GUIDE TO PECAN WATER USE

SAPPA
South African Pecan Nut Producers Association NPC

WATER RESEARCH COMMISSION

SP 179/24

Obtainable from:
Water Research Commission
Private Bag X03
Gezina
0031

Disclaimer
The Water Research Commission (WRC) has approved this book for publication. Approval does not signify that the contents necessarily reflect the views and policies of the WRC, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

PREPARED BY:
Nicolette Taylor, Ncamsile Shongwe, Seluleko Kunene, Robert Godfrey, Muhammad Pandor, Amogelang Molamu, Angelique Kritzinger, Colin Everson, John Annandale
Department of Plant and Soil Sciences, University of Pretoria

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Editor: Lani van Vuuren
Design and layout: Anja van der Merwe
Printed in the Republic of South Africa

SP 179/24
ISBN 978-0-6392-0656-1

CONTENTS

INTRODUCTION

Water is a scarce and valuable resource in South Africa and needs to be managed optimally in agriculture to optimise both yield and quality. Increasing competition for limited resources between a growing population, industry and agriculture is placing increased pressure on agriculture to use water more efficiently and to justify water used to produce a crop. As the vast majority of pecans are produced in semi-arid regions in South Africa, where irrigation is required to remain productive, using water productively is important to ensure the sustainability of the industry and to allow for any future expansion.

Pecans are also often viewed as a crop that uses a lot of water because of the large canopy, which means it is even more important to demonstrate good water management and productive use of the water applied. It is also important to make sure that fair water licenses are issued for pecan production.

Good irrigation scheduling involves meeting the full evapotranspiration (ET) requirements of the crop, while minimising water lost from the system through evaporation, run-off and deep percolation. This guide therefore aims to provide comprehensive information on irrigation management and scheduling in pecan orchards, in order to assist growers to use water more productively in pecan orchards.

This guide covers the following aspects:

- The water balance of an orchard
- Pecan orchard water requirements and factors impacting water use
- Scheduling irrigation and monitoring applied water
- What to do when there is not enough water

Principles of water movement in soils, water movement in plants and irrigation scheduling are discussed in order for the information to be applicable to a wide range of orchards using different irrigation system. Water use information focuses on evapotranspiration of orchards (total water lost from the orchard via transpiration and evaporation from the soil) with sets of crop coefficients (K_c) supplied for general irrigation planning in three different areas of South Africa.


02

THE WATER BALANCE OF AN ORCHARD

In order to improve irrigation efficiency from storage to field application it is important to understand the fate of the water, which means understanding the water balance of a farm. This allows the analysis of irrigation water use on farms and can assist growers to improve the productive use of water. In other words, achieving more pecan nuts per drop of water.

2.1 Consumptive and non-consumptive water use

All water extracted from a water source for the purpose of irrigation contributes to the consumed and non-consumed fraction at a point downstream of where it was extracted from (Figure 1). This water can be consumed either as a result of the intended purpose (beneficial consumption e.g. pecan tree transpiration) or an unintended purpose (non-beneficial consumption e.g. evaporation and transpiration of understory vegetation). The water that is not consumed remains in the system and can either be recovered and re-used (e.g. flows back into rivers and dams) or is not recoverable (e.g. flows into saline groundwater or out into the sea).

In order to improve water availability in a catchment, the focus should be on reducing non-beneficial consumptive water use and the non-recoverable non-consumed fraction. For a grower, it is also important to try and limit the loss of the non-consumptive recoverable portion of irrigation water, which typically occurs as a result of drainage below the root zone. This is particularly important when this fraction contains fertilizer that not only represents a cost for the grower but also a potential source of pollution for water sources in the catchment.

