al. (2013), we can suggest that orchards with high planting densities may use more water than low planting density orchards. However, if the low density orchard has a higher LAI, it is likely to transpire more than a higher planting density orchard.

With regards to the effect of tree age and canopy size on apple tree water use, Girona et al. (2011) investigated the water use of 'Golden Smoothie' trees from 2002 – 2006 (Table

2.1). The trees transpired a maximum estimated rate of $3 \text{ mm}\cdot\text{day}^{-1}$ in the 2002 season to maximum estimates of $6 \text{ mm}\cdot\text{day}^{-1}$ in the 2006 season, at a row spacing of $4 \text{ m} \times 1.6 \text{ m}$. The LAI increased from $0.94 \text{ m}^2 \text{ m}^{-2}$ in 2002 to $1.90 \text{ m}^2 \text{ m}^{-2}$ in 2006. In addition, when analyzing the study by Liu et al. (2012), it was observed that the tree canopy played an important role in tree water use with transpiration rates having a linear relationship with LAI ($r^2 = 0.73$) on sunny days. It is indicative from these studies that there was a direct correlation between canopy development and transpiration. There was an increase in transpiration rates as the trees grew older and as the canopy become larger throughout the season.

Other studies mention that different rootstocks of apple trees may lead to different amounts of water being transpired in a season. Li et al. (2002) did a study on canopy structure and transpiration of full bearing 'Golden Delicious' orchards on three different rootstocks namely, M9, MM106 and the local Hashibi rootstock and three different planting dates. The LAI of the orchard with the Hashibi rootstock was significantly lower than the M9 and MM106 rootstocks, however, there was very little difference in the LAI of the M9 and MM106 rootstocks. The M9 rootstock, which was of a dwarfing type, used less water (571 mm throughout the season) than the MM106 and Hashibi rootstocks with a planting density of $3 \text{ m} \times 3.3 \text{ m}$. The vigorous MM106 used 792 mm at a plant density of $4 \text{ m} \times 2 \text{ m}$. The Hashibi rootstock (vigorous) used 811mm throughout the season. Although we can conclude from this study that dwarfing rootstocks may use less water than vigorous rootstocks, more research needs to be done in this regard as the results could not give a clear relationship between the rootstocks, canopy structure and transpiration rates. Although many factors such as age, region and type of rootstock may play a vital role in apple tree water use, the information from literature in Table 2.1 below illustrates that the major factors in tree water use in different orchards is the planting density and the LAI. In Table 2.1, measurements that were carried out on low planting density orchards displayed less transpiration rates than the measurements done on high planting density orchards.

Table 2.1: Apple tree water use obtained from published literature

| Cultivar | Spacing | Location | Measurement Period | Technique | Components measured | Average water use | Reference | Age (years) |
|--------------------|----------------|-----------------|---------------------------|------------------|----------------------------|--|----------------------|--------------------|
| 'Yellow Delicious' | 4m x 1.6m | Spain | 2007 – 2008 | Lysimetry | T | 3.82 mm day ⁻¹ (max estimates) | Auzmendi et al. 2011 | 2 |
| 'Royal Empire' | 4.3m x 1.8m | U.S.A. | 10 weeks | Sap Flow | T | 4.7 mm day ⁻¹ | Dragoni et al. 2005 | 8 |
| 'Splendour' | 4m x 4m | New Zealand | 13 weeks | Sap Flow, TDR | T | 2.5 mm day ⁻¹ | Green 2003 | 14 |
| 'Golden Smoothee' | 4m x 1.6m | Spain | 2002 | Lysimetry | ET _c | 3 mm day ⁻¹ (max estimate) | Girona et al. 2011 | 3 |
| 'Golden Smoothee' | 4m x 1.6m | Spain | 2003 | Lysimetry | ET _c | 4 mm day ⁻¹ (max estimate) | Girona et al. 2011 | 4 |

| | | | | | | | | |
|--------------------------------|-----------|-------------|------------------|------------------------------|-----------------|--|--------------------|----|
| 'Golden Smoothie' | 4m x 1.6m | Spain | 2004 | Lysimetry | ET _c | 4 mm day ⁻¹ (max estimates) | Girona et al. 2011 | 5 |
| 'Golden Smoothie' | 4m x 1.6m | Spain | 2005 | Lysimetry | ET _c | 5.5 mm day ⁻¹ (max estimates) | Girona et al. 2011 | 6 |
| 'Golden Smoothie' | 4m x 1.6m | Spain | 2006 | Lysimetry | ET _c | 6 mm day ⁻¹ (max estimates) | Girona et al. 2011 | 7 |
| Apple (cultivar not specified) | 3m x 3.2m | China | April – Oct | Sap Flow and micro-lysimetry | ET | 2.3 mm day ⁻¹ (max estimates 6.1-6.5 mm day ⁻¹) | Gong et al. 2008 | 8 |
| 'Golden Delicious' | n/a | Germany | August – October | Lysimetry | T | 4.7 l day ⁻¹ | Blanke M. 1997 | 4 |
| 'Red Delicious' | n/a | New Zealand | 15 days (Summer) | Sap Flow | T | 27 l day ⁻¹ | Green et al. 1989 | 10 |

| | | | | | | | | |
|--------------------|--------------|--------|-------------|----------|---|-----------------------------|-------------------------|----|
| 'Golden Delicious' | 3.5m x 1.75m | Israel | May – Oct | Sap Flow | T | 571 mm season ⁻¹ | Li et al. 2002 | 10 |
| 'Golden Delicious' | 4m x 2 m | Israel | May – Oct | Sap Flow | T | 792 mm season ⁻¹ | Li et al. 2002 | 11 |
| 'Golden Delicious' | 4.5m x 2m | Israel | May – Oct | Sap Flow | T | 811 mm season ⁻¹ | Li et al. 2002 | 15 |
| 'Golden Delicious' | 4 m x 6m | China | 2008 - 2010 | Sap Flow | T | 4.5 mm day ⁻¹ | Liu et al. 2012 | 31 |
| 'Golden Smoothee' | 4m x 1.6m | Spain | May – Sept | Sap Flow | T | 4.6 mm day ⁻¹ | Villalobos. et al. 2013 | 9 |

2.4 Modelling apple tree water use

It is evident from Table 1 that apple transpiration rates vary widely between different orchards in different production regions and even within the same production region. As it is impossible to do continuous measurements of transpiration in a wide range of orchards due to time and budgetary constraints, it is important to be able to extrapolate measured water use to a wide range of conditions using various models. Apple (amongst other crops) water use has been modelled on many occasions through various models such as the FAO-56 crop coefficient model (Allen et al., 1998), a simplified canopy conductance model (Villalobos et al., 2013), and the Penman-Monteith equation using modelled estimates of canopy conductance (Green et al., 2003; Green and McNaughton 1997).

2.4.1 FAO-56 crop coefficient model approach

The FAO-56 crop coefficient model is one of the most widely used water use models in agriculture, due largely to its relative simplicity and robustness over a wide range of conditions. In this model water use of a crop is related to water use from a hypothetical reference crop (ET_o) using a crop coefficient (K_c) (Allen et al. 1998), such that

$$ET = K_c ET_o \quad (8)$$

The reference crop is defined as a hypothetical well-watered grass canopy surface with an assumed height of 12 cm, a fixed crop surface resistance of 70 m. s^{-1} and an albedo of 0.23. ET_o is estimated from weather parameters obtained from an automatic weather station (AWS) using the Penman-Monteith (FAO-56) equation (Allen et al., 1998), as follows

$$ET_o = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma (1+0.34 u_2)} \quad (9)$$

Where R_n is the net radiation of the crop surface, G the soil heat flux density, T is air temperature at 2 m height, u_2 is wind speed at 2 m height, e_s is saturation vapour pressure, e_a is actual vapour pressure, $e_s - e_a$ is the vapour pressure deficit, Δ is the slope vapour pressure curve and γ is the psychrometric constant (Allen et al., 1998). The value of the crop coefficient (K_c) increases from bud break parallel with the development of canopy

coverage. Input crop parameters include LAI and fractional radiation intercepted by the canopy.

K_c represents E and T from a cropped surface for typical wetting frequencies. However, as wetting frequency and crop characteristics can vary widely, FAO-56 introduced a dual crop coefficient (Allen et al. 1998) where

$$K_c = K_{cb} + K_e \quad (10)$$

K_{cb} is the basal crop coefficient representing T and background E from a drying soil surface, K_e is the evaporation coefficient that represents the contribution of E from the soil to ET. As the K_{cb} includes a residual diffusive evaporation component supplied by soil water below the dry surface and by soil water from beneath dense vegetation, it was proposed by Villalobos et al. (2013) that K_{cb} values calculated from direct measurements of transpiration via sap flow measurements should be termed transpiration crop coefficients (K_t) defined as

$$K_t = \frac{T}{ET_o} \quad (11)$$

To account for crop growth over the season from planting to harvest, Allen et al. (1998) divided the growing season into four growth stages. The stages are: initial, crop development, mid-season and late season (Allen et al. 1998; Doorenbos and Pruitt, 1977). Figure 2.3 below illustrates these stages of crop development. The initial stage begins from planting date to the time when 10% of the ground surface is covered by green vegetation. At this stage, the canopy has not fully developed and the leaf area is small. Consequently, ET is dominated by E from the soil surface. The crop development stage begins when 10% of the ground surface is covered until full canopy cover. Full canopy cover of tree crops is suggested to be reached when $LAI > 3 \text{ m}^2 \text{ m}^{-2}$ (Allen et al. 1998). As LAI increases, exponentially during canopy development, the dominant component of ET becomes T by the end of stage 2 (Campillo et al. 2012). The mid-season stage starts from full canopy cover and continues to full maturity. The length of this stage varies from crop to crop, for perennials and annuals it is a long period, but for vegetables it is a shorter period. The late season stage runs from maturity to harvest or full senescence. This stage

is often associated with lower stomatal conductance. Consequently, tree water use at this stage decreases and by the end of the stage it is once again evaporation from the soil surface which dominates (Allen et al. 1998).

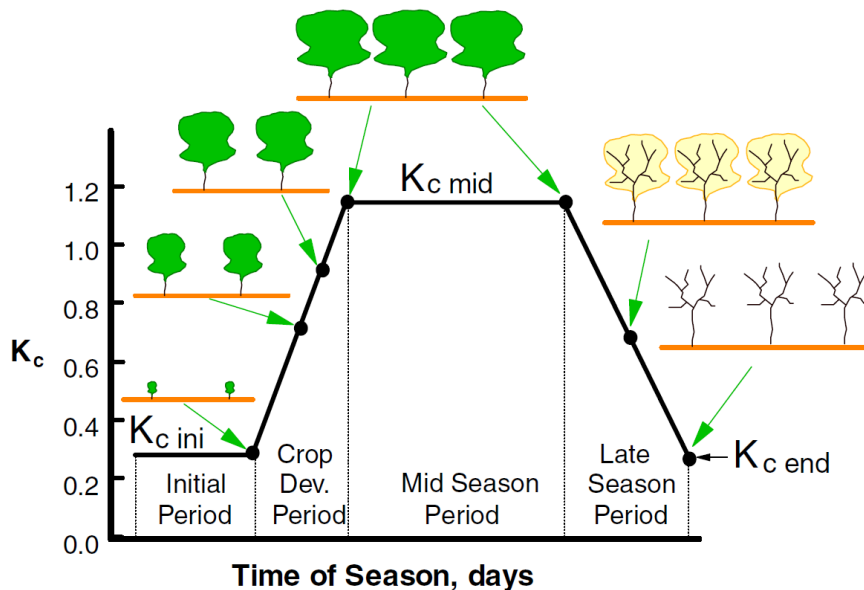


Figure 2.3 Crop coefficient curve for the different crop growth stages of a deciduous tree crop (Allen and Pereira 2009)

Due to changes in the ground and canopy cover, the crop coefficients will vary throughout the season. These variations are represented in the crop coefficient curve, whereby only three points are needed to complete the curve namely being, $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ (Allen et al. 1998). The FAO-56 Irrigation and Drainage paper tabulated crop coefficient values for different crops at each stage of crop development. Table 2.2 below presents crop coefficients that are recommended for apple orchards in FAO-56 (Allen et al. 1998) and in a refinement of the procedure for fruit tree crops by Allen and Pereira (2009). Both publications have different crop coefficient values for different scenarios. According to Allen et al. (2009), these crop coefficients can be adjusted for climatic conditions where relative humidity is at a minimum 45% or where wind speed is higher than $2\ m.s^{-1}$.

Table 2.2 Values for crop coefficients at different growth stages for a standard climate of $RH_{\min} = 45\%$ and $u_2 = 2 \text{ m s}^{-1}$ from the FAO-56; and crop coefficients (Allen and Pereira 2009)

| FAO-56 | $K_{c \text{ ini}}$ | $K_{c \text{ mid}}$ | $K_{c \text{ end}}$ | Maximum Crop Height (h) (m) |
|---|---------------------------------------|---------------------------------------|---------------------------------------|--|
| No ground cover, killing frost | 0.45 | 0.95 | 0.70 | 4 |
| No ground cover, no frost | 0.60 | 0.95 | 0.75 | 4 |
| Active ground cover, killing frost | 0.50 | 1.20 | 0.95 | 4 |
| Active ground cover, no killing frost | 0.80 | 1.20 | 0.80 | 4 |
| Apple (Allen and Pereira 2009) | | | | |
| No ground cover (High density) | 0.50 | 1.15 | 0.80 | |
| No ground cover (Med. Density) | 0.50 | 1.05 | 0.75 | |
| No ground cover (Low Density) | 0.40 | 0.70 | 0.55 | |
| Active ground cover, killing frost | 0.50 | 1.15 | 0.85 | |
| Active ground cover, no killing frost | 0.85 | 1.15 | 0.85 | |

However, in tree crops a linear relationship between ET from a short, smooth and uniform grass surface and a tall, very rough clustered orchard canopy does not always exist (Annandale and Stockle 1994; Testi et al. 2004). As a result, K_c values derived in one

location may not be readily transferred to another location. This limits the extrapolation of measured data to other orchards in different climatic zones and with different management practices. The variation in K_c values for different orchards is largely attributed to variety, rootstock, tree spacing, canopy height, ground cover, tillage, LAI, training and pruning system, method of estimating reference evapotranspiration, microclimate, shade netting, irrigation method and frequency and method of measuring ET (Snyder and O'Connell 2007; Naor et al. 2008).

To make crop coefficients more transferable between different locations Allen and Pereira (2009) developed a procedure for estimating crop coefficients, which considers vegetation density and height and the degree of stomatal control over transpiration under moist soil conditions relative to most other agricultural crops. Taylor et al. (2015) made modifications to this procedure to estimate K_t values for citrus. In this modified procedure K_t values were adjusted for variations in canopy cover by using a density coefficient (K_d) as follows:

$$K_t = K_d (K_{t\ full}) \quad (12)$$

where $K_{t\ full}$ is defined as the transpiration crop coefficient during peak plant growth at near full ground cover. $K_{t\ full}$ can be adjusted for climate and mean canopy height by using the FAO procedure for adjusting with the use of daily minimum relative humidity and wind speed as

$$K_{t\ full} = F_r \left(\min(1.0 + 0.1h, 1.20) + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \left(\frac{h}{3}\right)^{0.3} \right) \quad (13)$$

where F_r [0 – 1] is a relative adjustment factor for stomatal control, h is the mean monthly plant height (m), u_2 is average monthly wind speed ($m.s^{-1}$) at 2 m, and RH_{min} is the average monthly minimum relative humidity (%). The parameter F_r applies a downward adjustment ($F_r \leq 1.0$) if the vegetation exhibits more stomatal control on transpiration than is typical for most annual agricultural crops. As suggested by Allen and Pereira (2009), F_r is most often < 1 for fruit tree crops. F_r at full cover vegetation, based on the FAO Penman-Monteith equation and assuming full cover conditions is calculated as:

$$F_r \approx \frac{\Delta + \gamma(1 + 0.34u_2)}{\Delta + \gamma\left(1 + 0.34u_2 \frac{r_1}{100}\right)} \quad (14)$$

where r_1 is mean leaf resistance for the vegetation in question [s. m^{-1}], Δ is the slope of the saturation vapour pressure versus air temperature curve ($\text{kPa } ^\circ\text{C}$), and γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}$). The standard value for F_r is 1.0 because, for most annual agricultural crops, r_1 is often 100 s.m^{-1} (Allen and Pereira, 2009). Values for mean monthly r_1 can be estimated by inverting Eq. 14 after solving F_r by inverting Eq. 13, using known monthly values of $K_{t \text{ full}}$. Allen and Pereira (2009) caution that the value of r_1 calculated in this manner is only useful for reuse in equation 4, as it contains artefacts of the $K_{t \text{ full}}$ measurements.

The density factor (K_d) can be determined per Allen and Pereira (2009) as:

$$K_d = \min\left(1, M_L f_{c \text{ eff}}, f_{c \text{ eff}}^{\left(\frac{1}{1+h}\right)}\right) \quad (15)$$

Where $f_{c \text{ eff}}$ is the effective fraction of ground covered or shaded by vegetation [0.01 - 1] at solar noon, M_L is a multiplier on $f_{c \text{ eff}}$ describing the effect of the canopy density on shading and on maximum relative ET per fraction of ground shaded [1.5 – 2], and h is the mean height of the vegetation in m. $f_{c \text{ eff}}$ was calculated as the ratio of tree canopy width to inter-row spacing. For canopies, such as trees or randomly (non-row) planted vegetation, $f_{c \text{ eff}}$ can be estimated as (Allen and Pereira, 2009):

$$f_{c \text{ eff}} = \frac{f_c}{\sin(\beta)} \leq 1 \quad (16)$$

where f_c is the observed fraction of soil surface covered by vegetation as seen directly overhead. Generally, $f_{c \text{ eff}}$ can be calculated at solar noon (12:00), so that β can be calculated as:

$$\beta = \arcsin[\sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta)] \quad (17)$$

where φ is latitude and δ is solar declination, both in radians.

Alternatively, if LAI has been measured or can be estimated then K_d can be approximated using the following equation:

$$K_d = (1 - e^{[-0.7LAI]}) \quad (18)$$

Allen and Pereira (2009) suggested parameters for apples which can be used to derive K_t values for specific orchards where height and fractional cover are known. The value for apparent effective r_l for the initial and midseason periods was 140 s. m^{-1} and r_l at the end of the season was 450 m s^{-1} . M_L is given as 2.0.

Rosa et al. (2010) developed the SIMDualKc model to compute ET to simulate irrigation scheduling using the dual crop coefficient approach by Allen et al. (1998). The model was validated for several crops and climates. The results showed that there was a good agreement between the modelled and measured data. Further, Paço et al. (2012) calibrated and validated the SIMDualKc model by Rosa et al. (2010) in a peach orchard in Portugal. They adopted extensions proposed by Allen and Pereira (2009), whereby the density coefficient K_d and plant height were used to adjust for K_{cb} and K_c . A good agreement between modelled and measured transpiration values was found. Furthermore, it was suggested by the authors that the model could be useful for irrigation scheduling (Paço et al. 2012). These studies gave a good reflection of how the model proposed by Allen and Pereira (2009) could be useful in estimating tree water use.

Other authors have suggested the use of remote sensing to monitor vegetation cover changes. Consequently, it has been observed that there are similarities between crop coefficients and satellite derived vegetation indices. This similarity has shown potential for a modeling purpose. The normalized difference vegetation index (NDVI) has been used numerous times for the determination of vegetation mapping, yield assessments and severity of plant stress in many agricultural crops (Kamble et al. 2013; Kim and Glenn 2015). NDVI has also been used in vegetation mapping mainly because it can incorporate vegetation that is both highly reflective in the near infrared and highly absorptive in the visible red spectral wavelengths. Such a wide range of wavelengths can be used as an indicator for vegetation status and also provide information on the seasonal variability of canopy cover through multiple-time images (Xie et al. 2008).

2.5 Conclusion

To quantify apple tree water use, many factors must be taken into consideration such as those stated above. Knowledge in water and energy balances paves the way to a better understanding of water use in irrigated orchards. Optimizing water application by irrigation scheduling will potentially help in the conservation of water (Al-Yahyai 2012). It is therefore important to use models (e.g. the model proposed by Allen and Pereira 2009) to estimate tree water use. Many researchers have modeled tree water use successfully but many water use models require accurate information about the properties of plants to accurately estimate evapotranspiration (Jarvis 1976).