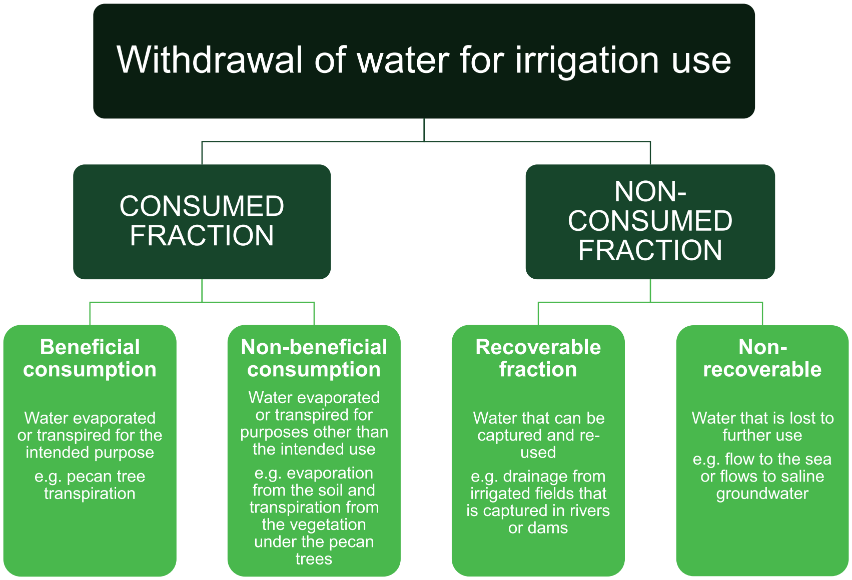


Figure 1. The water balance framework for irrigation management.

In addition, not all the water extracted from a dam or canal or river reaches the root zone of a pecan tree, with numerous losses occurring along the supply line, which can be as a result of leaks in the system. The water which reaches the root zone and is used for the intended purpose of tree water uptake is referred to as the **beneficial water use** component. If water is to be managed optimally in an orchard, this component should be maximised, which means supplying the water efficiently to the root zone at the ***right time*** in the ***right quantity***. Irrigation efficiency is not only about the irrigation system design and irrigation system used (e.g. micro-sprinkler vs drip), scheduling is also very important.

2.2 The orchard water balance

An orchard water balance is based on the principle of conservation of mass (Figure 2) and takes into account inputs and outputs to the system. Irrigation (I) and rainfall (R) add water to the root zone of crops, whilst this water can be lost via transpiration from the plant canopies (T), as soil evaporation (E_s), surface runoff (RO) and deep percolation (DP). A water balance is similar to a bank balance with 'deposits' and 'withdrawals' of water from the soil water 'bank'.