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CHAPTER THREE

MATERIALS AND METHODS

3.1 STUDY SITE

The study orchards were on the farm Kromfontein (32°57'07"S 19°14'27"E; 869 m.a.s.l.), which belongs to the Du Toit Agri Group (Figure 3.1). The farm is located in the Koue Bokkeveld approximately 50 km to the north of Ceres in the Western Cape Province. Full-bearing 'Cripps Pink' and 'Golden Delicious' orchards (Figure 3.2) were chosen for measurements, both planted on M793 rootstocks, in a north-south direction. The orchards are planted on cumulic soil of eluvic form (orthic A horizon over an E horizon) (Louis Reynolds, pers. comm.), with a rooting depth of 1 m (Stefan Bauer pers. comm.). The pollinator for both cultivars was 'Granny Smith', planted every 8th tree and arranged in a diamond shape. The pollinator therefore constitutes 10% (~167 trees ha⁻¹) of the trees in the block. The orchards were irrigated with medium range micro-sprinklers (medium), with one micro-sprinkler per tree and a delivery rate of approximately 32 litres per hour. The orchards were irrigated 2 - 3 times per week. To validate that the trees were well-irrigated and unstressed, predawn and midday stem water potential measurements were performed on the trees at regular intervals.



Figure 3.1 Aerial view of the orchards on Kromfontein Farm and the study sites within the orchards



Figure 3.2 A) 'Cripps Pink' full bearing orchard and B) 'Golden Delicious' full bearing orchard at Kromfontein

The full bearing 'Cripps' Pink' trees were planted in 2006 (eight years old at the start of the study) at a spacing of 1.5m x 4m ($6 \text{ m}^2 \text{ tree}^{-1}$, $1667 \text{ trees ha}^{-1}$). The block planted to this cultivar was approximately 6.04 ha. At the start of the study trees were 3.8 m tall and maximum measured LAI for the study was $2.83 \text{ m}^2 \text{ m}^{-2}$. The orchard floor beneath the trees was mulched with wood chips, which was added once every three years, while rye grass grew between the rows. Yield in the three seasons preceding the study were 55 t/ha in 2010/11, 65 t/ha in 2011/12 and an exceptionally high yield of 108 t/ha in 2012/13.

The full bearing 'Golden Delicious' trees were planted in 1992 (22 years old at the start of the study) at a spacing of 1.5 m x 4. m ($6 \text{ m}^2 \text{ tree}^{-1}$, $1667 \text{ trees ha}^{-1}$). The block planted to this cultivar was approximately 11 ha. At the start of the study trees were 4.5 m tall and maximum measured LAI for the study was $3.34 \text{ m}^2 \text{ m}^{-2}$. Figure 3.1 shows the block in which the sap flow systems (HPV3 and HPV4) were located. The trees where HPV3 were located was not mulched and had a grass cover between rows. However, the block in which HPV4 was located was mulched with wheat straw and had a grass covering between rows. Yield in the four years leading up to the study were consistently high, being 105 t ha^{-1} in 2010/11, 101 t ha^{-1} in 2011/12, 95 t ha^{-1} in 2012/13 and 100 t ha^{-1} in 2013/14.

Weather data was collected with the use of an automatic weather station that was situated in an open area approximately 500 m away from the measured orchards (Figure 3.3). The AWS had a pyranometer (Model SP 212 Apogee instruments, Inc., Logan UT, USA) which measured solar irradiance and it was installed horizontally on a north facing cross bar to avoid self-shading and cosine errors. Air temperature and relative humidity were measured with a temperature and humidity probe (Model CS500, Vaisala, Finland) installed at height of 1.6 m above the ground. A wind sentry (Model: 03001, R.M. Young, Campbell Scientific, Inc., Logan UT, USA) was used to measure wind speed and direction at 2 m height, while rainfall was measured with the use of a tipping bucket rain gauge (Model: TE525-L; Campbell Scientific, Inc., Logan UT, USA). All the sensors were connected to a data logger (Model CR1000 Campbell Scientific, Inc., Logan UT, USA) programmed with a scan interval of 10 s and the output signals processed at hourly and daily intervals, respectively. The Penman-Monteith reference evapotranspiration was determined according to Allen et al (1998).



Figure 3.3 Automatic weather station located near the apple orchards at Kromfontein

3.1.1 Canopy measurements

Canopy size (height, breadth and width) was determined using a tape measure and height rod. These measurements were performed on the trees instrumented for transpiration measurements in both the 'Cripps Pink' and 'Golden Delicious' orchards i.e. six trees per orchard. Fig 3.2 above illustrates the size of the tree canopy cover at Kromfontein apple orchards. The LAI of the full bearing 'Cripps Pink' and 'Golden Delicious' orchards were determined using a LAI-2200 plant canopy analyser (Li-Cor Inc., Lincoln, Nebraska, USA). Tree LAI was determined by doing measurements above the canopy and below the canopy of three (randomly) selected trees in a single row of each orchard. Orchard LAI was determined by taking measurements across the work row. Measurements were performed early in the morning or late in the evening under diffuse light conditions or at any time of day on cloudy days throughout the growing season.

Fractional interception of photosynthetically active radiation (PAR) by the tree canopy was determined using an AccuPARLP 80 ceptometer (Decagon Devices, Pullman, WA, USA) in a grid pattern within the area allocated to a representative single tree which was

6 m². The grid consisted of three straight lines perpendicular to the tree row, and each grid point was 1 m apart. Each line was composed of four grid points, giving a total of 12 grid points within the area allocated to the representative tree (Figure 3.4). Measurements were conducted in a continuous pattern i.e. from point 1 to 12, and from sunrise to sunset. Spot measurements were performed in each season i.e. spring, summer and autumn.

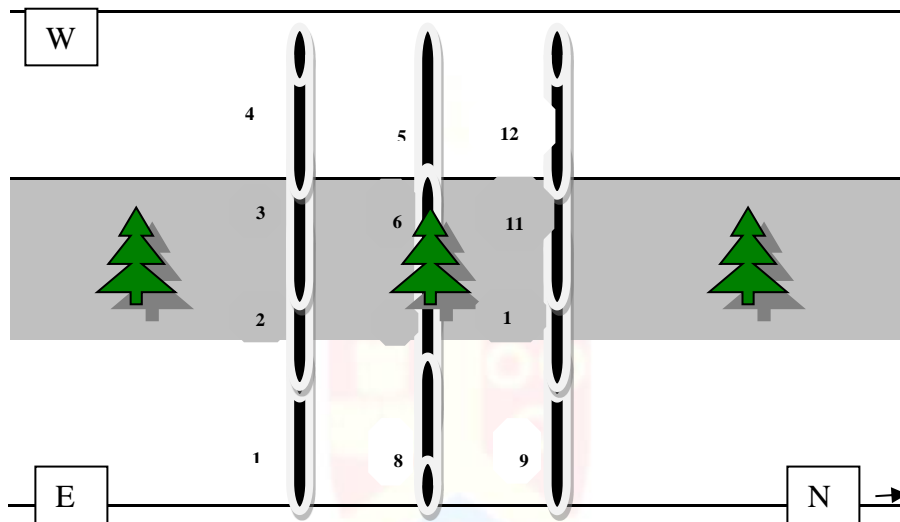


Figure 3.4 Grid for ceptometer measurements at Kromfontein

3.1.2 Transpiration measurements

The heat ratio method of the heat pulse velocity (HPV) sap flow technique (Burgess et al., 2001) was used to monitor hourly transpiration rates of six trees per cultivar, i.e. 12 in total from September 2014 to May 2015. Six trees were selected in the ‘Cripps Pink’ orchard and were denoted as ‘HPV 1’ (three trees) and ‘HPV 2’ (three trees). In the ‘Golden Delicious’ orchard, the trees were denoted as ‘HPV 3’ (three trees) and ‘HPV 4’ (three trees). Four heat pulse probe sets were inserted to four different depths (10-50 mm under the bark) in each tree trunk to account for the radial variation in sap flux within the conducting sapwood (Figure 3.5). These probe sets were inserted above the rootstock in the scion and below the first branch, with the probes being equally spaced around the trunk and randomly arranged, taking care to avoid any abnormalities in the trunk. Each probe set consisted of two Type T (copper/constantan) thermocouples (embedded in 2 mm outside diameter PFTE tubing), placed equidistantly (5 mm) upstream and downstream of the heater probe (1.8 mm). Heat pulse velocities were logged on an hourly

basis using a CR1000 data logger and an AM16/32B multiplexer (Campbell Scientific Inc., Logan, Utah, USA). The thermocouples, heater probes and relay control modules were locally manufactured (Andrew Everson, Pietermaritzburg). Integration of individual sap flow velocity measurements to obtain whole stem sap flux was performed according to the method of the weighted sum of sap flux densities with the associated sapwood area for each insertion depth (Hatton et al., 1990)

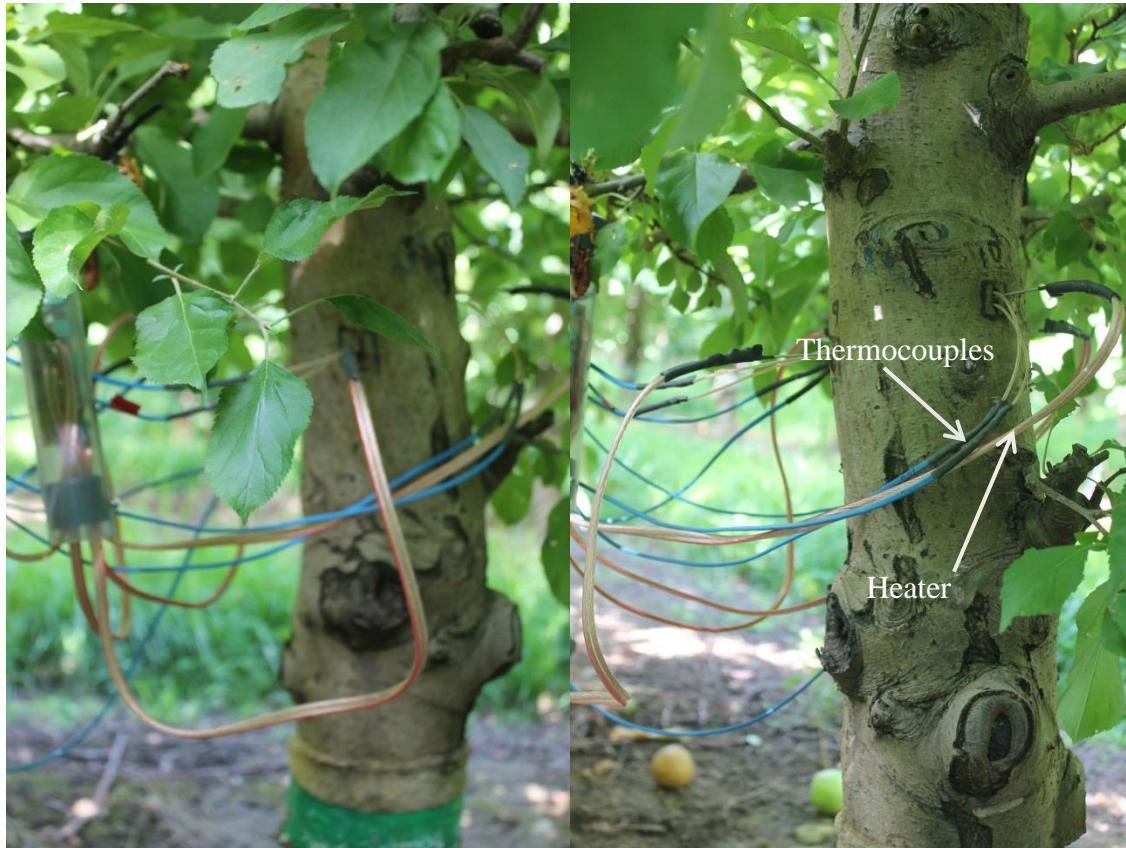


Figure 3.5 Arrangement and components of sap flow system

The theory behind the calculations of sap flux density are provided in Chapter 2 in section 2.2.1. Additional parameters required to convert heat pulse velocities to transpiration volumes included wound width, sapwood density (ρ_b), water content of the sapwood (m_c), and area of conducting sapwood. The wound widths were measured at five positions across the length of the wound created by sensor implantation using Vernier callipers. Mean values of the wound widths were 2.95 mm with a standard error in the mean (SEM)

of ± 0.11 mm for the full-bearing 'Golden Delicious' trees. For the 'Cripps' Pink' trees, the mean wound size was 3.12 mm with an SEM of ± 0.13 mm. The density of the sapwood was calculated as per Burgess et al. (2001):

$$\rho_b = \frac{w_d}{v_f} \quad (19)$$

where w_d is the oven dried wood mass (kg) and v_f is the volume (m^3) of the freshly excised sample of wood. The volume of the sample of wood was determined by immersing the sample in water and applying the Archimedes principle. Sapwood water content was calculated as per Burgess et al. (2001):

$$m_c = \frac{w_f - w_d}{w_d} \quad (20)$$

where w_f is the fresh mass of a freshly excised wood sample from three trees alongside the sample trees.

The area of conducting sapwood was determined by injecting methylene blue dye into the scion above the rootstock. Wood cores were then extracted a short distance above the dye injection location with the use of an incremental stem borer, approximately 40 min after the dye injection began. The conducting sapwood was visible on the cores by the methylene stain, and as a result the heartwood was also observed (Figure 3.6 A and B).



Figure 3.6 A) Wood core indicating the conducting sapwood area and heartwood and B) methylene blue dye injected in the stem

3.1.3 Pre-dawn leaf water potential and midday stem water potential measurements

Pre-dawn water potential measurements were taken on 18 February 2015 (before harvest) and 23 February 2015 (after harvest). Although these measurements were not indicative of the whole season, information from other researchers in the project suggested that the 'Cripps Pink' orchard had limited stress throughout the season. There were short periods of stress in the 'Golden Delicious' orchards.

Pre-dawn leaf water potential is considered the best representation of plant water status, as it is assumed that the plant will have reached its maximum allowable water content at this time (Ameglio, 1999). As transpiration is assumed to be zero at this time of day, there

are no water potential gradients within the plant and thus the predawn water potential is assumed to be equal to soil water potential. Therefore, this measurement is an assessment of whether the trees were stressed or unstressed specifically for this period. Midday stem water potential measurements are also important as it gives an indication of whole plant transpiration, as well as the capacity of water to move from the soil to the atmosphere. Therefore, both pre-dawn and midday stem water potential can be applied as water deficit indicators (Choné et al. 2001). The pressure chamber (Model 1000; PMS Instrument Company, Albany, OR, USA) was used for measurements; they were performed on the 'Golden Delicious' (HPV 4) orchard and done on four trees including three sap flow trees; from 4:30 am to 06:00 am. The same procedure was performed on the 'Cripps Pink' orchard, however measurements were performed for midday stem water potential from 12:00 pm – 14:00 pm.

3.1.4 Determination of yield

Yield was determined by stripping fruit and weighing the fruit from individual trees in both orchards. On 19 February 2015, 'Golden Delicious' (HPV 3) trees were strip harvested, with nine trees harvested, including the sap flow trees. 'Golden Delicious' (HPV4) trees were also strip harvested, but only two sap flow trees were harvested. In the 'Cripps Pink' (HPV 2) orchard, four trees were strip harvested on 24 March 2015 and these included three sap flow trees. In the 'Cripps Pink' (HPV 1) orchard, eight trees were strip harvested including two sap flow trees on 24 March 2015. Harvest was done early due to fruit maturity of the trees and also to avoid commercial harvesting in the orchards.

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CHAPTER FOUR

The response of transpiration of full-bearing apple trees to environmental variables and canopy characteristics

4.1 Introduction

In water, limited environments it is becoming increasingly important to accurately estimate evapotranspiration (ET) and its components to better manage water resources (Kool et al. 2014). In agriculture, these estimates are important for water management practices, irrigation system design and for government agencies to issue fair water use licenses. The partitioning of ET into T and E, and the separate measure of these components, is also important as these components are seen to have different functions within ecosystems. T is beneficial and is associated with plant productivity, whilst evaporation is non-beneficial and the minimization of this component can equate to significant water savings in different agro-ecosystems (Kool et al. 2014). As transpiration is associated with productivity it is important to understand factors determining transpiration rates and volumes to determine the minimum amount of water that needs to be supplied in order to maintain stomatal opening and therefore also carbon assimilation in orchards. Through a thorough understanding of the controlling factors, an appropriate modelling approach can be chosen that will allow the extrapolation of measured data to a wider range of conditions. This information is becoming increasingly important to the apple industry in the Western Cape Province of South Africa, as this area is subjected to frequent droughts and increasing competition with urban areas, which are predicted to intensify in future (Midgely and Lötze, 2011) justifying water use is key to the future sustainability of the industry. This study therefore aimed to assess seasonal transpiration rates for two full bearing orchards in the Koue Bokkeveld region and how transpiration rates varied according to environmental variables and canopy characteristics. Following this analysis, an appropriate modelling approach could be selected.

The hypotheses tested in this part of the study were as follows:

1. There is a linear relationship between atmospheric evaporative demand (ET_o) and transpiration rates throughout the season in mature apple orchards.
2. Hourly transpiration rates are directly related to an increase in solar radiation in the morning, but are reduced by increases in vapour pressure deficit (VPD) on days with high atmospheric demands.
3. There is a linear relationship between fortnightly transpiration crop coefficients and canopy cover as determined by in field measurements and remote sensing.

4.2 Materials and Methods

The full materials and methods for the study are provided in Chapter 3. The study orchards were on the farm Kromfontein ($32^{\circ}57'07''S19^{\circ}14'27''E$; 869 m.a.s.l.), which belongs to the Du Toit Agri Group. The farm is in the Koue Bokkeveld (a winter rainfall region with warm summers) approximately 50 km from the town of Ceres in the Western Cape Province. Full-bearing 'Cripps Pink' and 'Golden Delicious' orchards were chosen for measurements, both planted on M793 rootstocks, in a north-south direction. The leaf area index (LAI) of the full bearing 'Cripps Pink' and 'Golden Delicious' orchards were determined using aLAI-2200 plant canopy analyzer (Li-Cor Inc., Lincoln, Nebraska, USA). Estimation of NDVI was obtained from Fruitlook (www.fruitlook.co.za) which is an open web portal available for farmers in the Western Cape.

The FAO-56 model (Allen et al. 1998) provides a platform to determine ET from ET_o , calculated from meteorological data, and crop coefficients (K_c), as

$$ET = ET_o K_c \quad (21)$$

As K_c is influenced by the frequency of wetting by precipitation and irrigation and the type of irrigation employed, a dual crop coefficient was introduced where evaporation and transpiration can be estimated separately as

$$K_c = K_{cb} + K_e \quad (22)$$

Where K_{cb} is the basal crop coefficient representing primarily transpiration and some background evaporation from the soil when the surface is dry and K_e is the evaporation coefficient representing the contribution of soil evaporation to total ET. In this study a transpiration crop coefficient (K_t) was determined, as proposed by Villalobos et al. (2013), as only transpiration was measured. Transpiration crop coefficients were calculated as

$$K_t = \frac{T}{ET_o} \quad (23)$$

4.3 Results and Discussion

4.3.1 Weather Data

Climatic conditions play a central role in controlling transpiration, therefore it is important to evaluate and delineate the weather conditions that were experienced by the apple trees throughout this study. As this is a winter rainfall region, irregular and low rainfall was recorded during the time in which the trees were in leaf (total of 161 mm) and conditions were generally hot and dry in the summer months, with very few cloudy days. Weather data obtained from the weather station on the farm illustrated that the temperatures at the start of the trial in early spring were fairly low and gradually increased as summer approached and then decreased again in autumn towards the end of the trial (Figure 4.1). A maximum temperature of 38.7°C was recorded on 4 March 2015, whilst the minimum temperature of 1.2°C was recorded on 21 September 2015. January had the warmest average temperature and the highest ET_o , whilst September had the lowest average temperature and ET_o (Figure 4.2). Average daily temperature for the study period was 18.1°C.

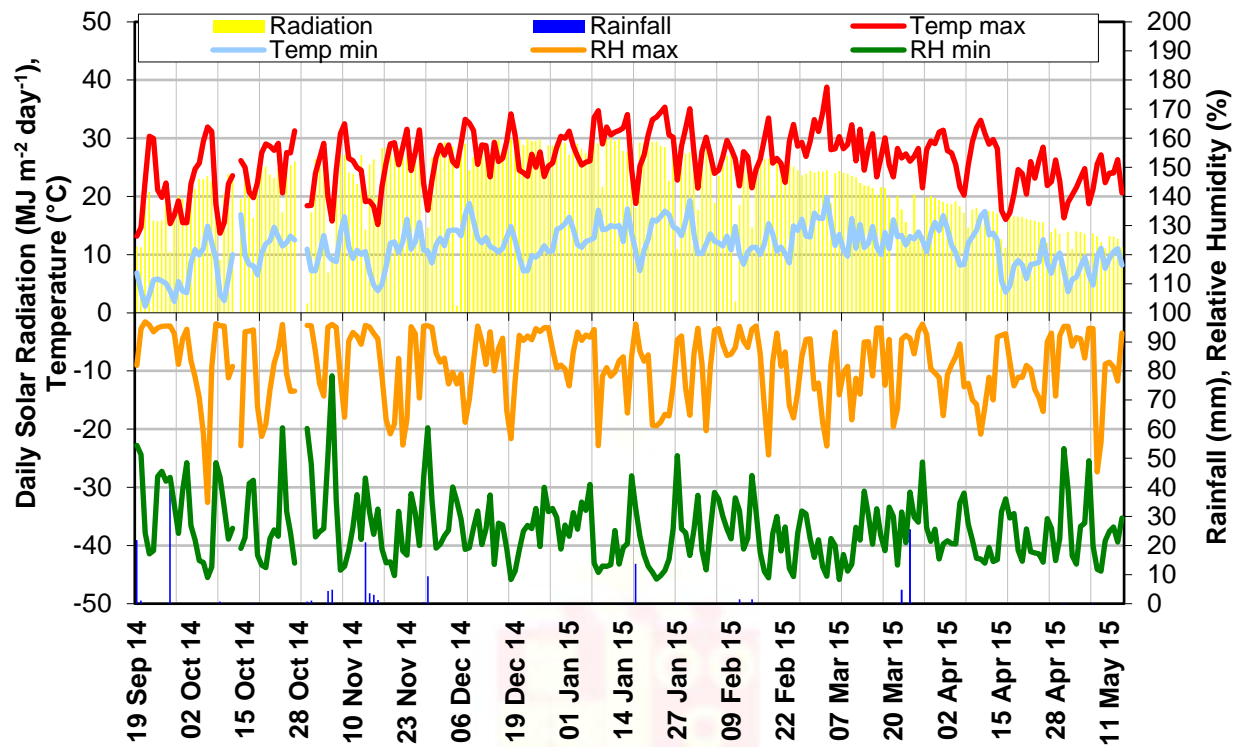


Figure 4.1 Daily climatic conditions at Kromfontein obtained from the weather station located close to the study site. Missing data on 28-29 October is a result of a logger failure.

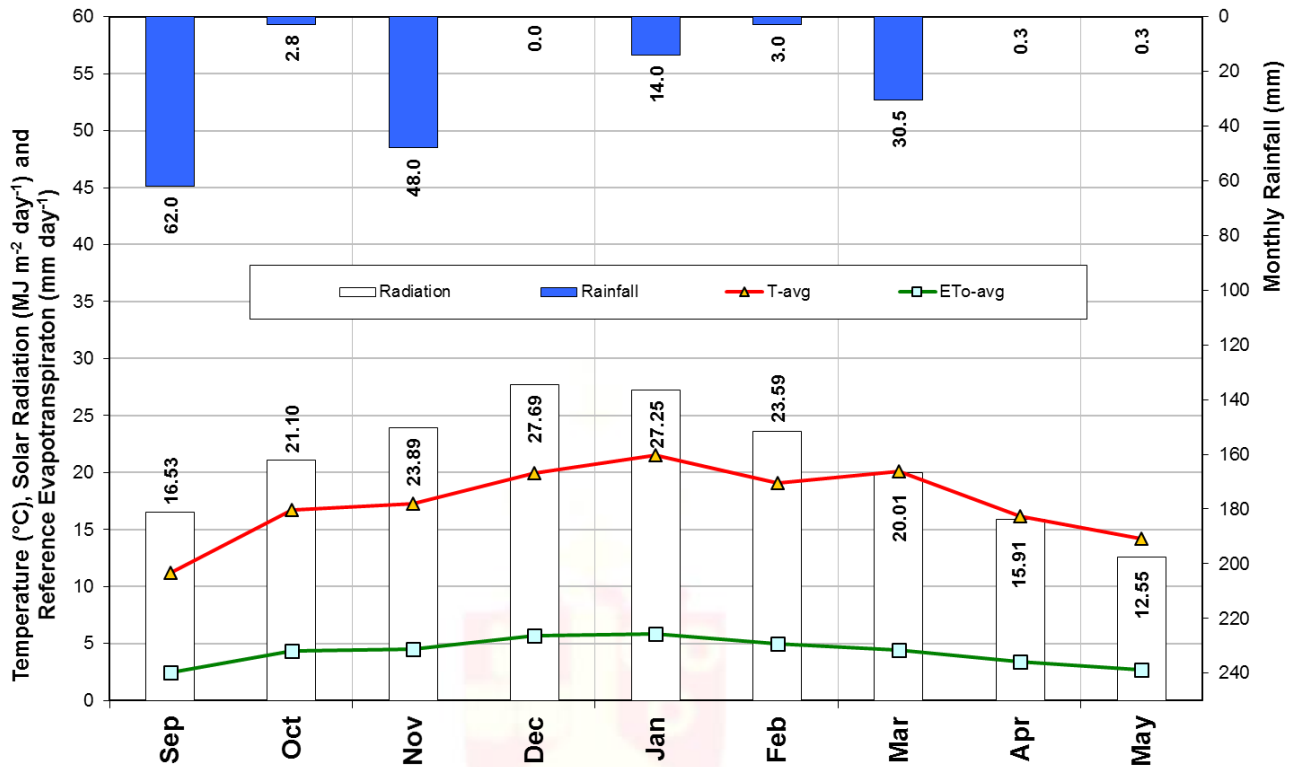


Figure 4.2 Monthly climatic conditions at Kromfontein obtained from the weather station located close to the study site.

These measured variables were used to calculate atmospheric demand (ET_o) using the FAO-56 Penman-Monteith equation (Allen et al. 1998, Pereira et al. 2015). ET_o varied between 0.66 and 8.55 $mm\ day^{-1}$, with an average of 4.52 $mm\ day^{-1}$ over the study period (Figure 4.3). During the hot summer months ET_o was on average 5.5 $mm\ day^{-1}$. Average daily maximum vapour pressure deficit (VPD) varied between 0.38 and 6.2 kPa, with an average daily maximum of 2.6 kPa over the study period.

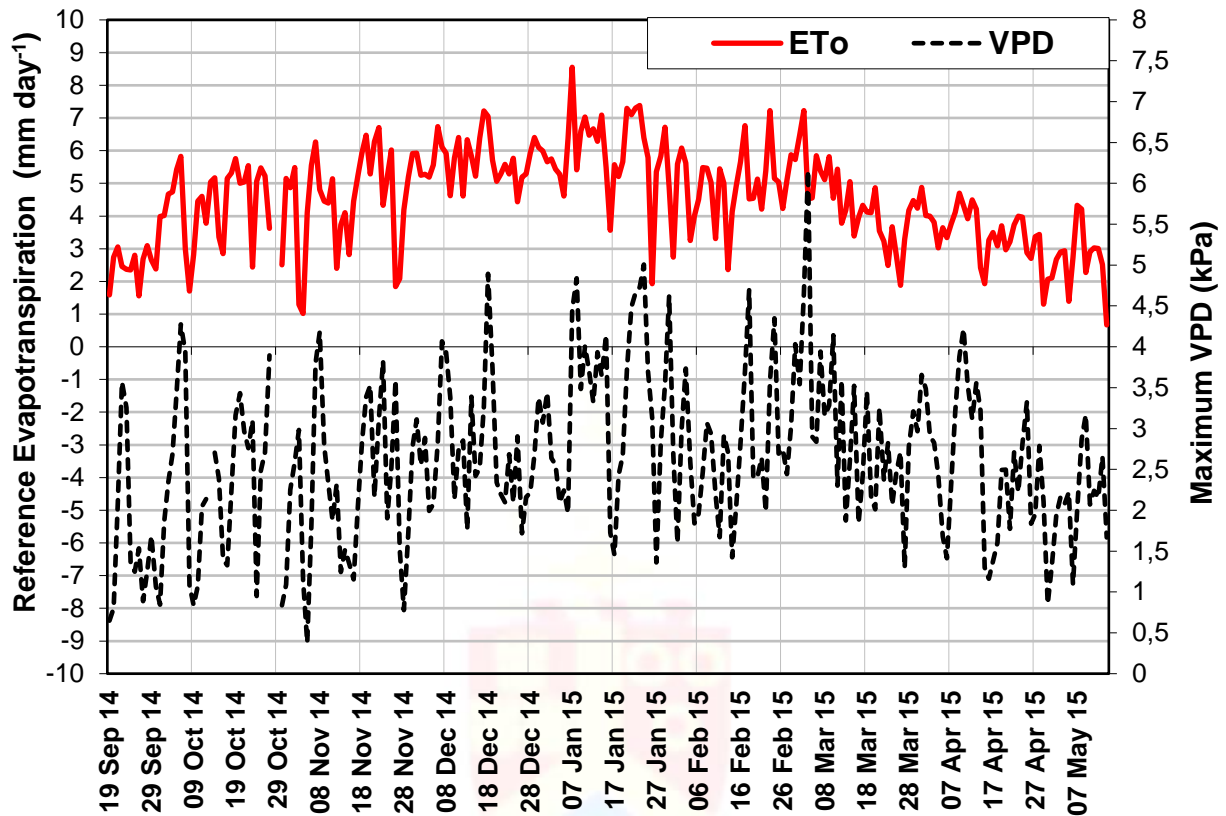


Figure 4.3 Reference evapotranspiration (ET_o) and daily maximum vapour pressure deficit (VPD) for the period 19 September 2014 to 14 May 2015

4.3.2 Transpiration of the mature, full-bearing apple orchards

Transpiration data from all six trees in the ‘Cripps Pink’ orchard was averaged to provide an estimate of transpiration from the orchard. Daily ET_o and transpiration showed considerable variation from day to day throughout the season, with transpiration responding particularly positive to ET_o on days with low atmospheric demand. A similar response on hot and dry days was, however, not observed as transpiration on these days did not increase at the same rate as atmospheric demand. Daily transpiration of the ‘Cripps Pink’ trees varied between 0.02 and 3.51 mm day⁻¹, with an average of 2.14 mm day⁻¹ throughout the season. Transpiration gradually increased in spring (2.73 mm.day⁻¹), reached maximum rates in summer (2.86 mm.day⁻¹) and then steadily decreased in autumn (1.82 mm.day⁻¹) (as shown in Table 4.1 below). This trend was largely associated with the change in weather conditions (Figure 4.4) throughout the growing season and the change in the LAI throughout the season, as a result of apples being a deciduous

crop. The individual trees instrumented with sap flow equipment were harvested on 26 March 2015 and a slight decrease in the transpiration rate was observed on this day, as indicated by the arrow in Figure 4.4. However, this decrease seems to be associated with a decline in ET_0 , as transpiration rates returned to similar pre-harvest rates within a day. The transpiration crop coefficients (K_t) did, however, decline for approximately a week after harvest, before returning to pre-harvest values (Figure 4.5). The total transpiration measured for the season in the 'Cripps' Pink' orchard was 594mm. However, the orchard was instrumented slightly after the trees came into leaf and thus the total transpiration for the season should be slightly higher.

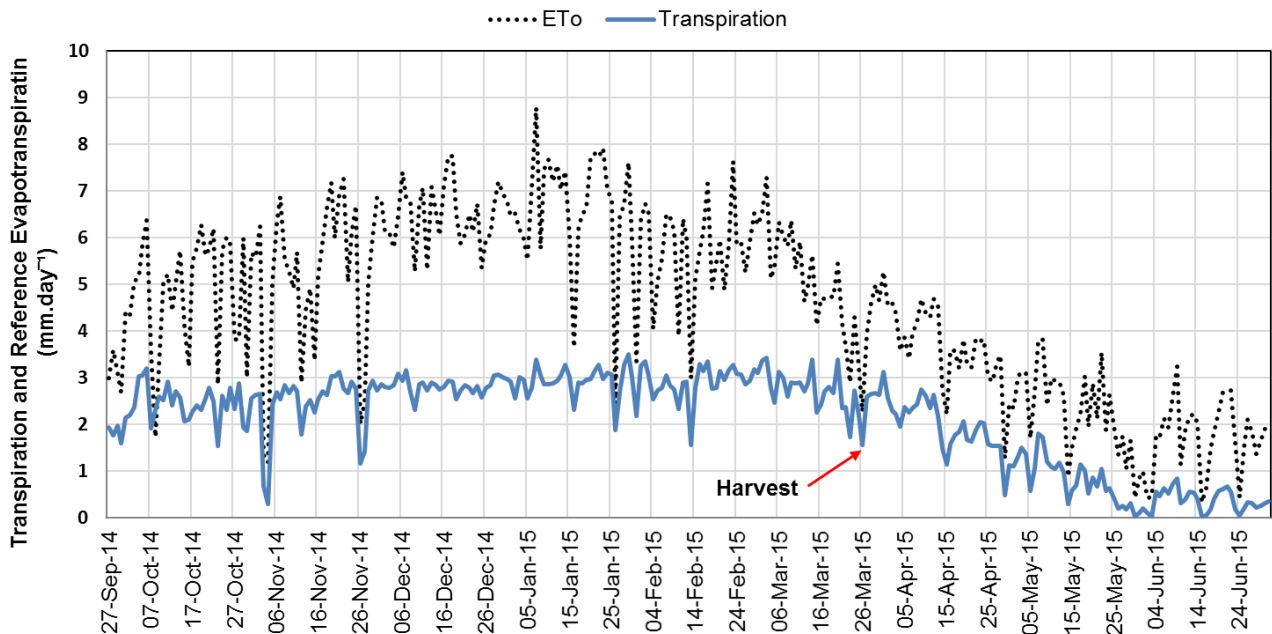


Fig 4.4 Daily transpiration and reference evapotranspiration (ET_0) in the 9-year-old 'Cripps Pink' orchard throughout the season, from 28 September 2014 to 1 July 2015. The arrow indicates when harvesting took place in the orchard

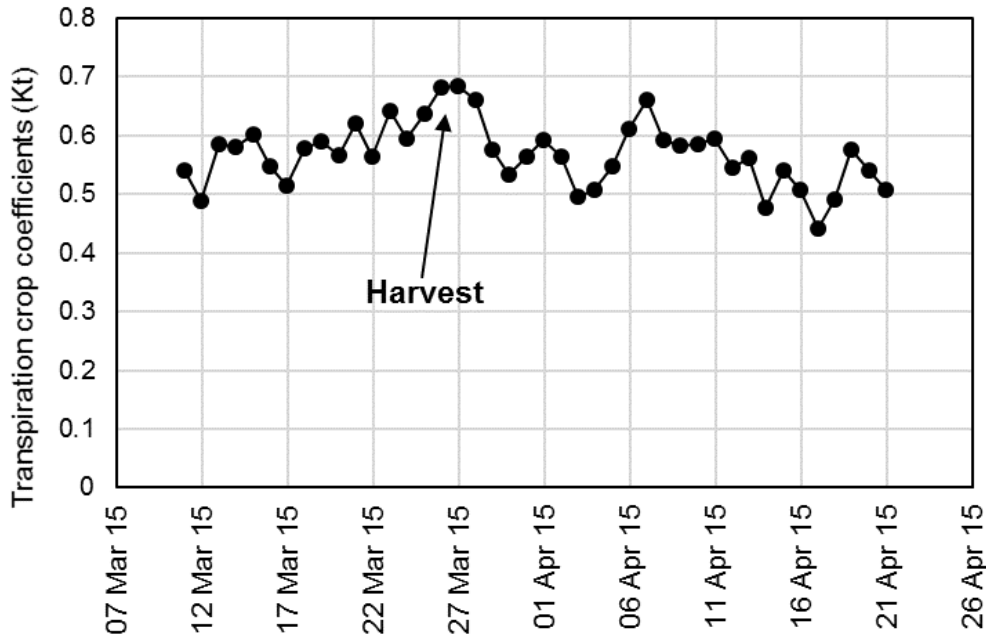


Figure 4.5 Transpiration crop coefficients (K_t) in the nine-year-old ‘Cripps Pink’ orchard prior to and after harvest

Table 4.1 Summary of tree transpiration of the ‘Cripps Pink’ orchard at Kromfontein for the 2014/2015 season

| Cultivar | Age | Spring (mm day ⁻¹) | Summer (mm day ⁻¹) | Autumn (mm day ⁻¹) | Total T (mm) | Yield (t ha ⁻¹) |
|-------------------|-----|-----------------------------------|-----------------------------------|-----------------------------------|-----------------|--------------------------------|
| ‘Cripps’ Pink’ | 9 | 2.73 | 2.86 | 1.82 | 594 | 109 |

As in the ‘Cripps’ Pink’ orchard, transpiration from the six measurement trees was averaged to obtain orchard transpiration in the ‘Golden Delicious’ orchard and the same trend in transpiration rates were observed in the ‘Golden Delicious’ orchards as in the ‘Cripps Pink’ orchard. However, the transpiration rates of the ‘Golden Delicious’ orchards were higher than that of the ‘Cripps Pink’ trees. The harvest (18 February 2015) and pruning (12 April 2015) dates are indicated in Figure 4.6 and it is evident that these actions

had very little impact on transpiration rates, as seen in the ‘Cripps’ Pink’ orchard. Daily transpiration of the ‘Golden Delicious’ trees varied between 0.52 and 5.02 mm day⁻¹, with an average of 3.19 mm day⁻¹ throughout the season. The ‘Golden Delicious’ orchard transpired an average of 3.51 mm.day⁻¹ in spring, 3.66 mm.day⁻¹ in summer and 2.16 mm.day⁻¹ in autumn (Table 4.2). The total seasonal transpiration was 787 mm. However, a drop in the K_t values after harvest suggests a decrease in water use at this time relative to atmospheric demand (Figure 4.7). Pruning did not appear to have any influence on K_t values.