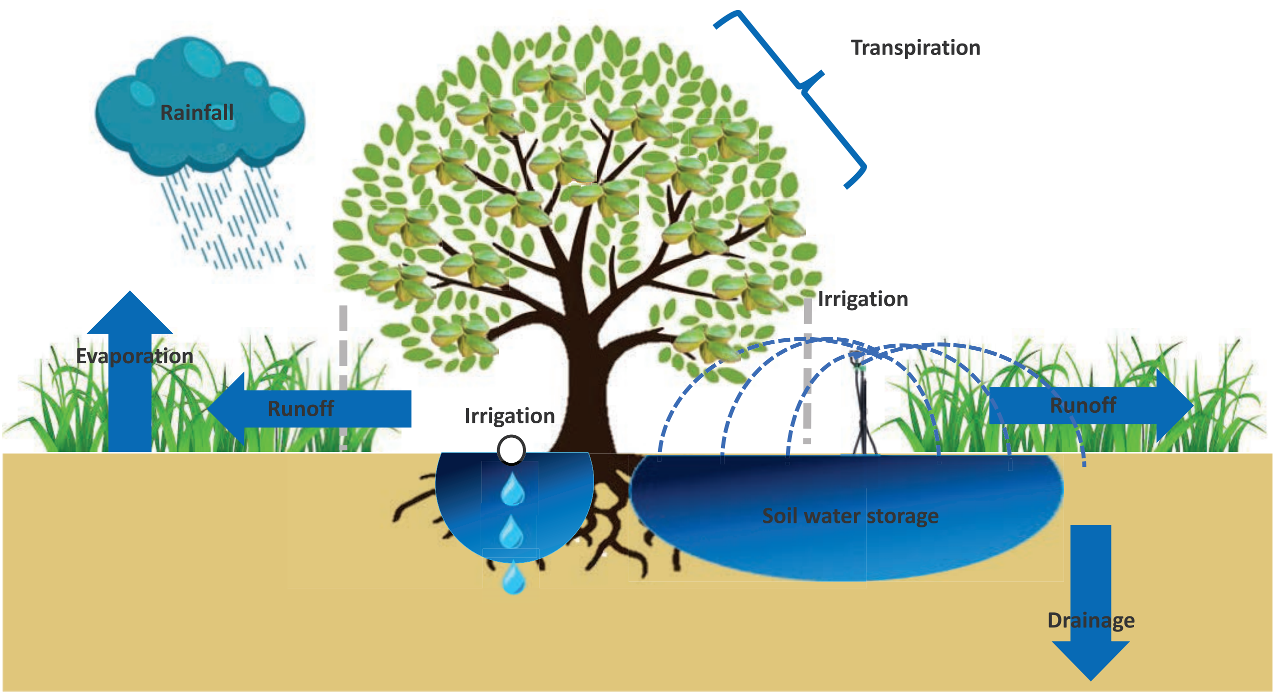


Figure 2. A pecan orchard water balance showing inputs and outputs to the system.

The sum of transpiration and soil evaporation components gives the evapotranspiration (ET) which can be determined with the following equation:

$$ET = I + R - RO - DP \pm \Delta\theta \qquad (1)$$

where Δθ is the change in the soil water storage in the root zone, RO is runoff and DP is deep drainage, which is normally considered to be negligible in most cases. Runoff and deep percolation need to be minimised, while soil water storage needs to be maximised. In order to do this, the volume of irrigation water applied should not exceed the soil water storage of the root zone. Good irrigation scheduling involves applying the correct amount of water at the correct time. Irrigation needs to be done when readily available soil water is depleted and before the onset of plant stress.

Different irrigation systems have different system efficiencies and these need to be accounted for during irrigation system design. Irrigation efficiency is defined as the **ratio of the net irrigation requirement to the gross irrigation demand**. Gross irrigation demand takes into account the assumed in-field losses, which include spray evaporation and wind drift, in field conveyance, filter and other minor losses.

Net irrigation requirement refers to the planned water volume that needs to be supplied to the crop. Losses and efficiencies of different irrigation systems that can be used in pecan orchards are detailed in Table 1.

Importantly, in order to achieve these efficiencies the system must be operating optimally and managed carefully. Through the comparison of the values in Table 1 with in-field measured values, significant water loss components can be identified and improvements can be made. Notably, low crop yields caused by uneven irrigation across a field, as a result of poor system uniformity, are unlikely to be corrected by applying more water. In this case the uniformity of the system must first be improved.

Adopting the approach of 'measure, assess, evaluate and improve' should be used in conjunction with the water balance of an orchard to improve irrigation efficiency. No matter what your system it is important to be quantitative with irrigation. Record volumes applied and measure changes in either soil water content or soil matric potential (described in section 4.1). It is also important to know maximum daily crop water requirements and how much water is required for a season when selecting the best system to use and to design the system.

The changing water requirements of an orchard from establishment through to maturity also need to be taken into account. Both canopy size and rooted volume will change over this time and if over irrigation is to be avoided when the trees are young and under-irrigation when the trees are mature, care needs to be taken when choosing the delivery rate of the irrigation system.

Table 1 Default irrigation system efficiencies (Reinders, 2010; Reinders, 2022)

	Losses				Default system efficiency (net to gross ratio)	
Irrigation system	Non-beneficial spray evaporation and wind drift (%)	In-field conveyance losses (%)	Filter and minor losses (%)	Total losses (%)	Min (%)	Max (%)
Drip (surface and subsurface)	0	0	5	5	90	95
Microsprinkler	10	0	5	15	80	85
Flood: piped supply	0	0	5	5	80	95
Flood: lined canal supplied	0	5	5	10	70	90
Flood: earth canal supplied	0	12	5	17	60	83
Sprinkler permanent	8	0	2	10	75	90
Sprinkler movable	10	5	2	17	70	83
Travelling gun	15	5	2	22	65	78