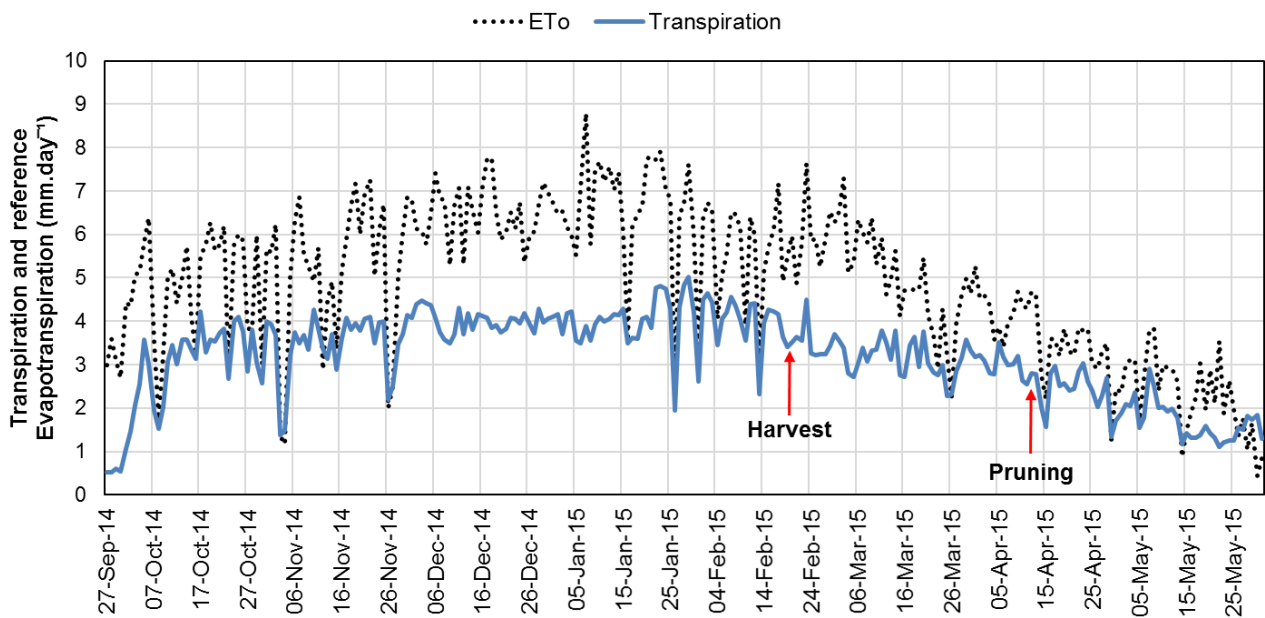


Figure 4.6 Daily transpiration and reference evapotranspiration (ET_o) of the 22-year-old ‘Golden Delicious’ orchard from 27 September 2014 to 30 May 2015. The arrows indicate when harvesting and pruning took place in the orchard

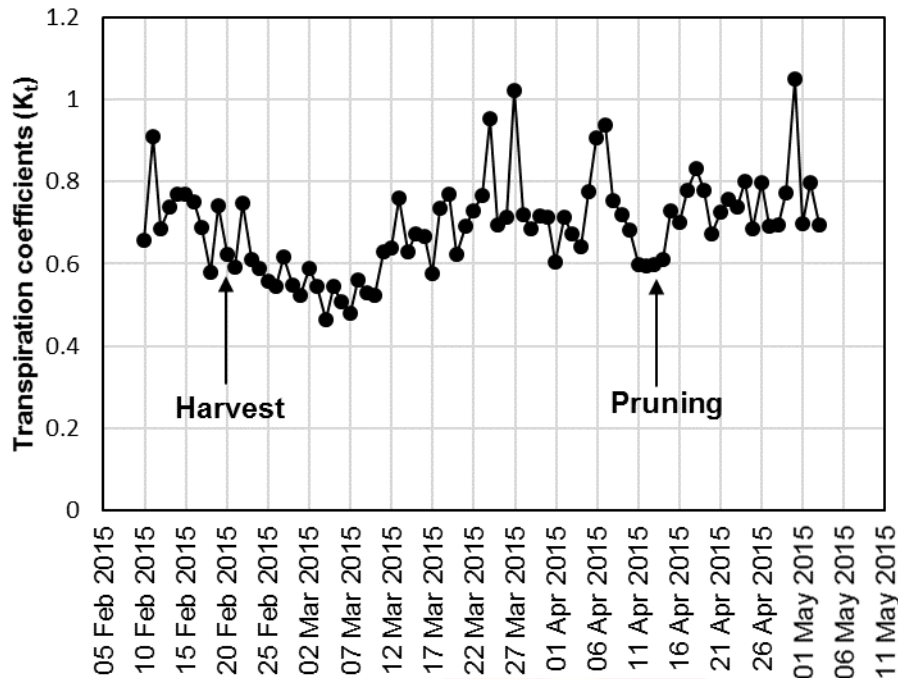


Figure 4.7 Transpiration crop coefficients (K_t) in the 22-year-old ‘Golden Delicious’ orchard prior to and after harvest and pruning

Table 4.2 Summary of tree transpiration of the ‘Golden Delicious’ orchard at Kromfontein for the 2014/2015 season

| Cultivar | Age | Spring | Summer | Autumn | Total | T | Yield |
|--------------------|-----|-------------------------|-------------------------|-------------------------|-------|----|-------|
| | | (mm day ⁻¹) | (mm day ⁻¹) | (mm day ⁻¹) | | | |
| ‘Golden Delicious’ | 22 | 3.51 | 3.66 | 2.16 | 787 | 85 | |

Total seasonal transpiration for the ‘Golden Delicious’ orchard was over 100 mm more than the Cripps’ Pink orchard, which was harvested later than the ‘Golden’ Delicious’ trees and experienced leaf fall later in the season (personal communication S Dzikiti). However, the canopy of the ‘Golden Delicious’ trees was larger than the ‘Cripps’ Pink’ trees, as demonstrated by the differences in LAI between the two orchards (Figure 4.8). The

'Cripps' Pink' trees were pruned and thinned in order to allow solar radiation and improve fruit colour.. This could explain why the LAI was much lower in this orchard and why under the same climatic conditions, the 'Cripps' Pink' trees used less water. This demonstrates the dominant effect of canopy size during the peak of the season when evaporative demand is highest.

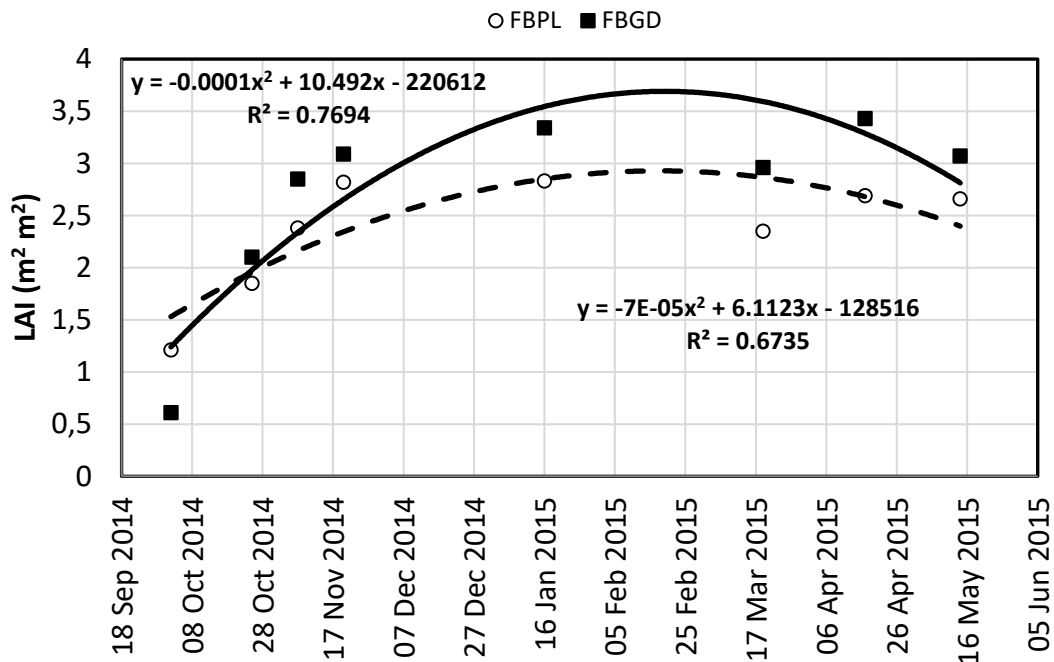


Figure 4.8 Seasonal leaf area index (LAI) of full-bearing 'Cripps Pink' (FBPL) and 'Golden Delicious' (FBGD) trees

The results from this study are very similar to those reported in literature, especially considering that specific orchard microclimate and management practices will play a key role in determining transpiration rates. In a similar study on 12-year-old 'Cripps' Pink' trees in the same area, Gush and Taylor (2014) found that the trees transpired on average 3.2 mm day⁻¹, with a peak rate of 8.4 mm day⁻¹. Average seasonal total transpiration for the two seasons of measurement was 797 mm. These values are higher than for the 'Cripps' Pink' orchard in this study, but the trees were older and had bigger canopies (LAI of 3.2, as opposed to 2.6 in this study). Li et al. (2002) quantified transpiration of 'Golden Delicious' trees on three different rootstocks (average LAI 3.03-3.76) in Israel using a sap flow technique. On average throughout the study period the trees transpired 3.9 mm day⁻¹.

¹, with peak rates between 3.9 and 5.5 mm day⁻¹ for the three orchards. The trees used an average of 3.1 mm.day⁻¹ to 4.4 mm.day⁻¹ for the growing season. This is very comparable to the results in the current study. Liu et al. (2012) recorded peak transpiration rates of 4.5 mm day⁻¹ in widely spaced 'Golden Delicious' trees in a temperate climate in China.

A decrease in water use relative to ET_o after harvest has been previously noted in apple trees on a lysimeter in Spain (Girona et al. 2011), where there was an immediate drop in the K_c after harvest. This is often attributed to a reduction in stomatal aperture and photosynthesis down-regulation following fruit removal, which results in decreased transpiration. This has been demonstrated in both peach (*Prunus armeniaca*) and apple (DeJong et al. 1987; Wunsche and Ferguson 2005; Reyes et al. 2006; Pretorius et al. 2008). Although a similar trend was observed in both orchards in this study, it was not as obvious as in the study by Girona et al. (2011). The impact of crop load on water use throughout the season was also not clear in this study, as crop load in the 'Cripps' Pink' orchard was 109 t ha⁻¹ (Table 1), as opposed to 85 t ha⁻¹ for the 'Golden Delicious' orchard (Table 4.2), yet total seasonal transpiration was higher in the 'Golden Delicious' orchard. Therefore, in this study canopy size was most likely the main tree factor determining transpiration rates.

4.3.3 Transpiration crop coefficients of the orchards

The K_t curves for both the 'Golden Delicious' and 'Cripps' Pink' orchards followed the typical four-stage curve proposed by Allen et al. (1998), however, not all four stages were clear in both orchards (Figures 4.9 and 4.10). The daily K_t values varied between 0.08 and 0.80 for the 'Cripps' Pink' orchard and between 0.15 and 1.05 for the 'Golden Delicious' orchard. The K_{t mid} (mid-season K_t) for the 'Cripps' Pink' orchard was 0.50, whilst it was 0.68 for the 'Golden Delicious' orchard. The higher K_t values observed in the 'Golden Delicious' orchard was confirmed when comparing monthly K_t values for the two orchards (Figure 4.11). Allen and Pereira (2009) suggest a K_{cb mid} of 1.1 for a high-density orchard, where f_{c eff} is 0.7, whilst Marsal et al. (2014) reported a K_{cb mid} of 0.95 for apples in Spain. Both are significantly higher than the average values for the mid-season for the study site. This could be because water use may have been reduced by the water deficit

in the 'Golden Delicious' orchard (see discussion below) and because shoot growth was reduced in the 'Cripps' Pink' trees with Regalis®. However, several other factors could have influenced water use, which impacts the transferability of K_c from one orchard to the next. This includes the pruning system, rootstock, tree spacing, variety and microclimate.

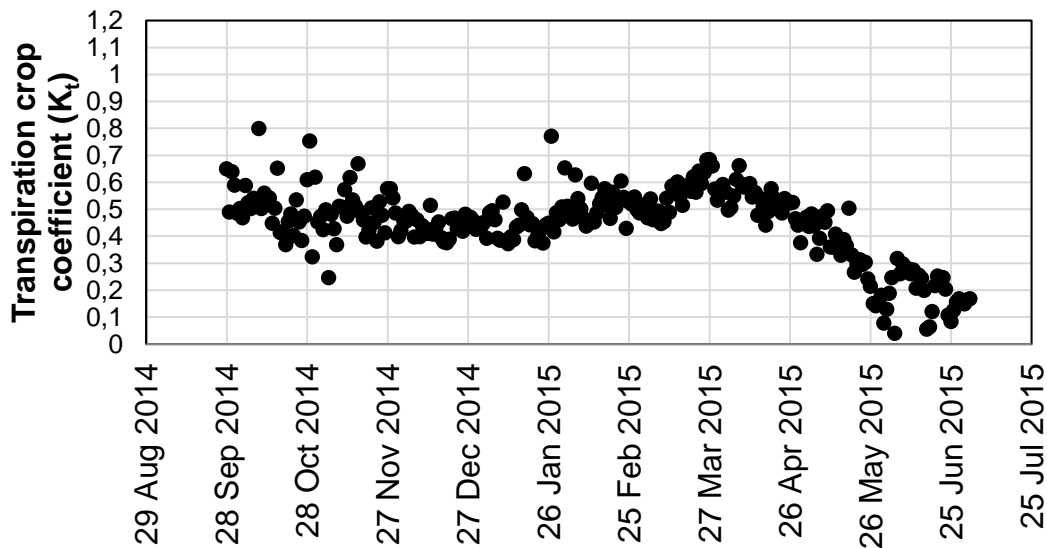


Figure 4.9 Daily transpiration crop coefficients (K_t) for the 'Cripps Pink' orchard

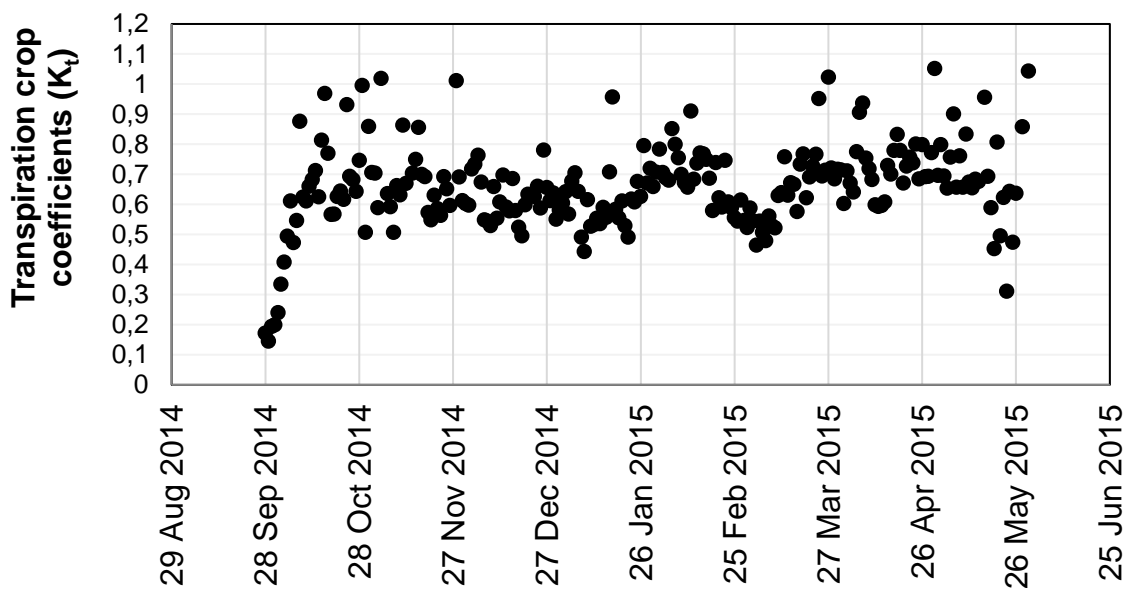


Figure 4.10 Daily transpiration crop coefficients (K_t) for the 'Golden Delicious' orchard

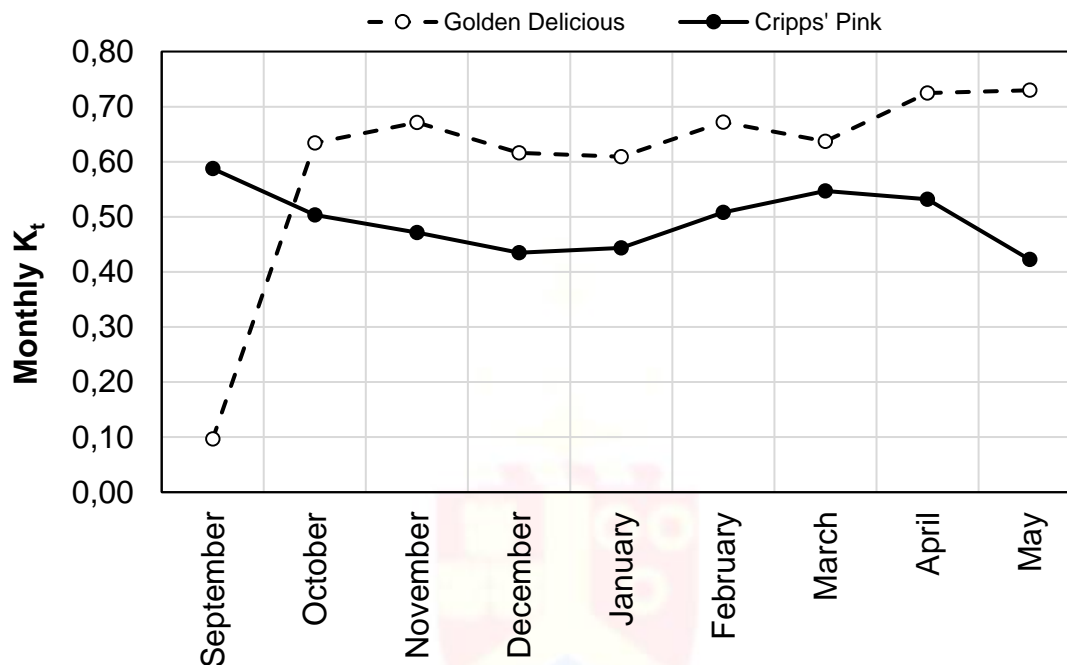


Figure 4.11 Monthly transpiration crop coefficients (K_t) for the mature, full bearing orchards at Kromfontein for the 2014/2015 season.

Pereira et al. (2015) stresses that standard K_c values reflect crops grown under optimal or unstressed conditions. It is more likely that K_c values determined in one orchard will be transferable to a similar orchard if measurements are made under optimal conditions. It is therefore important to indicate occurrence of stress in an orchard when reporting crop coefficient values, as it will influence the ability to extrapolate results to a similar orchard. Pre-dawn leaf water potential (Ψ_{PD}) and midday stem water potential¹ (Ψ_{MD}) measurements were performed on sap flow measurement trees to provide an indication of possible stress in the orchard. Midday stem water potential measurements indicated a degree of water stress in the 'Golden Delicious' orchard in January and February, as values dropped below -1 MPa (Figure 4.12). Naor and Cohen (2003) noted values above -1 MPa for control unstressed trees for Ψ_{MD} and values closer to -1.5 MPa for stressed trees in a water stress experiment on apples in Israel. Pre-dawn water potential

¹Measurements performed by Giverson Mupambi from Stellenbosch University.

measurements the day before harvest also indicated that the ‘Golden Delicious’ trees were stressed, as values were close to -1 MPa ($-0.95 \text{ MPa} \pm 0.11$), but following irrigation values increased to $-0.69 \text{ MPa} \pm 0.07$ the following day. Results from soil water measurements used to do a soil water balance also suggest that the ‘Golden Delicious’ orchard was under-irrigated at times during the season, whilst in the ‘Cripps’ Pink’ orchard soil water deficits seldom occurred (per Dr S Dzikiti). Some caution therefore needs to be exercised when attempting to extrapolate the results from the ‘Golden Delicious’ orchard to other orchards. The ‘Cripps Pink’ measurements could not be taken for February 2015 due to rainy weather conditions.

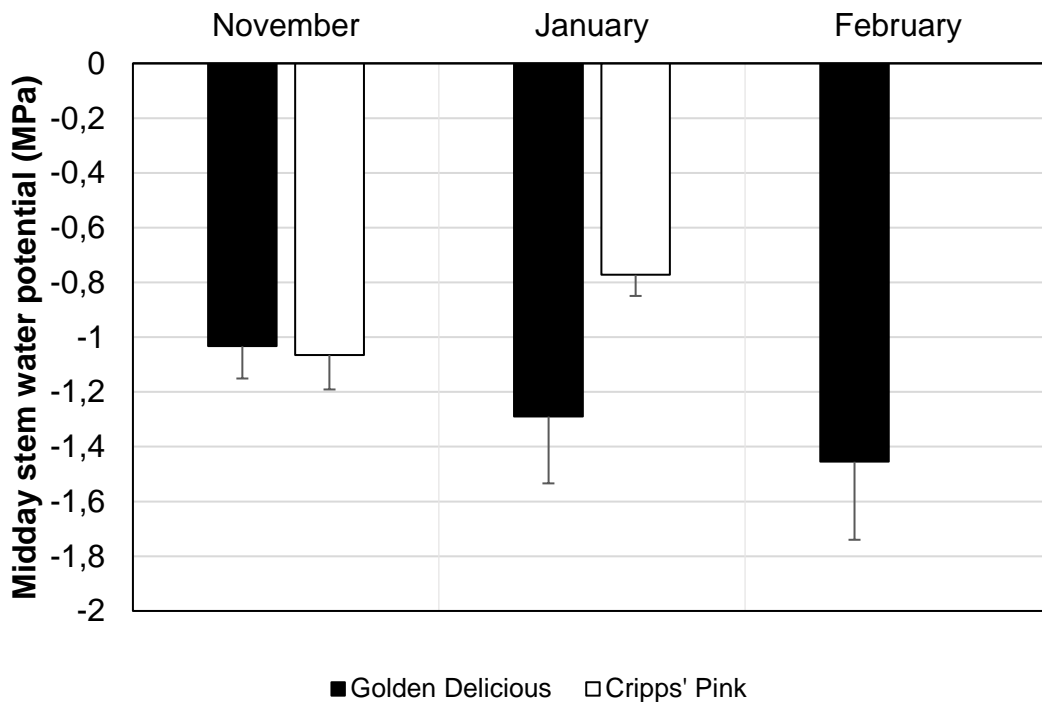


Figure 4.12 Midday stem water potential measurements in the ‘Golden Delicious’ and ‘Cripps Pink’ orchards from November 2014 to February 2015. Measurements performed by Giverson Mupambi from Stellenbosch University.