The next important consideration is the distribution uniformity of the water. This is important because if water is not uniformly applied to an orchard, there will be areas that will be over-irrigated and areas that will be under-irrigated. Irrigation systems need to be assessed routinely for distribution uniformity. Flood irrigated orchards may have areas receiving less water as a result of changes in slope in the orchard. In micro-sprinkler irrigated orchards distribution can differ as a result of changes in pressure in the system, clogged emitters and broken emitters. Drip systems can be quite easily blocked and regular maintenance is required to ensure that drippers remain functional and deliver the correct amount of water. Regular inspection of irrigation systems is therefore important to prevent over or under-irrigation throughout an orchard.

2.3 Flood irrigation

Flood irrigation is relatively easy to use and inexpensive, but can be very inefficient. There is a low initial investment as expensive equipment is not required, which means it can be a cost-effective technique for growers with limited resources. As water is moved by gravity, there is no need for pumps which require electricity or diesel. Run-off water can be recycled to improve efficiency. However, as a large surface area is wet during irrigation events evaporation rates from the soil surface can be very high, with increased runoff. It can also lead to uneven distribution of water over a field due to the uncontrolled nature of application. This problem is exacerbated when there are changes in soil texture within an orchard. Labour is required as levees need to be built and broken down in preparation for irrigation and after irrigation. The orchard also needs to be levelled to ensure even distribution of water throughout the orchard. Soil water content can go from saturation immediately after flooding to a deficit which results in some plant stress, depending on time between events. Due to the large volume of water applied, erosion can be a risk.

Figure 3. Flood irrigated pecan orchard. The black arrow shows the earth levees that need to be constructed to keep water within the basins surrounding a tree.

2.4 Micro-sprinkler irrigation

Micro-sprinkler systems allow for both localised and full-surface irrigation and, compared to drip systems, they are able to wet a much larger volume of soil very uniformly (Figure 4). As a larger volume of water is applied in each irrigation event, there is typically a greater soil water depletion between irrigation events than drip irrigation systems. This creates some room for rain in between irrigation events. As a result, this system typically allows for easier management of irrigation. While it is easier to identify emitter blockages, micro-sprinklers are more easily damaged than drip lines and therefore have higher maintenance costs. This system requires regular checks to ensure system uniformity.

An important part of irrigation system maintenance is checking operating pressures. If pressures are higher than the recommended operating pressure over application will result, but if the pressure is lower than recommended, then under application will result. Checking application rates from individual micro-sprinklers can help identify potential pressure problems across an orchard. It is also difficult to work in an orchard when irrigating. As a larger area is wet by irrigation, evaporation losses are higher than drip systems and run-off from the soil surface can occur. In very windy areas, spray drift can be a serious problem impacting irrigation uniformity. As the micro-sprinkler can supply a fairly large volume of water within a limited time, it is important to match delivery rate with the infiltration capacity of the soil to avoid run off and ensure water infiltration into the root zone, but not beyond the root zone.

The wetted diameter and distribution from the micro-sprinkler should also match the size of the root zone (Figure 4). As pecan trees are small initially, but very large when mature, choose a micro-sprinkler where the wetted diameter can be changed to match the size of the root system. When choosing the droplet size of the micro-sprinkler the environmental effect and crop type needs to be considered. Small droplets evaporate easily and can increase humidity in the canopy, creating a cooling effect. Larger droplets are able to penetrate through dense foliage covering the soil, as a result of a greater energy. When selecting a micro-sprinkler choose the largest possible nozzle opening to prevent clogging and with insect protection.

Figure 4. A typical micro-sprinkler.

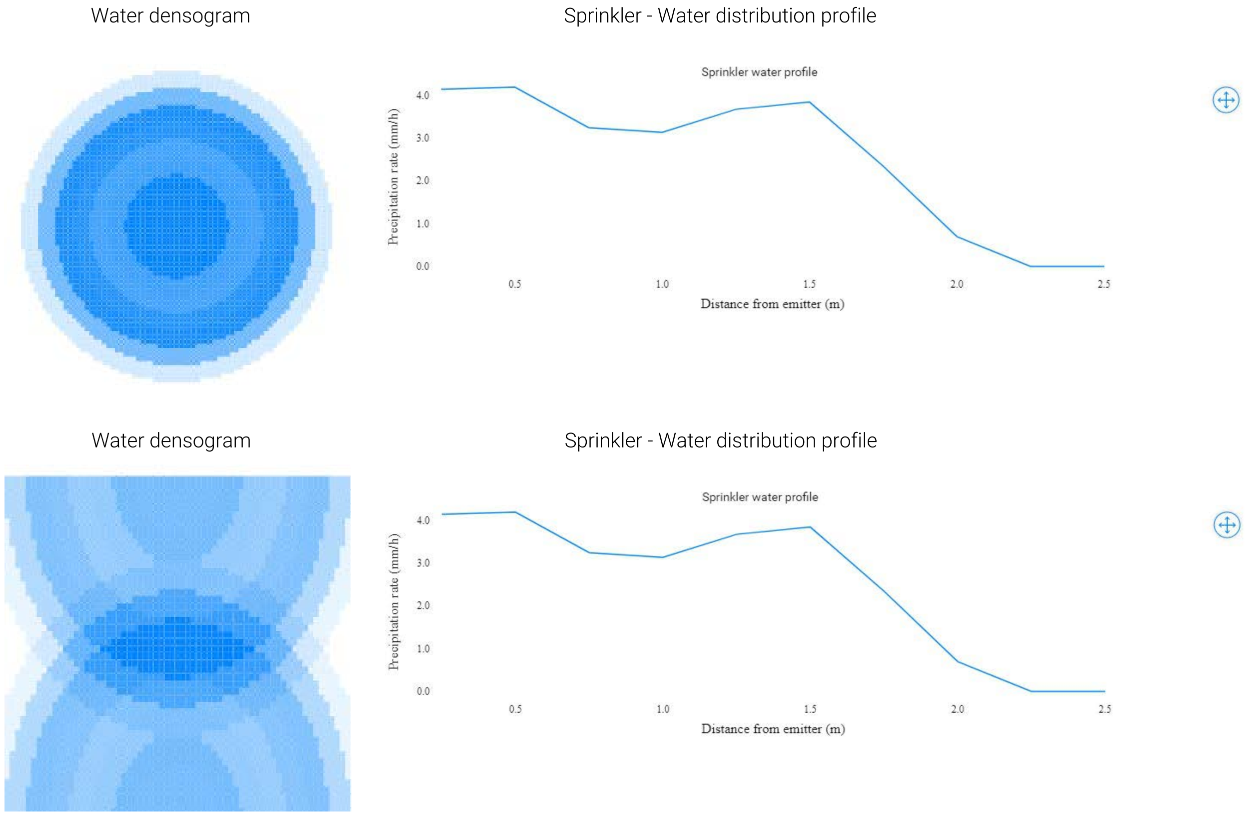
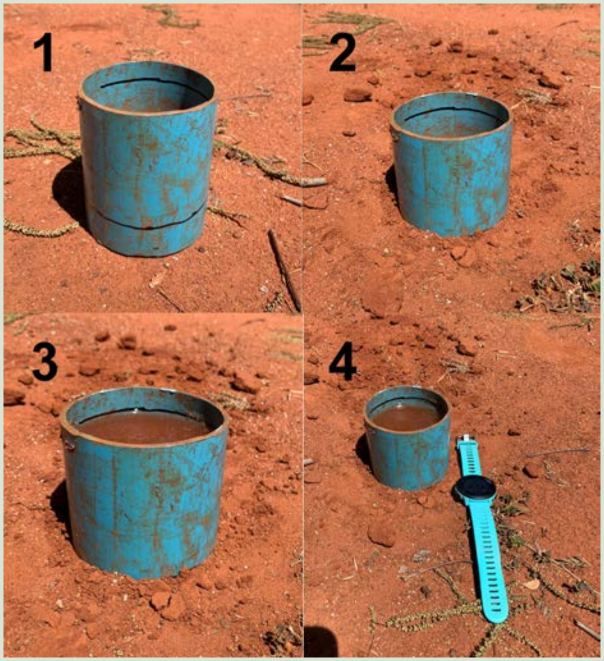


Figure 5. Examples of water densograms from sprinklers and water distribution profiles from a sprinkler. Data was generated from Netafim's NetSpeX™ website.