4.3 Factors controlling transpiration in the full-bearing apple orchards

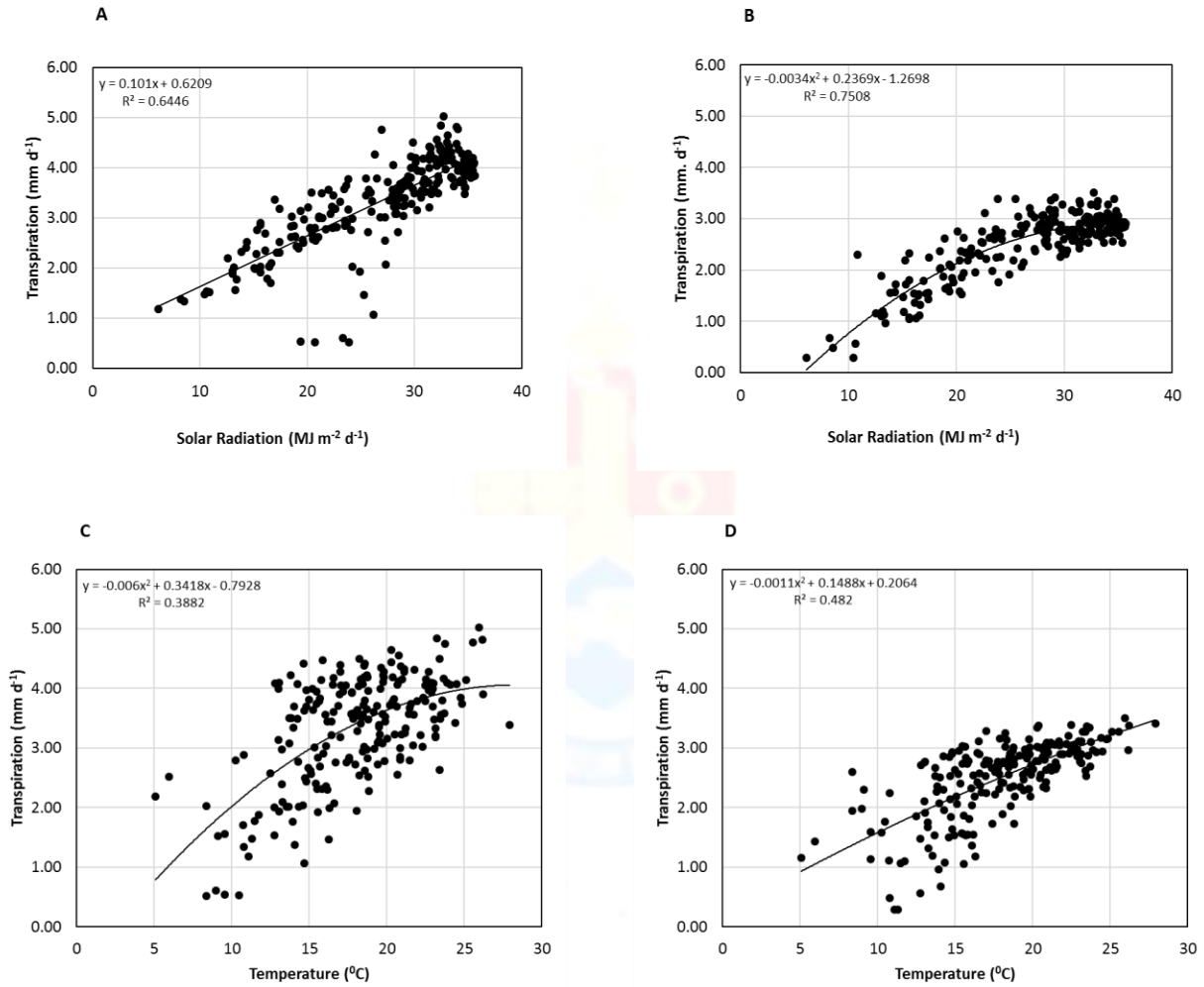
4.3.1 Meteorological variables

Fruit tree crops respond differently to fluctuating weather conditions and information regarding this is vital in understanding water use by the crop and therefore how much irrigation water should be supplied on a day to day basis. Variables such as solar radiation, temperature and vapour pressure deficit (VPD) are the main drivers of transpiration and these variables can be combined to determine atmospheric demand, calculated as reference ET_0 . Figure 4.13 below illustrates the different correlations between transpiration and weather variables obtained from the AWS located close to both orchards.

Fairly good relationships were found between transpiration and solar radiation and transpiration and reference evapotranspiration (Figure 4.13 A, B, G, H) in both orchards. However, poor relationships between temperature and VPD and transpiration were found in both orchards (Figure 4.13 C, D, E, F). Daily transpiration rates were linearly correlated with daily solar radiation in the full-bearing 'Golden Delicious' trees (Figure 4.13A), but in the 'Cripps Pink' orchard there was a parabolic relationship between transpiration and solar radiation (Figure 4.13B). This relationship accounted for 64% of the variation in transpiration in the 'Golden Delicious' orchard and 75% in the 'Cripps' Pink' orchard. Solar radiation provides the energy to evaporate water and the non-linear relationship in the 'Cripps' Pink' orchard suggests that even though energy is available there is some tree imposed control over transpiration. Similar evidence of tree imposed control over transpiration is found in the response of transpiration to VPD, which was non-linear in both orchards (Figure 4.13 E, F).

The relationship between transpiration and temperature was curvilinear for both orchards, with temperature only explaining 38% of the variation in the 'Cripps Pink' orchard and 48% in the 'Golden Delicious' orchard. In the 'Cripps Pink' orchard VPD explained 29% of the variation in transpiration, whilst in the 'Golden Delicious' orchard VPD accounted for 46% of the variation. A non-linear response of transpiration to atmospheric demand (reference evapotranspiration, ET_0) was also observed in both orchards (Figure 4.13 G

and H), indicating that past a certain threshold there was no longer a linear increase in transpiration with an increase in ET_0 . ET_0 accounted for 70% of the variation in transpiration in the 'Cripps' Pink' orchard and 81% in the 'Golden Delicious' orchard.



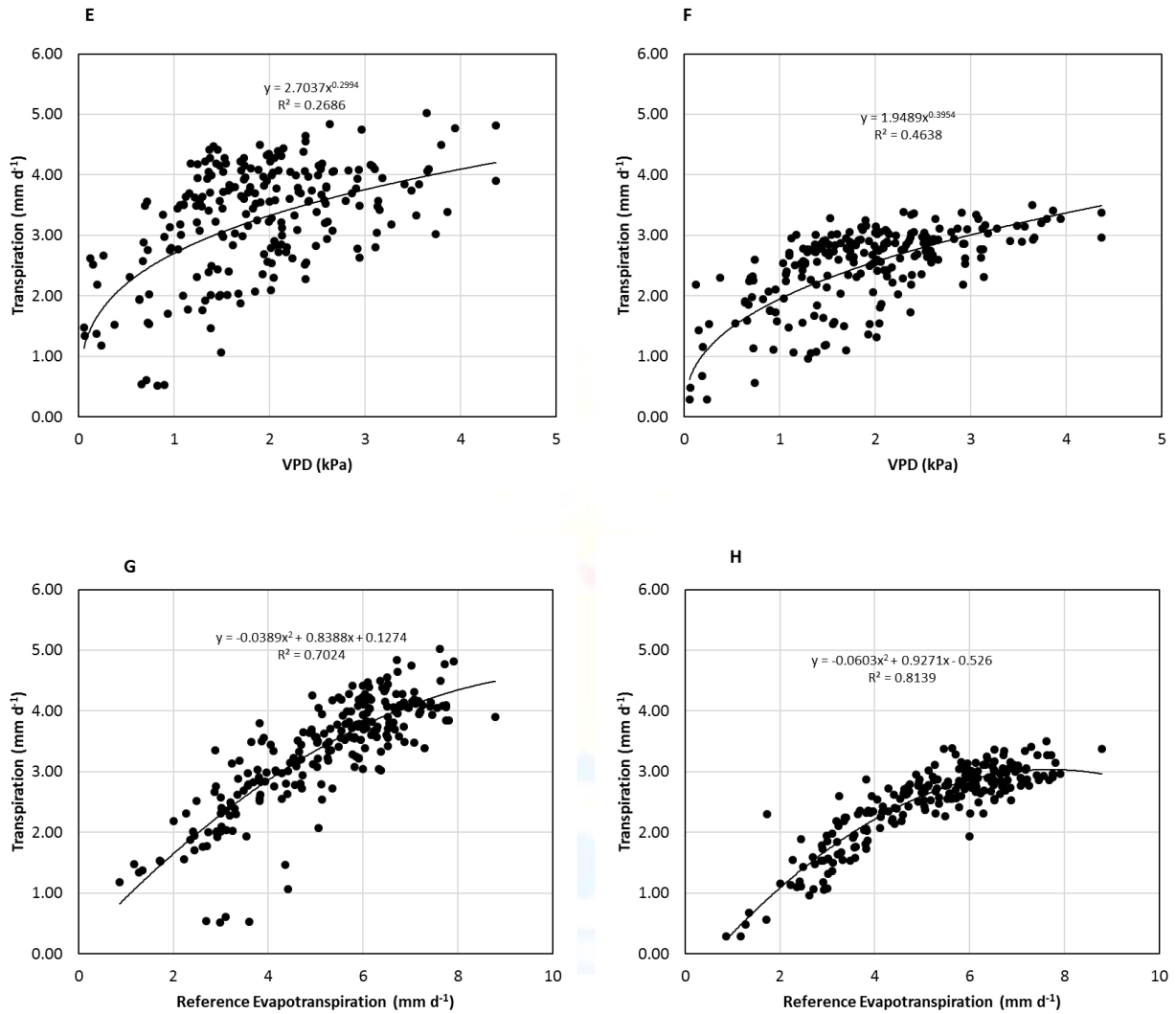


Figure 4.13 The response of transpiration to environmental variables in the full-bearing ‘Golden Delicious’ orchards (A, C, E and G) and full-bearing ‘Cripps Pink’ (B, D, F and H). Environmental variables included solar radiation (A and B), temperature (C and D), vapour pressure deficit of the air (E and F) and the reference evapotranspiration (G and H)

When examining the relationship between hourly solar radiation before and after noon with transpiration (Figure 4.14 A, B, C and D) it is evident that there was substantial variation in the data. However, there appeared to be more variation in the data after noon than before noon, with a linear relationship between solar radiation and transpiration accounting for 42% of the variance before noon (Figure 4. 14 A) and only 25% of the variation after noon (Figure 4.14 B) in the 'Cripps' Pink' orchard. A similar trend before and after noon was also evident in the 'Golden Delicious' orchard. Due to a bigger canopy, more solar radiation was intercepted by the 'Golden Delicious' trees consequently leading to higher transpiration rates and a linear relationship between the two variables that accounted for 53% of variation before noon (Figure 4. 14 C) and 21% after noon (Figure 4.14 D). As radiation increases in the morning, stomata open and transpiration increases as air temperature increases and the VPD gradient from the leaf to the air increases (Thorpe et al.1978). However, as VPD increases throughout the day stomata tend to close and transpiration stabilizes (Landsberg et al. 1975). Thus, in the afternoon as VPD increases above a certain point (approximately 2 kPa in the current study, Figure 4.15 A, B, C and D) stomata start to close to regulate water loss from the leaf, rather than responding to photosynthesis (Lakso et al. 2014).

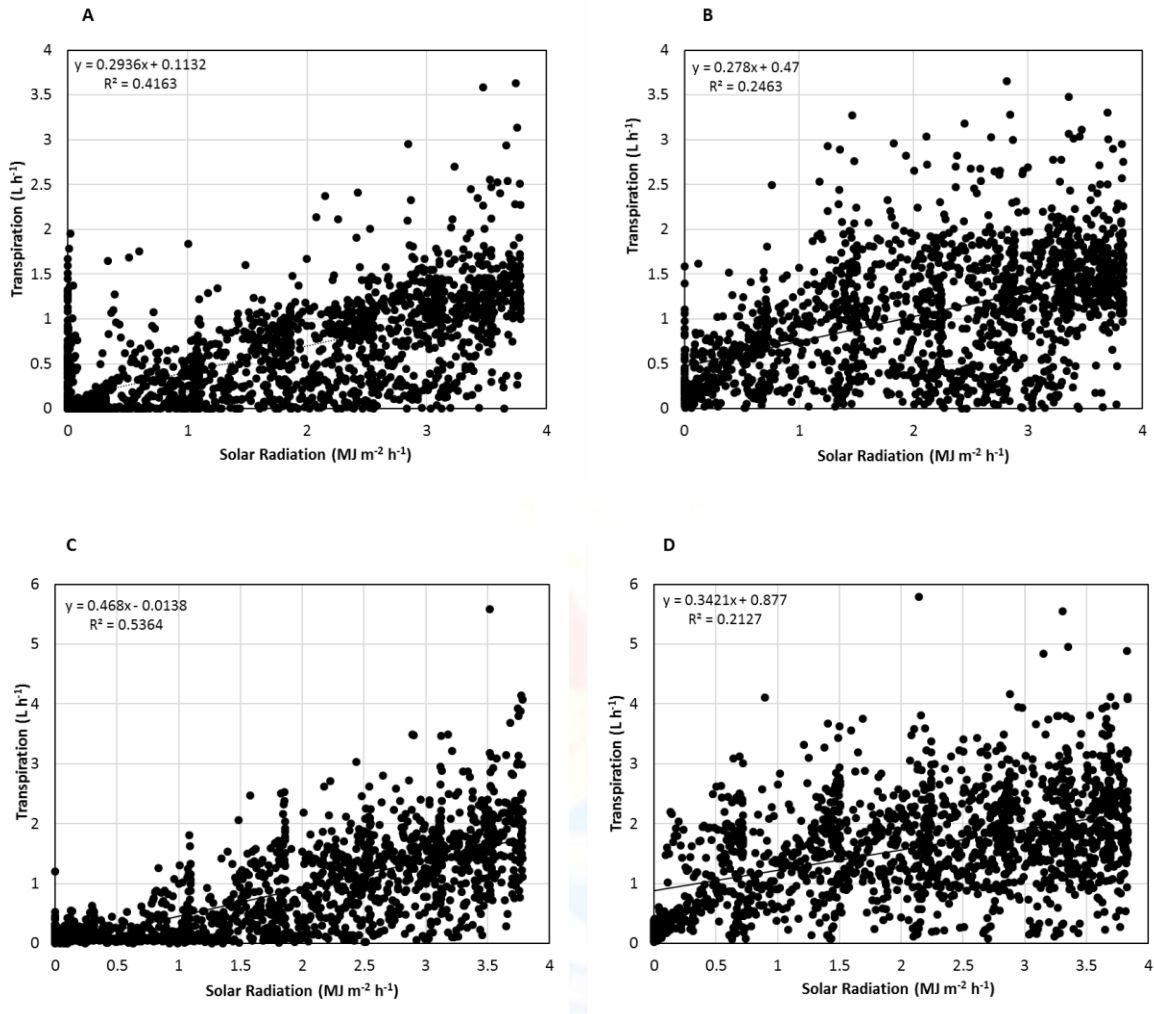


Figure 4.14 Relationship between transpiration and solar radiation before noon (A), and after noon (B) in the ‘Cripps Pink’ orchard, and (C and D) in the ‘Golden Delicious’ orchard

When looking at the relationship between hourly transpiration and VPD before and after noon, more variation in the data was observed after noon (Figure 4.15 B and D) than before noon (Figure 4.15 A and C). As expected VPD was higher in the afternoon than in the morning and as with the daily data, very little of the variation in transpiration was accounted for by changes in VPD (Figure 4.13 E and F, above). When considering maximum transpiration rates at increasing VPDs, it is evident that no further increases in transpiration occurred above VPDs of 2 kPa.

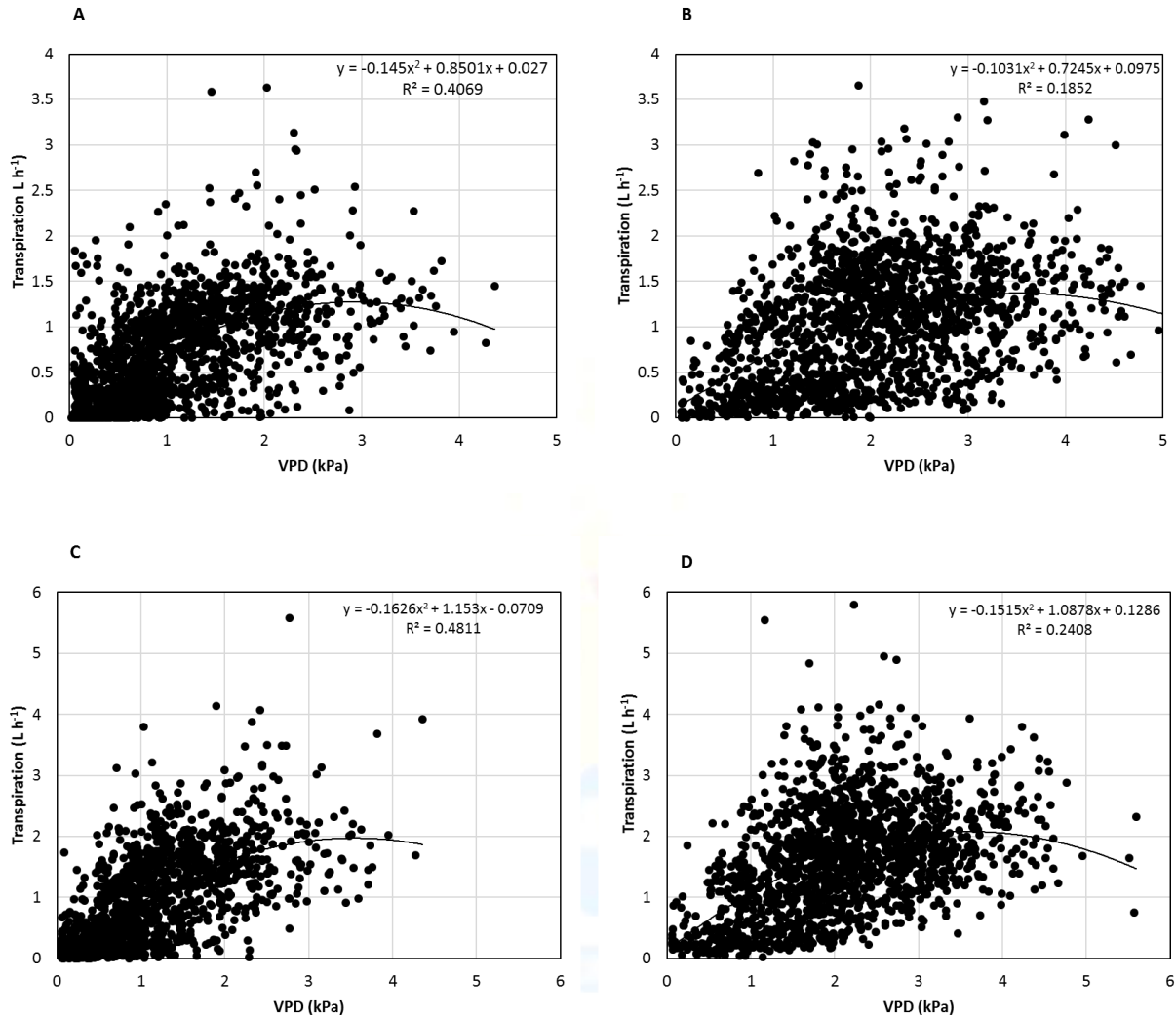


Figure 4.15 Relationship between hourly transpiration and vapour pressure deficit (VPD) before noon (A) and after noon (B) in the ‘Cripps Pink’ orchard and (C and D) for the ‘Golden Delicious’ orchard

4.4.2 Canopy size

Canopy size or canopy cover is extremely variable between orchards and is a major determinant of water use, as observed in the difference in seasonal water use between the ‘Golden Delicious’ and ‘Cripps’ Pink’ orchards in this study, especially considering that the ‘Golden Delicious’ trees were stressed at times. Through the determination of crop coefficients comparisons of water use between orchards are possible after normalizing for climate by dividing transpiration by reference evapotranspiration. Several authors

have suggested a relationship between canopy cover and crop coefficients, with good relationships found between midday canopy light interception and crop coefficients in peach (Johnson et al. 2000, 2002; Ayars et al. 2003) and grapevine (Williams et al 2003; Williams and Ayars 2005). Girona et al. (2011) found a positive exponential regression between intercepted PAR at solar noon and K_c values in lysimeter grown apple trees, which accounted for 90% of the variation in K_c .

When comparing measured K_t values with measured LAI values in the current study a good linear relationship was found between LAI and K_t values in the ‘Golden Delicious’ (Figure 4.16 A), with an R^2 of 0.75. However, a poor negative relationship was found between LAI and K_t values in the ‘Cripps’ Pink’ orchard (Figure 4.16 B). The poor correlation in the ‘Cripps’ Pink’ could possibly be attributed to the spraying of Regalis® (active ingredient Prohexadione-Ca) in the orchard, which altered canopy structure by creating a more compact tree. It is possible that there was no change in LAI, but as a result of the more compact canopy transpiration was reduced.