Determining water infiltration rates

Basic infiltration tests are easy to perform and replicate across your orchard. If soil texture changes or soil structure then the test should be replicated. All you need is a section of PVC pipe (20 cm high and 10 cm in diameter in this example, but any pipe will work if you know the dimensions), a hammer, a block of wood, water and a timer.

- Mark the outside of the PVC pipe at 10 cm and on the inside 2 cm from the top.
- Hammer the pipe into the soil up to the 10 cm mark on the outside of the pipe, making sure it is level.
- Fill the cylinder with water up to the mark on the inside of the pipe (2 cm from the top of the pipe).
- Time how long it takes for the water to infiltrate into the soil.



In order to determine the infiltration rate, the volume of water added to the cylinder needs to be determined in mm and the cross-sectional area of the pipe needs to be determined. The volume of the pipe can be calculated as

$$\text{Volume} = \pi \times \text{radius}^2 \times \text{height}$$

For a 10 cm diameter pipe that is filled to 8 cm, the volume of water will be 628 cm^3, which is equivalent to 0.628 L of water. The cross sectional area of the pipe can be calculated as

$$\text{Area} = \pi \times \text{radius}^2$$

For a 10 cm diameter pipe the cross sectional area is 78.5 cm^2 which is 0.0078 m^2. The depth of water added or mm can then be calculated by dividing the volume in L by the area in m^2 (0.628 L / 0.0078 m^2 in this example). The depth of water in the pipe was 80 mm.

If it took 30 min for the water to infiltrate into the soil, then the infiltration rate is 80 mm/0.5 h, which is 160 mm/h. This value can then be compared to application rates from micro-sprinklers.

The infiltration rate will depend on soil texture and soil structure (the arrangement of soil particles). Soil structure is altered by compaction, which will slow down infiltration rates. The grower therefore has some control over infiltration rates and good soil preparation will ensure good water infiltration and a well-drained profile. Water will infiltrate a dry soil faster than a wet soil. This means that during irrigation events water will infiltrate fast at first and then slow down as the profile fills up with water. If the infiltration rate is exceeded water will run off the surface if there is a slope or pool on the surface.

2.5 Drip irrigation

Water application rates of drip systems can vary from 0.7 to 20 L/h. Due to low application rates and localised water application, only a limited part of the soil is wet and this is targeted to the rooted volume. Water leaving the dripper flows into the soil profile by capillarity and gravity forces and the surface wet by irrigation is limited by factors determining the horizontal flow of water. Drip irrigation allows soil water content to be maintained closer to field capacity for a longer period of time. Irrigation frequency is usually higher than micro-sprinkler and can be 2-3 times per week to every day.

Initial set-up costs can be high, and the system can be more challenging to manage than micro-sprinklers. Maintenance to avoid clogging of drippers is essential, as once a dripper is clogged, flow cannot easily be restored. Filtering water is critical for water sources containing sediments to avoid clogging of drippers. It is not necessary to level fields, where land preparation is key for flood irrigation. Energy savings can be achieved as drip system operate at lower pressures than micro-sprinkler systems. When selecting a dripper, consideration should be given to delivery uniformity and efficiency, together with resistance to clogging. A good combination of these will generally lead to increased cost but the investment should pay off in the long run. For orchards that are sloping, choose a pressure compensated dripper. Heavy wall dripper lines are more suited to long term installations, as they offer greater resistance to damage and can withstand varying pressure. Water usage can be reduced if scheduled correctly, as a result of lower evaporative losses. As a smaller surface area and a smaller soil volume is wet by drip irrigation systems (Figure 5), weed growth in orchards with drip irrigation systems is reduced, especially in low rainfall regions. Fertigation is also ideally suited to drip irrigation systems. Wetting patterns of different drip delivery rates in different textured soils should also be considered when scheduling drip irrigation (Figure 6 and Figure 7).

Figure 6 and 7. Surface wetting by drip irrigation system

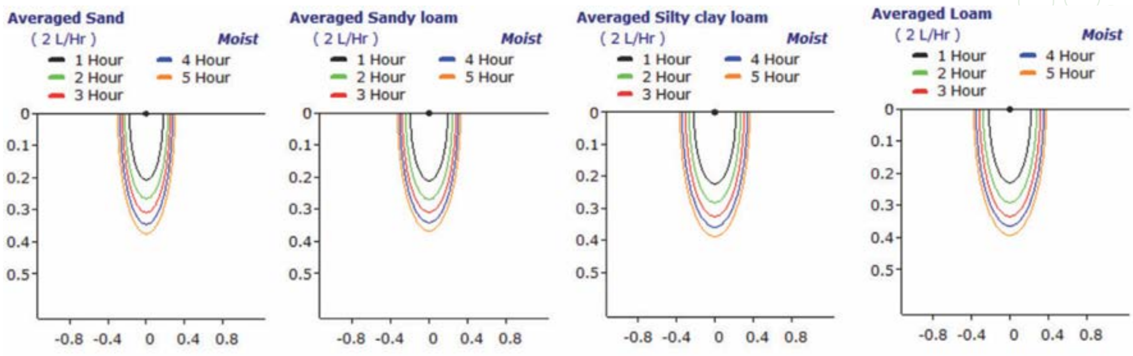


Figure **7.** *Wetting patterns in different textured soils from a 2 L h^{-1} dripper run for 5 hours*

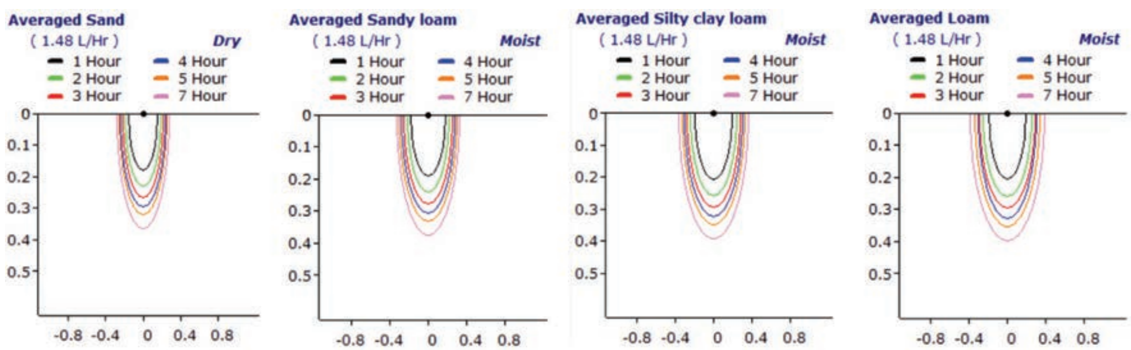


Figure 8. Wetting patterns in different textured soils from a 1.48 L h^{-1} dripper run for 7 hours.

2.6 Irrigation water and soil salinity

All irrigation water contains dissolved salts which over time build up in the root zone. The rate at which salts accumulate and the nature of the salts depends on the source of irrigation water and the quality thereof. If these salts are allowed to accumulate in the root zone, they can impact orchard production and reduce yield. This is because the build-up of salts in the soil creates an osmotic stress, making it harder for roots to extract water from the soil. A similar effect to a water deficit stress, but salts accumulating in the tree can also be harmful. Leaching is an important practice to remove salts from the root zone. This can either be achieved through increasing irrigation volumes or through rainfall. In areas where irrigation water contains considerable salts and rainfall is low, irrigation volumes may need to be increased to ensure sufficient salts are leached out of the root zone. However, if there is a low concentration of salts in the irrigation water and it is a high rainfall area, rainfall may be sufficient to leach salts out the root zone.