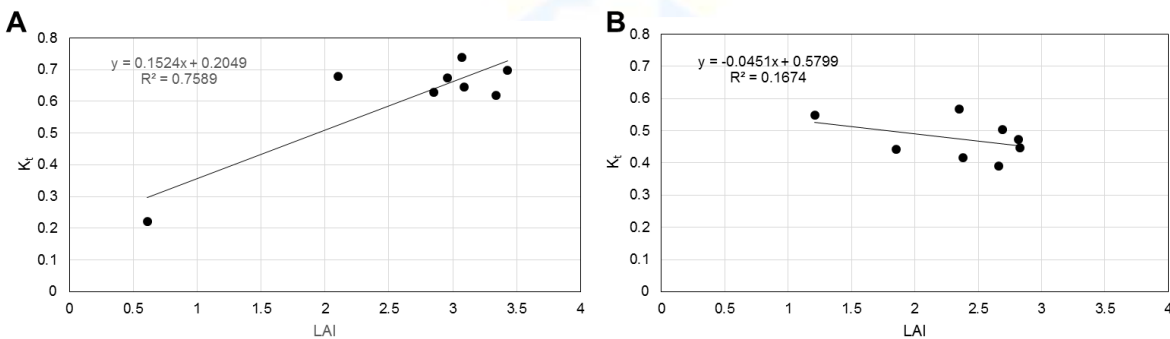


Figure 4.16 Relationship between measured K_t and measured LAI in A) full-bearing ‘Golden Delicious’ trees and B) full-bearing ‘Cripps Pink’ trees

As midday light interception by a canopy or LAI is not readily measurable by growers, some authors have investigated the relationship between crop coefficient curves and remotely sensed vegetation indices to determine crop coefficients in orchards where no water use measurements have been made (Singh and Irmak 2009; Campos et al. 2010; Carrasco-Benavides et al. 2012). If such a relationship exists for apples, then it could be used to adjust crop coefficients for orchards of different ages and planting densities. As

this data is available from a commercial product in the Western Cape (www.Fruitlook.co.za) it could to be very useful for the derivation of orchard specific K_t values for the vast number of apple orchards in the Western Cape which differ in planting density and tree size. Vegetation indices derived from reflectance data (NDVI) is a measure of the canopy “greenness” and is therefore useful in the assessment of active photosynthesizing and transpiring foliage (Glenn et al. 2007). Vegetation indices are suggested to be more indicative of biophysical processes, such as transpiration, than traditional ‘ground’ measurements of LAI and canopy cover, which are also often difficult to measure non-destructively.

The trend in NDVI values throughout the season were very similar in both the ‘Cripps’ Pink’ and ‘Golden Delicious’ orchards despite differences in measured LAI between the two orchards (Figure 4.17). This was expected as a moderate non-linear relationship is acknowledged to occur between NDVI and measured LAI on the ground (Glenn et al. 2007). In addition, NDVI reaches a maximum at LAI values of >3 (Glenn et al. 2007; Allen et al. 2011) and as the maximum LAI value in the ‘Golden Delicious’ orchard was 3.4 (Figure 4.8), it could explain why very little difference was observed between the two orchards. The pixel size from the satellite images used for the Fruitlook application is also 30 m x 30 m and therefore the inter-row is included in the NDVI estimates and in the study orchards there was a considerable grass cover in between the tree rows which could have influenced the values obtained (Figure 4.18). Moreover, it is important to state that although the orchards were comparable in canopy volume, differences in LAI values were influenced by a greater stacking of leaves in the ‘Golden Delicious’ orchard.

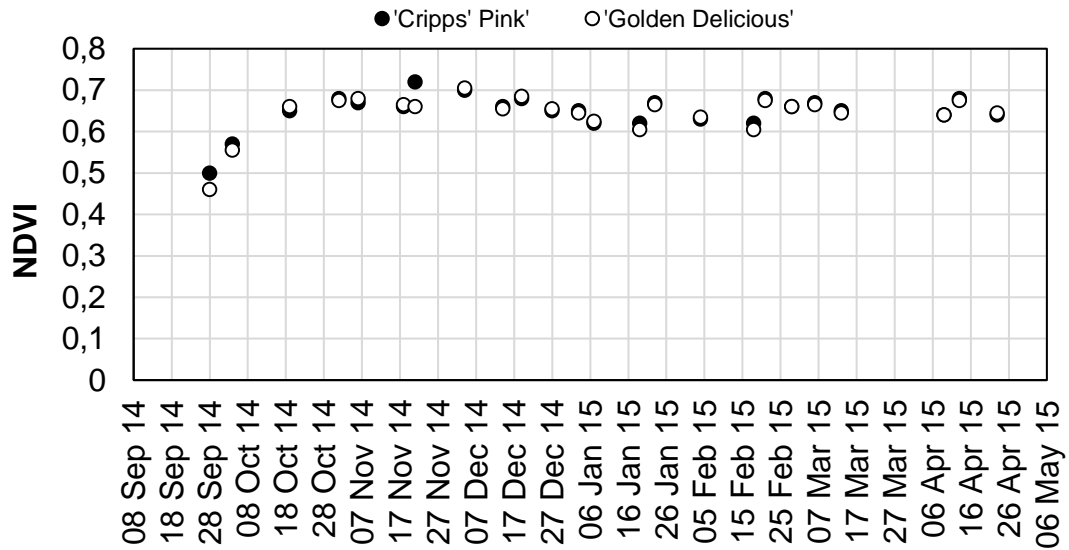


Figure 4.17 Variation of normalized difference vegetative index (NDVI) values for the 'Cripps' Pink' and 'Golden Delicious' orchards for the period 25 September 2014 to 22 April 2015.



Figure 4.18 Photographs of the A) 'Golden Delicious' and B) 'Cripps' Pink' orchards showing the grass cover in between the tree rows

When NDVI was plotted against the K_t in the full-bearing ‘Golden Delicious’ orchard, a positive correlation was observed with a coefficient of determination of $R^2 = 0.58$ and a regression equation of $K_t = 2,016 \text{ NDVI} - 0.695$. Contrasting results were, however, found in the full-bearing ‘Cripps Pink’ orchard results, where the relationship between NDVI and K_t was negative with a coefficient of determination of $R^2 = 0.310$ (Figure 4.19A).

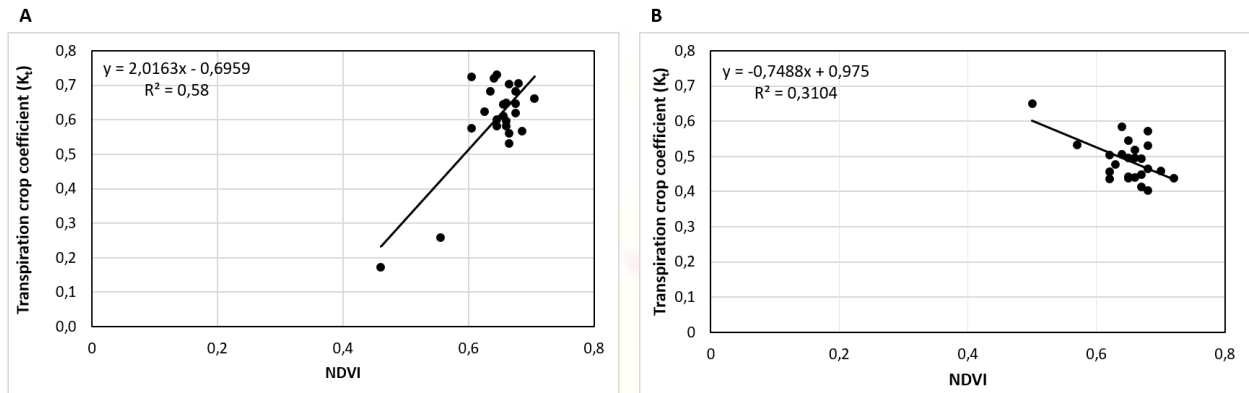


Figure 4.19 Relationship between K_t and NDVI in A) full-bearing ‘Golden Delicious’ trees and B) full-bearing ‘Cripps Pink’ trees

The poor relationship in the ‘Cripps’ Pink’ orchard could reflect a quite narrow range of NDVI and K_t values in this orchard during the measurement period. This was probably due to measurements starting after bud break in this orchard and thus the trees were already in leaf when measurements began. Allen et al. (2011) warns that stomatal control over transpiration may vary between crops, which could cause a variation in the relationship between NDVI and K_t . Massonnet et al. (2007) has also suggested that different degrees of stomatal control over transpiration exist in some apple cultivars, which could also explain the differences in the relationship between the two orchards. Further comparisons in a greater number of orchards need to be conducted to establish if such a relationship exists in apple orchards.

4.7 Conclusion

Many environmental variables play an important role in tree water use. Much of the variation in transpiration was accounted for by changes in solar radiation and reference evapotranspiration (ET_o). However, although there was a good relationship between atmospheric demand and transpiration in the study orchards it was non-linear, suggesting some form of tree regulation of transpiration when ET_o increased above a certain level. This is most likely attributable to stomatal closure in response to increasing VPD, which has previously been noted in apple (Landsberg et al. 1975; Lakso 1985). Such a mechanism is important to maintain leaf water potential in severely dry environments, which often occur in the summer months in the Western Cape. It would therefore have important implications for the use of crop coefficients for estimating apple water use, as this approach implies that ET is demand-limited and under high VPDs transpiration may be supply-limited. Internal factors, such as carbon balance, may also play a role in regulating stomatal aperture and therefore transpiration (Jones et al. 1985), with some studies reporting a decrease in crop coefficients immediately following harvest (Girona et al. 2011). Although not as significant, a slight transient decrease in K_t values were observed in both orchards following harvest. This suggests some feedback control on stomatal conductance via photosynthesis, but was unlikely to be a significant factor regulating transpiration in the current study orchards.

Many authors have suggested that VPD plays an important role in the regulation of transpiration in fruit trees. It was hypothesized that transpiration would be directly related to an increase in solar radiation in the morning, but in the afternoon, it would be more closely related to VPD. This was probably an oversimplified hypothesis as many more factors play a role in controlling transpiration rates. What was clear is that hourly transpiration was more closely related to both solar radiation and VPD in the morning than in the afternoon. This could possibly reflect differential stomatal closure in the afternoon in response to a number of factors.

Although the orchards were very close to one another and were of similar height, it was evident that the K_t values differed significantly between the two orchards. If the K_t values derived on one orchard were used to schedule irrigation for both orchards there would

have either been under or over irrigation in the second orchard. This stresses the need for orchard specific crop coefficients which are based on canopy size (Allen and Pereira 2009). In an attempt to relate K_t values to canopy size, the relationship between K_t values and various vegetation indices was evaluated. Whilst fairly good relationships were found between LAI and NDVI in the 'Golden Delicious' orchard. A poor relationship was found in the 'Cripps' Pink' orchard due to an assessment of the orchard starting fairly late after leaf area had developed. Due to the ease with which NDVI values can be derived from remote sensing products (e.g. FruitLook in the Western Cape) the relationship between K_t or K_c values and NDVI should be explored in a greater number of orchards, as this could assist many growers in determining orchard specific K_t or K_c values for irrigation scheduling.



4.8 References

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CHAPTER FIVE

DETERMINING APPLE ORCHARD SPECIFIC TRANSPIRATION CROP COEFFICIENTS (K_t) USING CANOPY SIZE AND TREE HEIGHT

5.1 Introduction

Water use measurements (as reported in Chapter 4) are too costly and time consuming to carry out under all possible combinations of climate and management practices and thus, crop models are often used to extrapolate measured data to a wide range of conditions to facilitate decision making. The FAO-56 approach by Allen et al. (1998) is a very popular modelling approach, as it is relatively easy to use and requires relatively few input data to provide good estimates of crop evapotranspiration (ET). However, in tree crops there is not always a linear relationship between ET from a short grass surface and ET from the tall trees (Annandale and Stockle 1994; Testi et al. 2004). This is mainly due to differences in aerodynamic conductance above short and tall crops. Thus, crop coefficients (K_c) derived in one location may not be readily transferable to other locations. Due to this, Allen and Pereira (2009) developed an extension of the FAO-56 modelling approach that attempts to estimate water requirements of crops with incomplete ground cover and high frequency irrigation by adjusting crop coefficients using canopy cover and plant height. This approach has subsequently been tested in peaches (Paco et al. 2012; Rosa et al. 2012) and citrus (Taylor et al. 2015), with some success. It was therefore tested in two mature, full-bearing apple orchards to assess if this modelling approach would also be suitable for apples. Although a non-linear relationship was found between reference evapotranspiration (ET_o) and transpiration in Chapter 4, the relationship was fairly good and it was hypothesized that transpiration crop coefficients (K_t) can be accurately adjusted for different mature apple orchards, based on canopy height and fraction of ground shaded by the vegetation. Transpiration crop coefficients were calculated as suggested by Villalobos et al. (2013). As the basal crop coefficient (K_{cb}) includes some diffusive background evaporation from a mostly dry soil and in this study, only the transpiration component was measured using a sap flow technique

5.2 Model description

Transpiration crop coefficients (K_t) were determined according to Allen and Pereira (2009) by scaling the estimated transpiration crop coefficient during peak growing conditions ($K_{t\ full}$, when LAI>3.0), using a density coefficient (K_d) which corresponds with the amount of vegetation, as follows:

$$K_t = K_d K_{t\ full} \quad (1)$$

The K_d can either be estimated as a function of leaf area index (LAI) or as a function of the fraction of the orchard floor shaded at midday. The K_d describes the increase in K_t with increasing vegetation. In this study the K_d was calculated using LAI as follows, as measurements of LAI were available for both orchards throughout the season:

$$K_d = (1 - e^{[-0.7LAI]}) \quad (2)$$

$K_{t\ full}$ was approximated as a function of mean plant height (m) and adjusted for climate as follows (Allen et al. 1998),

$$K_{t\ full} = F_r \left(\min(1.0 + 0.1h, 1.20) + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \left(\frac{h}{3}\right)^{0.3} \right) \quad (3)$$

where h is the mean maximum plant height in m, u_2 is the mean value for wind speed at 2 m height during the mid-season in $m\ s^{-1}$, RH_{min} is the mean value for minimum relative humidity during the mid-season in %, and F_r [0-1] is an adjustment factor used to adjust $K_{t\ full}$ for crops which exhibit stomatal control over transpiration. If the tree canopy exhibits more stomatal control over transpiration than the typical agricultural crop, then F_r may be <1 for some types of trees and natural vegetation. Allen et al. (1998) suggested the following equation for F_r for full cover vegetation, based on the FAO Penman-Monteith equation and assuming full cover conditions,

$$F_r \approx \frac{\Delta + \gamma(1 + 0.34u_2)}{\Delta + \gamma(1 + 0.34\frac{r_l}{100})} \quad (4)$$

where r_l is the mean leaf resistance for the vegetation in question [$s\ m^{-1}$], Δ is the slope of the saturation vapour pressure versus air temperature curve ($kPa\ C^{-1}$) and γ is the psychrometric constant ($kPa\ C^{-1}$). The r_l value is often approximated as $100\ s\ m^{-1}$ for most agricultural crops, which means the F_r value will be 1.0. Allen and Pereira (2009) provide suggested r_l values for several crops, but they also suggest that r_l values can be estimated by inverting Eq. 4 after solving for F_r by inverting Eq.3 using known values of $K_{t\ full}$. The application of Eq. 4 and the value assigned to r_l refers to full cover conditions for both the reference and the vegetation in question. Full cover conditions can be assumed to occur when the LAI exceeds about 3. For apples (no killing frost) an r_l value of $140\ s\ m^{-1}$ is suggested for the initial and midseason periods, increasing to $370\ s\ m^{-1}$ at the end of the season.

5.3 Results and discussion

Values of K_t for both the 'Golden Delicious' and 'Cripps Pink' orchards were initially derived from parameters for apples (no frost) provided by Allen and Pereira (2009) and measured canopy dimensions and weather variables. When comparing the estimated K_t values with the measured K_t values it was evident that the estimated values overestimated the actual K_t values in both orchards quite considerably (Figure 5.1 A and B). If these estimated K_t values were used to estimate transpiration over the season, it would have resulted in a 64.4 % overestimation of transpiration in the 'Golden Delicious' orchard and a 99.3 % overestimation in the 'Cripps Pink' orchard (Figure 5.2 A and B). When comparing the two orchards, it appeared that overestimation of transpiration was much higher in the 'Cripps Pink' orchard (Figure 5.2 A) than the 'Golden Delicious' orchard (Figure 5.2 B), particularly during summer. These values illustrate that adjusting only for canopy size and using r_l parameters provided by Allen and Pereira (2009) for apple orchards, did not provide reasonable estimates of K_t values for the apple orchards at Kromfontein. Moreover, this also suggested that the K_t were not easily transferable from one orchard to the other. The model was evaluated with statistical parameters such as coefficient of determination (R^2), mean absolute error (MAE) and the Willmont index of agreement (D) (Willmont 1982). The performance of the model was considered satisfactory when $R^2 > 0.8$, $MAE < 20\%$ and $D > 0.8$ (de Jager 1994). Statistical analysis

showed that the model performed poorly in the ‘Cripps Pink’ orchard (Figure 5A) with MAE = 127% and $D = 51$. Similarly, poor performance was observed in the ‘Golden Delicious’ orchard (Figure 5B) with MAE = 64% and $D = 0.71$.

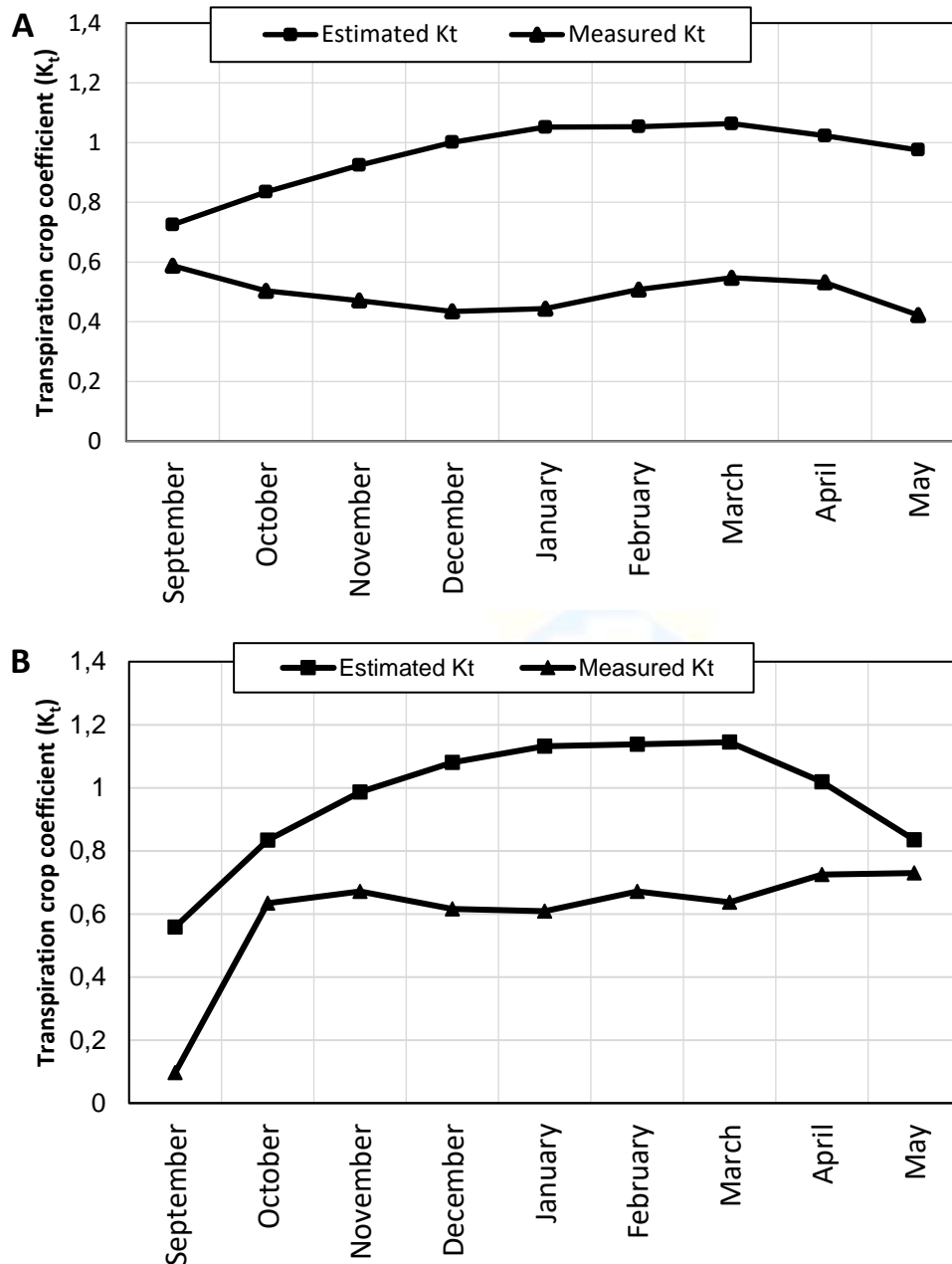


Fig 5.1 Comparison between monthly measured K_t values derived from sap flow measurements and monthly estimated K_t values using parameters suggested by Allen and Pereira (2009) for the A) ‘Cripps Pink’ and B) ‘Golden Delicious’ orchards.

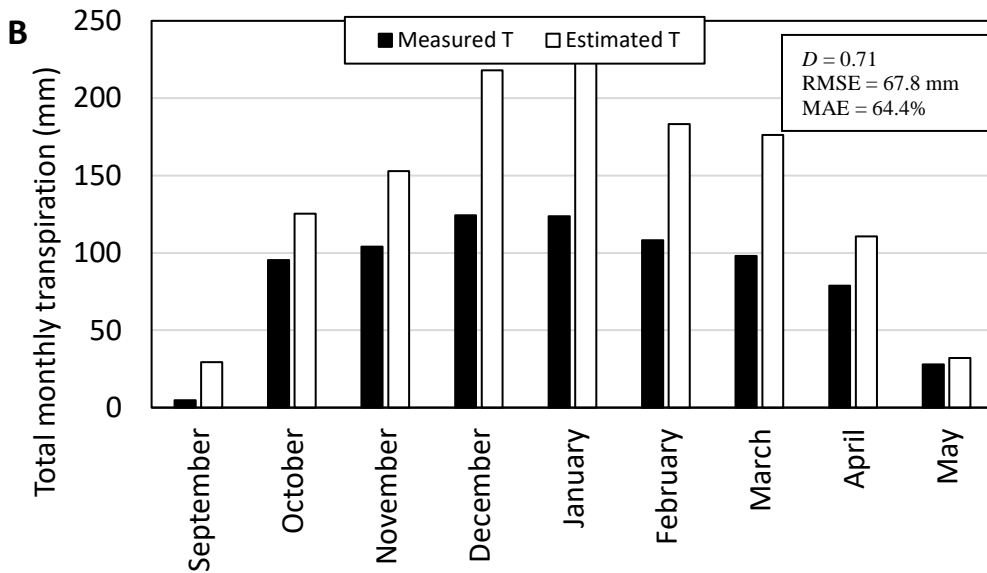
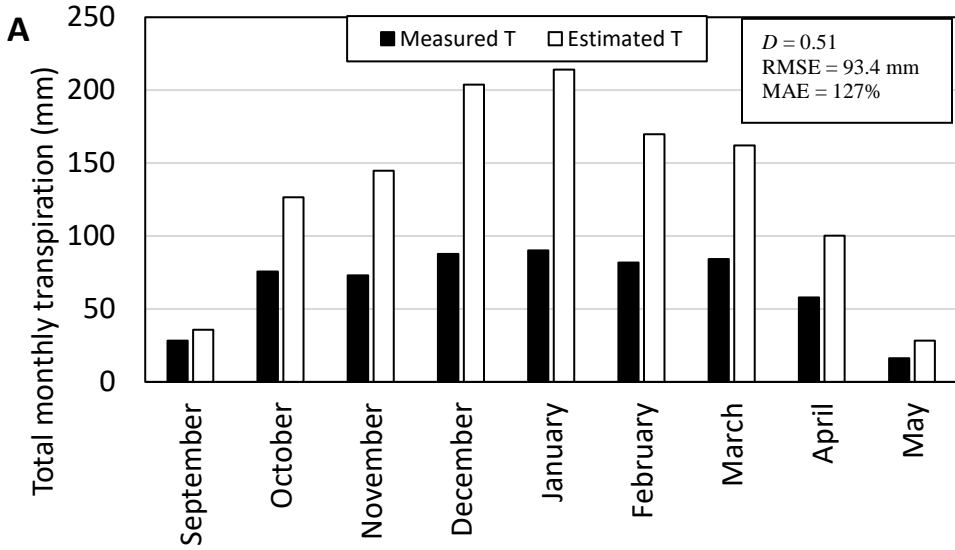


Fig 5.2 Comparison between monthly measured transpiration using calculated K_t values derived from sap flow measurements and monthly estimated transpiration using calculated K_t values derived from parameters suggested by Allen and Pereira (2009) for the A) 'Cripps Pink' and B) 'Golden Delicious' orchards.

As the only generic parameters used to estimate K_t values were the η values for the initial, mid and end season (Allen and Pereira 2009), orchard specific η values were estimated by inverting Eq.4 after solving for F_T using Eq. 3, using known values of $K_{t,full}$, which were

calculated using K_t and K_d values. When comparing the generic n values for apples with those determined in this study, it was evident that the generic n values were much lower than the values determined from the study site, particularly in the middle of the season (Figure 5.3). During this period, i.e. November 2014 to February 2015, there was a significant increase in the leaf stomatal resistance for both orchards. The n values in the 'Cripps Pink' orchard (Figure 5.3) gradually increased from 249 $s.m^{-1}$ in spring, to 867 $s.m^{-1}$ in summer, decreasing slightly towards the end of summer and increasing again in autumn. The 'Golden Delicious' orchard (Figure 5.3) showed a similar trend to the 'Cripps Pink' orchard with regards to leaf resistance throughout the season. This orchard displayed n values of 281 $s.m^{-1}$ at the beginning of the season, with an increase in resistance to 595 $s.m^{-1}$ during mid-season, and a decrease to 413 $s.m^{-1}$ in autumn. The study orchards were within 500 m of each other, yet the n values were significantly different. This could possibly reflect cultivar differences, as Massonnet et al. (2007) observed that the VPD threshold beyond which stomatal conductance began to decline differed between 'Fuji' and 'Braeburn' trees.

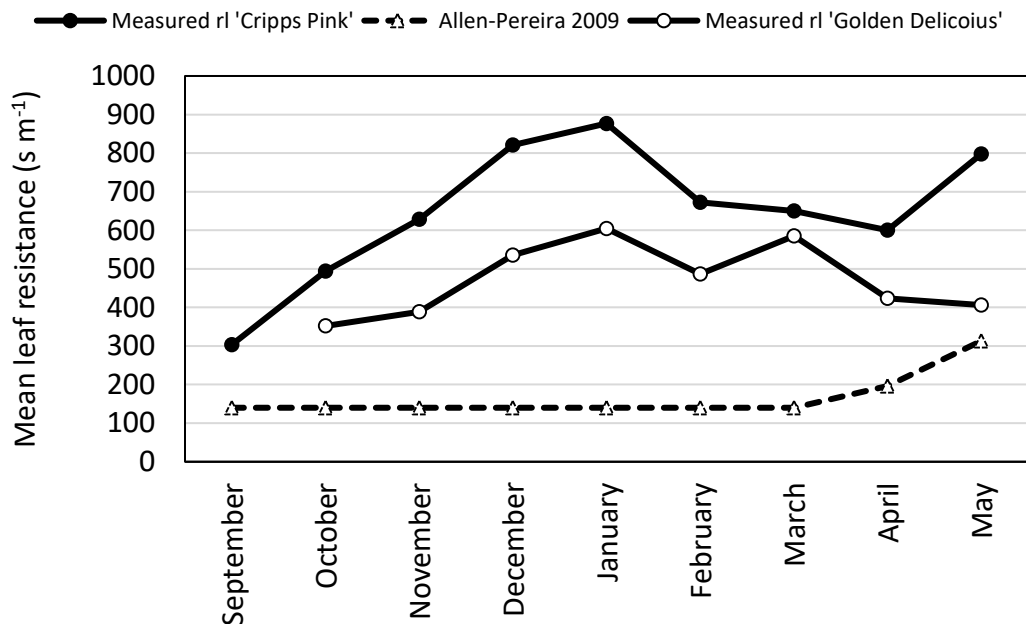


Fig 5.3 Comparison of monthly mean leaf resistance (n) of 'Cripps Pink' and 'Golden Delicious' orchards to monthly n values for apples as suggested by Allen and Pereira (2009).

Moreover, Atkinson et al. (2000) and Li et al. (2002) state that an increase in tree vigour is related to an increase in stomatal conductance and that stomatal sensitivity is also related to VPD and will vary both within and between species (Oren et al. 1999). It is therefore possible that stomatal responses to VPD could differ between 'Cripps Pink' and 'Golden Delicious' trees, which resulted in higher mean leaf resistances in the 'Cripps Pink' trees as opposed to the 'Golden Delicious' trees. These results could also reflect a difference in canopy structure between the two orchards, because of the 'Cripps Pink' orchard being sprayed with a growth inhibitor (Regalis®), which would have resulted in a more compact canopy via less shoot growth, with reduced vigour. Massonnet et al. (2007) reported differences in branch transpiration between species and suggested that this could be due to differences in branch architecture, which resulted in changes in solar radiation distribution through the canopy.

A comparison of monthly estimates of λ with measured data from the orchards, using a porometer (Figure 5.4A and B), indicate that λ estimates were considerably higher than those estimated using a porometer. Stomatal conductance in the 'Golden Delicious' varied between 159 s m^{-1} and 284.1 s m^{-1} in February 2015, whilst in the 'Cripps Pink' orchard, varied between 108.07 s m^{-1} and 117.8 s m^{-1} in March 2015. These values are closer to the 140 s m^{-1} suggested for apple by Allen and Pereira (2009), but are much lower than the calculated 600 m s^{-1} for λ . As suggested by Allen and Pereira (2009), the calculated λ values are likely to be biased by the calculation procedure. Through this procedure all the error in calculation is assigned to the λ term, which is unlikely to reflect reality. Measurements over a greater number of days could also provide a better monthly estimate of λ . This will be particularly important in the hot and dry summer months.

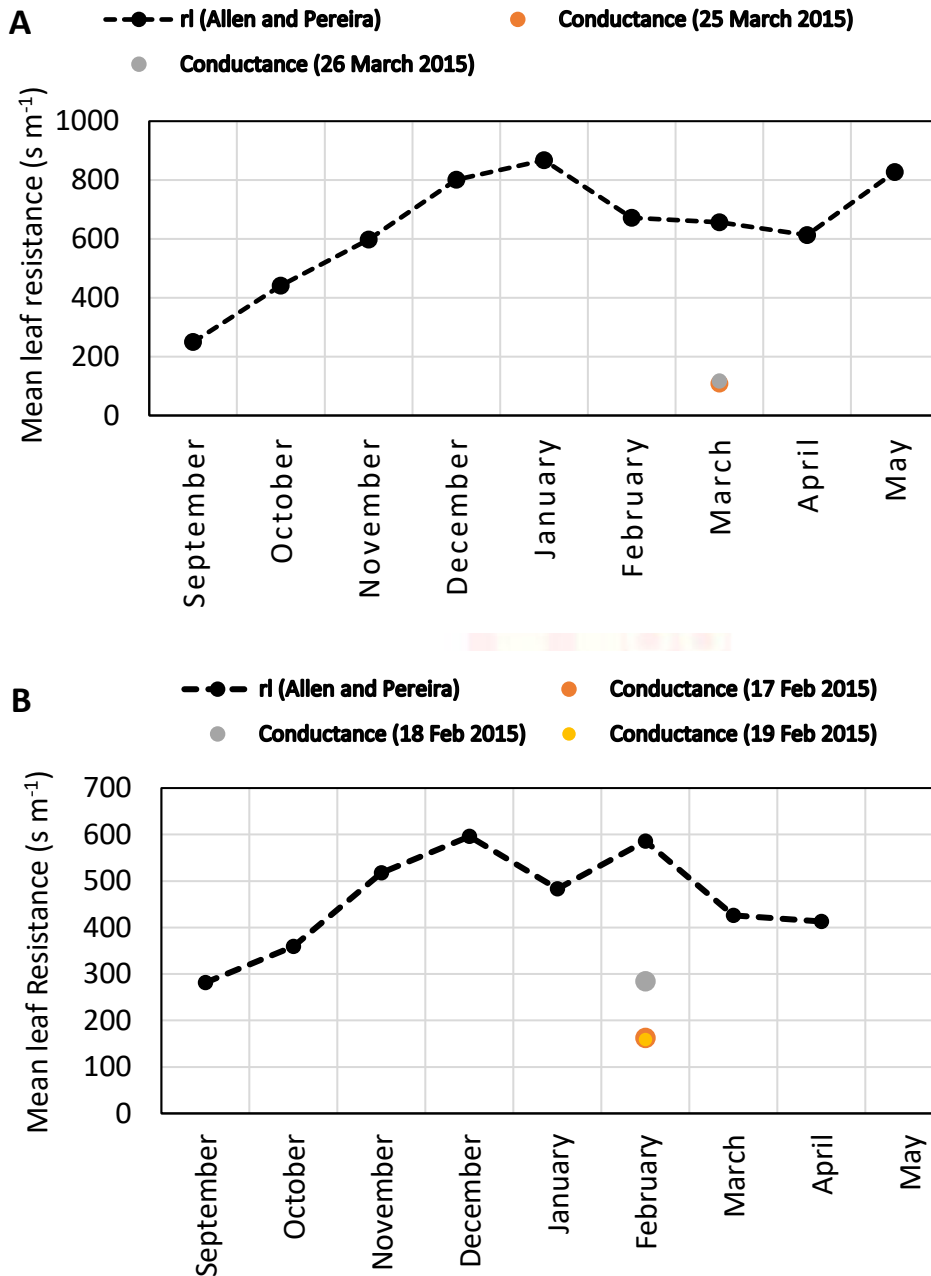


Figure 5.4 Comparison between monthly leaf resistance (r_l) for apples as suggested by Allen and Pereira (2009) and Stomatal Conductance in the A) 'Cripps Pink' and B) 'Golden Delicious' orchards.

The reasons for the higher η values in this study, as compared to those proposed by Allen and Pereira (2009), could be due to several factors. However, perhaps the most compelling argument is the negative relationship between high VPD and stomatal conductance reported for apple (Lakso 2014). Apple growing regions in South Africa differ quite significantly from many of the apple growing regions of the world, especially in terms of climate. The relative humidity is generally very low and the VPD is higher than other regions during summer; and this could explain why η values for the current study differed so significantly to those proposed by Allen and Pereira (2009).

These estimated η values were then used to estimate K_t , which resulted in perfect agreement between K_t measured and K_t estimated (Figure 5.5A and B). This was not surprising as the measured K_t values were used to derive the η values. Obviously there was also good agreement between measured and estimated monthly transpiration (data not shown).

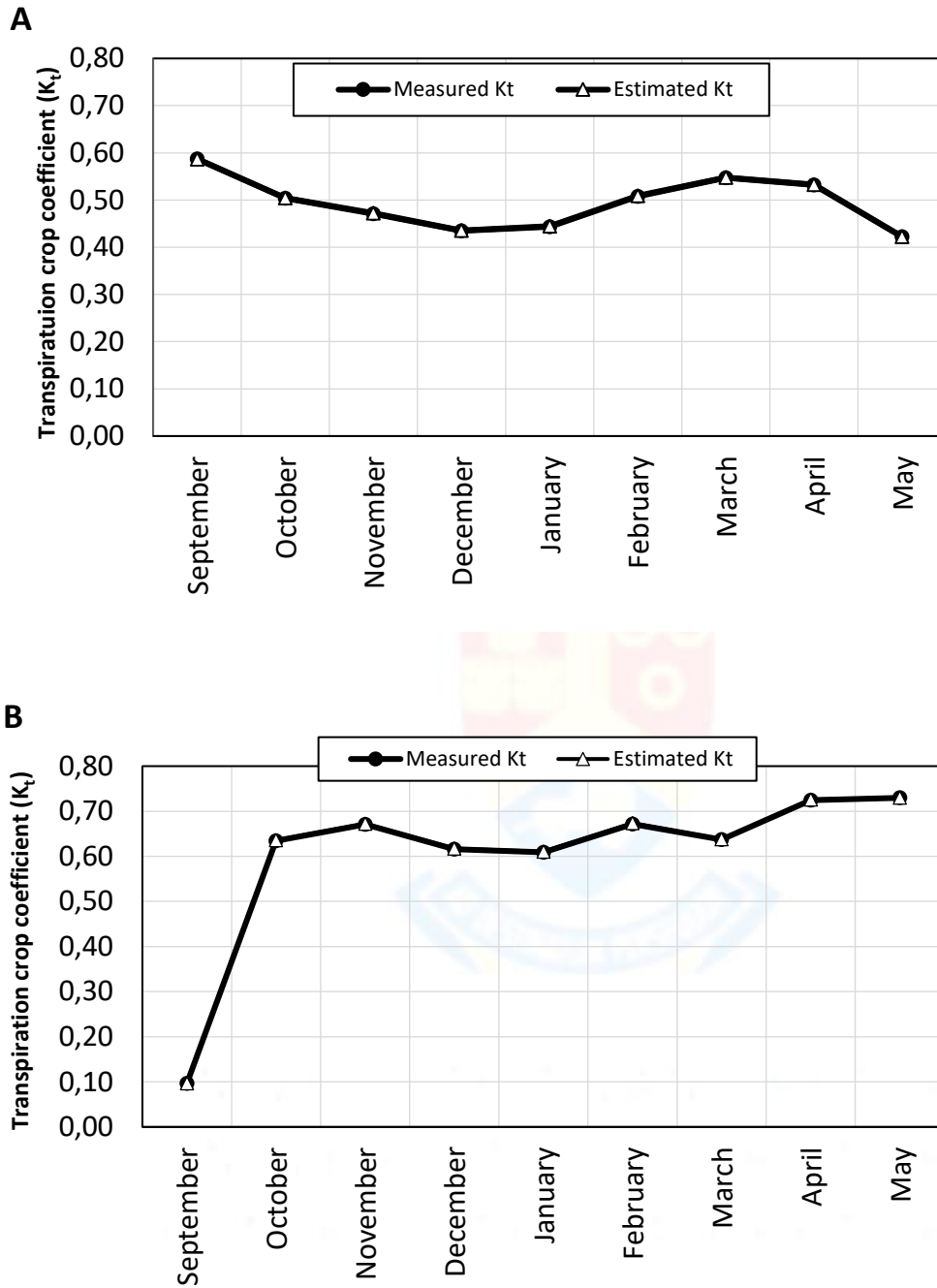
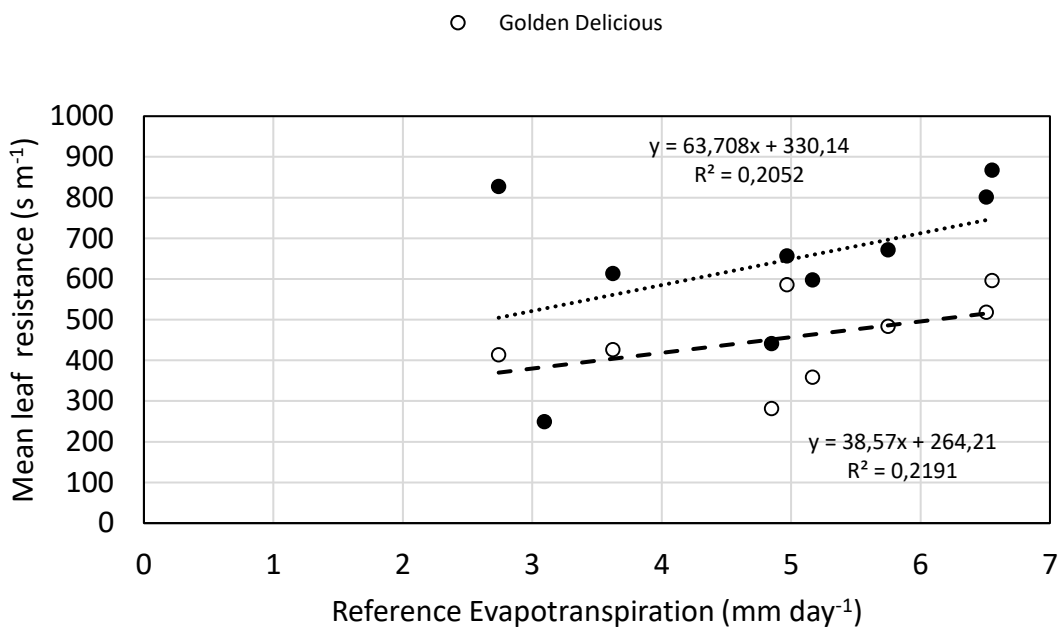


Fig 5.5 Comparison between monthly measured K_t values derived from sap flow measurements and monthly estimated K_t values using orchard specific calculated n values for the A) 'Cripps Pink' and B) 'Golden Delicious' orchards.

Whilst the model performed extremely well when r_l values were used, that were derived from measured transpiration, it is the determination of the r_l values which limits the use of this model across a wide range of orchards, as observed by Taylor et al. (2015) in citrus. Taylor et al. (2015) used a regularly measured weather variable to try and obtain an estimate of r_l . These authors found a reasonable relationship between ET_o and r_l . Relationships between weather variables and r_l were therefore determined for the current study. There was a linear relationship between ET_o and r_l for both ‘Cripps Pink’ and ‘Golden Delicious’ orchards, however, the relationship between these variables was poor ($R^2 = 0.20$ and 0.21) (Figure 5.6) and therefore would not provide good estimates of r_l . The linear relationship between r_l and VPD was better with a coefficient of determination of $R^2 = 0.45$ for the ‘Cripps Pink’ orchard and $R^2 = 0.57$ for the ‘Golden Delicious’ orchard (Figure 5.7).



5.6 Relationship between mean leaf resistance and reference evapotranspiration in the A0 ‘Cripps Pink’ and B) ‘Golden Delicious’ orchards.

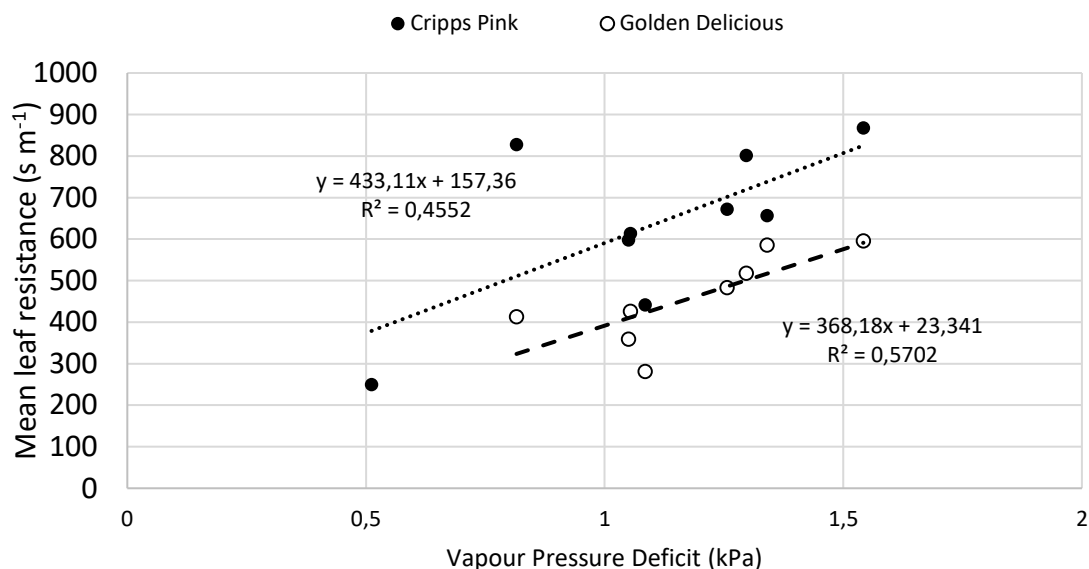


Fig 5.7 Relationship between leaf resistance and Vapour Pressure Deficit in the A) ‘Cripps Pink’ and B) ‘Golden Delicious’ orchards.

In order to test the usefulness of the relationship between VPD and η values, the regression equation in Figure 5.7 for the ‘Golden Delicious’ orchard whereby $\eta = 368,18 \text{ VPD} + 23,34$ was used to determine η values. The same equation was used in the ‘Cripps Pink’ orchard and the resultant η values were then used to derive monthly transpiration rates for both orchards (Figure 5.7). It was interesting to find that, although estimated transpiration values were not in perfect agreement with the measured transpiration for both orchards, they were better than the Allen and Pereira (2009) estimates in Figure 5.2 A and B. In the ‘Cripps Pink’ orchard (Figure 5.8 A), measured transpiration was overestimated by 139 mm throughout the season, which was most noticeable during the hottest period of the year. In general better estimates of transpiration were obtained in the ‘Golden Delicious’ orchard, which is not surprising as the η VPD relationship was derived in this orchard (Figure 5.8 B). In this orchard, transpiration was underestimated 25.3 mm at the start of the season, but overestimated 12.3 mm from the middle to the end of the season. The good performance of the model in the ‘Golden Delicious’ orchard was confirmed by the statistical parameters $D=0.90$, the RMSE was 10.8 and a MAE of 8.21%. However, the performance in the ‘Cripps Pink’ orchard was not as good, where $D = 0.94$, RMSE = 21.7 and MAE = 30.02%. The estimation of η using VPD therefore shows

some promise in apple orchards for the monthly and yearly estimation of water use of apple orchards. This needs to be investigated further but could potentially be used for strategic water management decisions in a wide range of apple orchards.

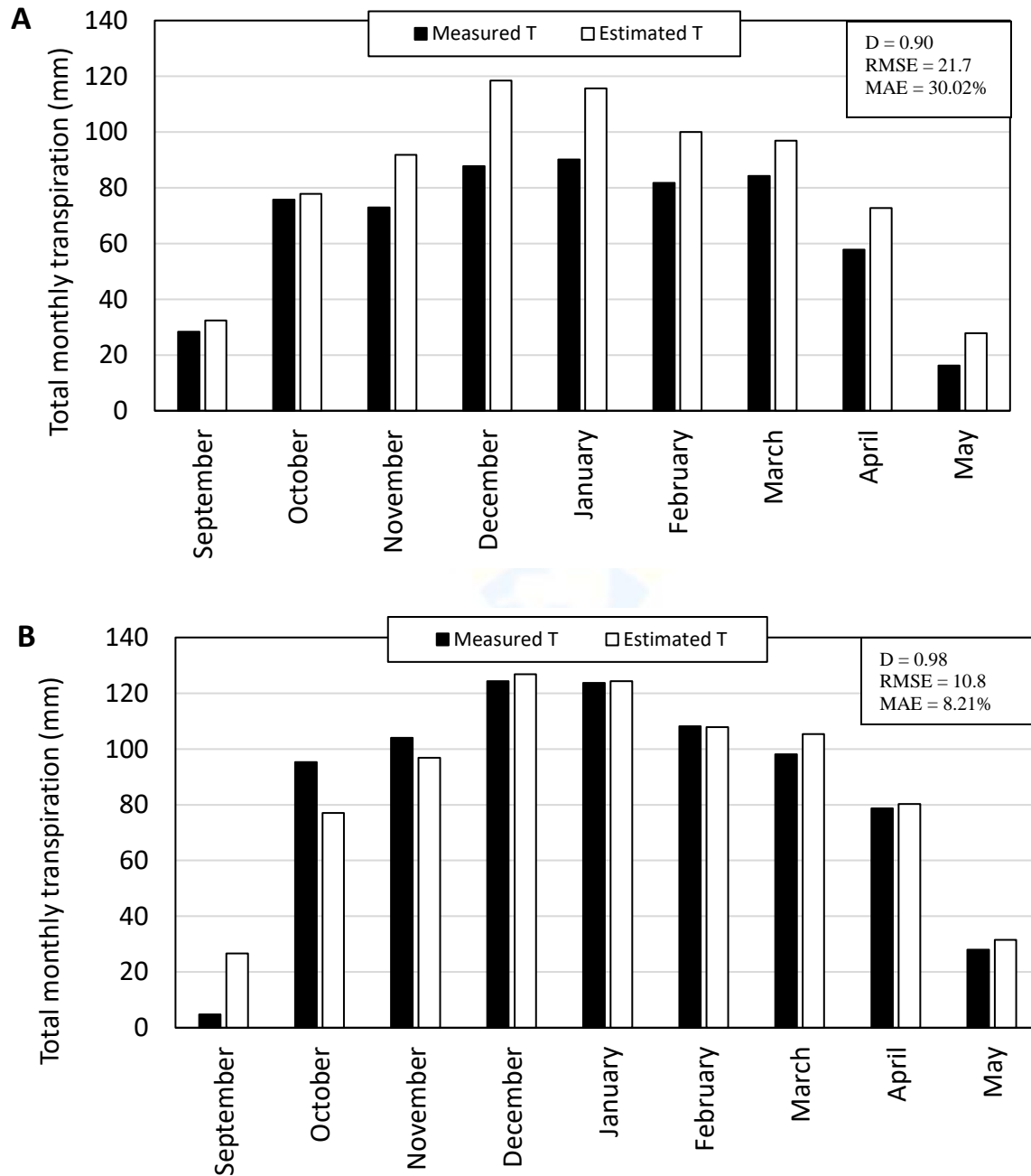


Fig: 5.8 Monthly estimates of transpiration using the relationship between n and VPD compared to measured transpiration in the A) ‘Cripps Pink’ and B) ‘Golden Delicious’ orchards.

5.4 Conclusion

Due to a reasonably good relationship between atmospheric demand and transpiration in the previous chapter, it was assumed that transpiration crop coefficients could be adjusted for crop height and canopy cover as suggested by Allen and Pereira (2009) and provide good estimates of transpiration in the study orchards. This approach would allow K_t values to be transferred to different regions and orchards of different canopy covers for the estimation of tree water use. When calculating K_t values using the model proposed by Allen and Pereira (2009), the K_t values differed significantly from the measured values from the study orchards, resulting in significant overestimations of transpiration. This was attributed to the much higher r_l values in the study orchards as compared to those suggested by Allen and Pereira (2009).

However, it is the ease with which the r_l values can be estimated that limits the use of this approach to determine site specific K_t values. The relationship between atmospheric demand and r_l was then investigated and although it was linear, the coefficient of determination was low for both the 'Cripps Pink' and 'Golden Delicious' orchard. A better relationship between r_l and VPD was observed with a higher coefficient of determination of $R^2 = 0.57$ for the 'Golden Delicious' trees and $R^2 = 0.45$ for the 'Cripps Pink' trees. As a result the relationship between r_l and VPD in the 'Golden Delicious' orchard was used to derive estimates of r_l in both orchards for the determination of orchard specific K_t values, which could be used with ET_o to derive transpiration.

When the estimated monthly transpiration rates derived from the r_l in the regression equation was compared to the measured monthly transpiration rates, a very good agreement was observed in the two orchards. From this approach, we can deduce that the values proposed by Allen and Pereira (2009) for apple did not give good values of transpiration coefficients for apple orchards under local conditions and this was attributed mainly to the low values of generic leaf resistance values. By taking into account the increased leaf resistance, possibly due to very high VPDs in the study orchards, it was possible to derive reasonable estimates of transpiration which can be used for planning purposes but not tactical irrigation scheduling decisions. It would also be useful to carry-out more research on the relationship between VPD and r_l of apple trees to develop a

simple way of determining crop coefficients that would accurately represent environmental conditions at orchard scale.

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CHAPTER SIX

GENERAL DISCUSSION AND CONCLUSIONS

Transpiration is viewed as a beneficial process for plants (Sinclair et al. 1984) due to its intimate link with plant productivity. Therefore, minimizing transpiration whilst maximizing CO₂ intake for the trees could be potentially important for farmers and farmers will irrigate to ensure that there is no decrease in CO₂ intake due to stomatal limitation throughout the season. Based on this study, transpiration rates are mainly dependent on climatic conditions and canopy size, which both vary throughout a production season. It is for this reason why we quantify transpiration under varying conditions. Understanding the factors controlling transpiration will in turn allow modelling of transpiration and extrapolation to a wide range of conditions. There are numerous methods to quantify transpiration, but the heat ratio sap flow method has proven to be accurate and reliable in estimating transpiration of fruit trees in a number of studies (Green et al. 2003; Fernández et al. 2008; Burgess et al. 2001). In this study, measurements were performed to estimate the transpiration of two mature apple orchards of full bearing Golden Delicious and Cripps Pink cultivars and to determine the main driving factors for tree water use. A simple modelling approach was then evaluated for estimating monthly apple water use. It is envisaged that by modelling the water use of mature apple orchards using this simple approach farmers will be able to design their irrigation systems better and plan irrigation throughout a season.

Since apple trees are deciduous, the tree canopy varied in size throughout the season and this led to a variation in transpiration rates. According to the crop coefficient curve (Allen et al. 1998), the canopy of deciduous fruit tree crops is expected to follow three stages i.e. initial, mid-season and end stage. As the canopy developed from the beginning of the season, tree transpiration began to slowly increase in spring, reaching maximum rates in summer and slowly declining in autumn. The 'Golden Delicious' orchard transpired more water than the 'Cripps Pink' trees throughout the 2014/2015 growing season and this was attributed to the 'Golden Delicious' trees having a larger canopy volume than the 'Cripps Pink' trees. The 'Golden Delicious' trees transpired a daily average of 3.19 mm day⁻¹ and the total transpiration for the season was 787 mm. The 'Cripps' Pink' orchard had lower

rates with a daily average of 2.14 mm day^{-1} and seasonal total of 594 mm. This illustrated that although the orchards were located close to each other, the only difference was the canopy size. Many authors such as Li et al. (2002) and Liu et al (2012) have noted similar trends of transpiration rates whereby there is a steady increase in transpiration at the beginning of the season, followed by maximum rates during midseason and a decline at the end of the season for apples throughout the season. However, orchard specific climate also greatly influences the fluctuation of transpiration rates.

Climatic conditions played a critical role in determining daily transpiration of apple trees and were responsible for much of the observed daily variation observed in this study. Reference evapotranspiration (ET_o) calculated according to FAO-56 (Allen et al. 1998), had a curvi-linear relationship with transpiration throughout the season, possibly indicating stomatal control over transpiration at high atmospheric demands. A decrease in water loss through the leaves due to stomatal closure in response to increased solar radiation, temperature and vapour pressure deficit has previously been reported (Jones 2004). Solar radiation and VPD appeared to be the two variables that accounted for most of the variation in transpiration. This was expected as transpiration results from the net radiation absorbed by the trees for photosynthesis and the increasingly dry atmosphere.

Since both solar radiation and VPD play a role in controlling stomatal aperture, which is the controlling point for gaseous exchange for both photosynthesis (Wullschleger et al 1998), and transpiration, the hourly relationships between transpiration, solar radiation and VPD were assessed. Hourly transpiration rates had a direct relationship with solar radiation before noon; however, this was reduced after noon due to increased VPD. In order for the trees to preserve water under hot and dry conditions, there must be stomatal closure. This is greatly influenced by the hydraulic resistances from the roots to the leaves as water is maintained within the crop as a function of leaf water potential (Williams et al. 2001). Therefore, the increase in hourly VPD rates just before noon resulted in stomatal closure which resulted in the control over transpiration rates.

Although good transpiration estimates were obtained for a single season in these orchards, it is unlikely to give a good reflection of apple tree water use in all the apple

orchards in the Western Cape. Since it is not possible to measure apple tree water use for all the orchards in the Western Cape, there is a need to model tree water use in order to make the results in this study relevant to other regions. However, it is important to choose a model that is easy to use for farmers, requires little inputs and provides accurate results. In this study, the FAO-56 crop coefficient model was used because this model is simple to use and takes into account meteorological variables and canopy cover as determined by LAI measurements. Since only transpiration was measured, transpiration crop coefficients (K_t) as defined by Villalobos et al. (2013) were determined. This model has been used in many studies and has previously provided good estimates (Allen et al. 1998; Girona et al. 2011). The measured K_t were variable throughout the season and were lower when compared to the values published by Allen et al. (1998) in FAO-56 for apple trees with active ground cover and no killing frost. The values published by Allen et al. (1998) therefore did not provide good estimates of the K_t obtained at the study orchards. This is not unexpected, as Allen et al. (1998) advises that the crop coefficient curve should be adjusted for local conditions.

Since canopy cover and canopy height vary in orchards and influence water use, Allen and Pereira (2009) consolidated the FAO-56 approach by considering the physical characteristics of the crop for the determination of site-specific crop coefficients and adjustment for stomatal control over transpiration. Therefore, in an attempt to evaluate this procedure K_t were calculated with parameters provided by Allen and Pereira (2009) for apple trees. An important parameter was the apparent, effective leaf resistance (r) and Allen and Pereira (2009) suggested that for apple the initial and midseason value was 140 s m^{-1} and 450 s m^{-1} at the end of the season. This parameter was important due the curvi-linear nature of relationship between ET_0 and transpiration in the study orchards. The K_t values derived using parameters suggested by Allen and Pereira (2009) were higher than the measured K_t . Consequently, monthly estimated transpiration was overestimated by 64.4% for the 'Golden Delicious' trees and 99.3% for the 'Cripps Pink' trees. This meant that the K_t derived from canopy height and fraction of ground shaded by the vegetation could not be accurately adjusted for the apple orchards in this study when using values suggested by Allen and Pereira (2009).

To take into account the stomatal control over transpiration, leaf resistance (r_l) values were calculated by using K_t full (determined from K_d and K_t values derived from measurements). The r_l values were much higher than the published values by Allen and Pereira (2009) for apples, with 'Cripps Pink' having maximum values of 867 s.m⁻¹ and 595 s.m⁻¹ for 'Golden Delicious' in the summer months. It is possible that there was higher stomatal control over transpiration during summer in the orchards, as VPD in apple orchards in the Western Cape during the growing season is likely to be higher than most other apple production regions. Using these orchard specific r_l values provided good estimates of K_t values, but the challenge is then how to obtain orchard specific estimates of r_l without transpiration measurements. r_l and VPD were therefore regressed to calculate r_l as a function of VPD. This relationship from the 'Golden Delicious' orchard resulted in reasonable K_t values, which in turn provided reasonable estimates of monthly transpiration. In order to validate this approach, the same regression equation from the 'Golden Delicious' orchard was used to determine r_l values in the 'Cripps Pink' orchard. These values also produced better transpiration estimates than the estimates derived from Allen and Pereira (2009), however there was an over estimation of 23.4% for the season. Therefore, by taking into account stomatal control over transpiration, the model proposed by Allen and Pereira (2009) provided reasonable estimates of monthly transpiration (when compared to the overestimation of 99.3% mentioned above), which can be used for strategic decisions.

As mentioned above, canopy size as determined by LAI measurements plays an important role in tree water in this study, but it needs to be measured in a manner that can be done without growers having to use expensive equipment. Remote sensing technology has been found to be a valuable tool in estimating vegetation indices and for estimating crop coefficients (Campos et al. 2010). This approach can be helpful as NDVIs show the development of the canopy at each stage of the growing season and the relationship between NDVI and crop coefficients can be used as a base for modeling water use in the orchards. This relationship was therefore evaluated in the current study, but a poor relationship was found between K_t and NDVI in the 'Cripps Pink' orchard; however, a linear relationship was found in the 'Golden Delicious' orchard. The linear relationship suggested that indeed there was a relationship between NDVI and K_t and it

could be possible to estimate apple tree water use with remote sensing. However, due to the weakness in this relationship, more research on this relationship needs to be conducted for more seasons to attain accurate orchard specific K_t values that can assist farmers with irrigation planning.

6.1 Recommendations

Due to a gap in knowledge on apple tree water use in South Africa, and this research has meaningfully plugged the gap by providing a better understanding of tree water use of mature apple orchards in relation to environmental conditions. In recent years low rainfall levels have been experienced in the Koue Bokkeveld region, as well as throughout South Africa, resulting in droughts. Previously, the Status Quo Report (2011) stated that the frequency of droughts was most likely to increase resulting in water restrictions being applied more frequently. With this in mind, it is therefore advisable for farmers to decrease evaporation by mulching or apply night time irrigation for now and the immediate future. With the use of water use models, such as the one proposed by Allen and Pereira (2009) as suggested in this study, farmers may be able to plan their irrigation effectively throughout the season. This would prevent orchards being under or over irrigated and farmers can avoid paying more for water. However, a single season is not effective enough to determine crop coefficients which can be easily transferred to other regions.

Quantifying apple tree water use of orchards has provided sufficient information on the interrelationships between transpiration and stomatal conductance, leaf area and the effect of solar radiation in trees. All these variables have to a certain degree, a pivotal role to play in tree water use. Moreover, it was evident that orchard management practices that include irrigation, harvesting, mulching, pruning, as well as the application of growth regulators also played an integral role in apple tree water use. Therefore, it is important for farmers to take into account which management practice to use and when to use them. Lastly, the use of remote sensing to estimate water use should be researched even further. With this technology, farmers would be able to determine tree water use without doing any physical measurements on their orchards. This technology is currently available in the Western Cape and there is free access for data needed.

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