For more information on South African irrigation water quality guidelines visit NB Systems and download ***SA Water Quality Guidelines for Irrigation (IrrigWQ)***.


03

PECAN ORCHARD WATER REQUIREMENTS

Orchard water use or evapotranspiration (ET) is the sum of transpiration (T) of the trees and any other vegetation in the orchard and water lost from the surface as a result of evaporation (E). As explained above it is important to maximise transpiration, whilst if water is to be used more efficiently, the evaporative component should be reduced. Traditionally irrigation should replace the full ET requirements of the crop, which means estimates of ET are required for irrigation management and scheduling.

3.1 Measured daily and seasonal transpiration, evaporation and evapotranspiration of pecan orchards

Daily and seasonal estimates of orchard water use are very important for irrigation system design, irrigation planning, irrigation scheduling and the validation of water licenses. In South Africa, water use of three orchards has been measured over a number of seasons. These orchards were all mature orchards, with slightly different fractional canopy cover, different irrigation systems and different orchard floor management strategies (Figure 9 and Table 2). Average values over three seasons in Cullinan (Gauteng), five seasons in Vaalharts and four in Groblershoop (both Northern Cape) are presented in Table 2. It is important to note that these are average values and there were considerable differences from year to year, especially in the Northern Cape. In Cullinan T varied from 846-888 mm, ET varied from 985 – 1050 mm and ET_o from 945 – 1035 mm. In Vaalharts T varied from 420-705 mm, ET from 930-1210 mm and ET_o from 1290-1575 mm. In Groblershoop T varied from 400-810 mm, ET from 1215-1275 mm and ET_o from 1455-1675 mm.

Evapotranspiration volumes from a mature orchard are critical for irrigation planning and will allow growers to determine the area of land that can be planted to pecans. Maximum transpiration and ET rates are also important for irrigation system design, as systems need to be able to supply this maximum amount of water required by the trees in a day in order to avoid tree stress.

Figure 9. 1) Orchard in Cullinan with weeds growing in between rows, 2) orchard in Vaalharts with a grass cover between rows which is kept short for most of the season, and 3) orchard in Groblershoop which is clean cultivated.

Table 2. Average measured transpiration (T), evapotranspiration (ET) and reference evapotranspiration (ET_o) for three regions (Cullinan, Vaalharts and Groblershoop)

	Cullinan*	Vaalharts#	Groblershoop#
Average maximum fractional cover	0.92	0.73	0.78
Seasonal T (mm)	865	570	550
Seasonal ET (mm)	1025	1055	1245
Seasonal ET_o (mm)	1000	1400	1560
Maximum T (mm/day^{-1})	7.1	4.1	4.2
Average daily T (Nov to April, mm/day^{-1})	3.9	2.4	2.8
Maximum ET (mm/day^{-1})	8.10	9.66	11.11
Average daily ET (Nov April, mm/day^{-1})	4.40	4.36	5.81

**Planted in a triangular planting of 9 m x 9 m x 9 m (142 trees/ha^{-1})*
#Planted at 10 m x 10 m (100 trees/ha^{-1})

The seasonal trend in water use in pecan orchards is clearly shown when assessing monthly total ET (Figure 10). ET was low in orchards at the start of the season in August and steadily increased in September and October, reaching a maximum in December and January. ET then began to decline again, reaching a minimum in June. This trend reflects the change in canopy cover and weather conditions over a season. As the trees come into leaf and summer approaches, water use starts to increase until maximum canopy cover is achieved in January. Towards autumn, when canopy senescence starts and temperatures start to decline, water use decreases. In mature orchards the components of ET (transpiration and evaporation) will also change over the season. At the start and end of the season, when the canopy cover is fairly low, evaporation will be a greater proportion of ET than transpiration, whilst in the middle of the season when canopy cover is high, transpiration will be higher than evaporation.

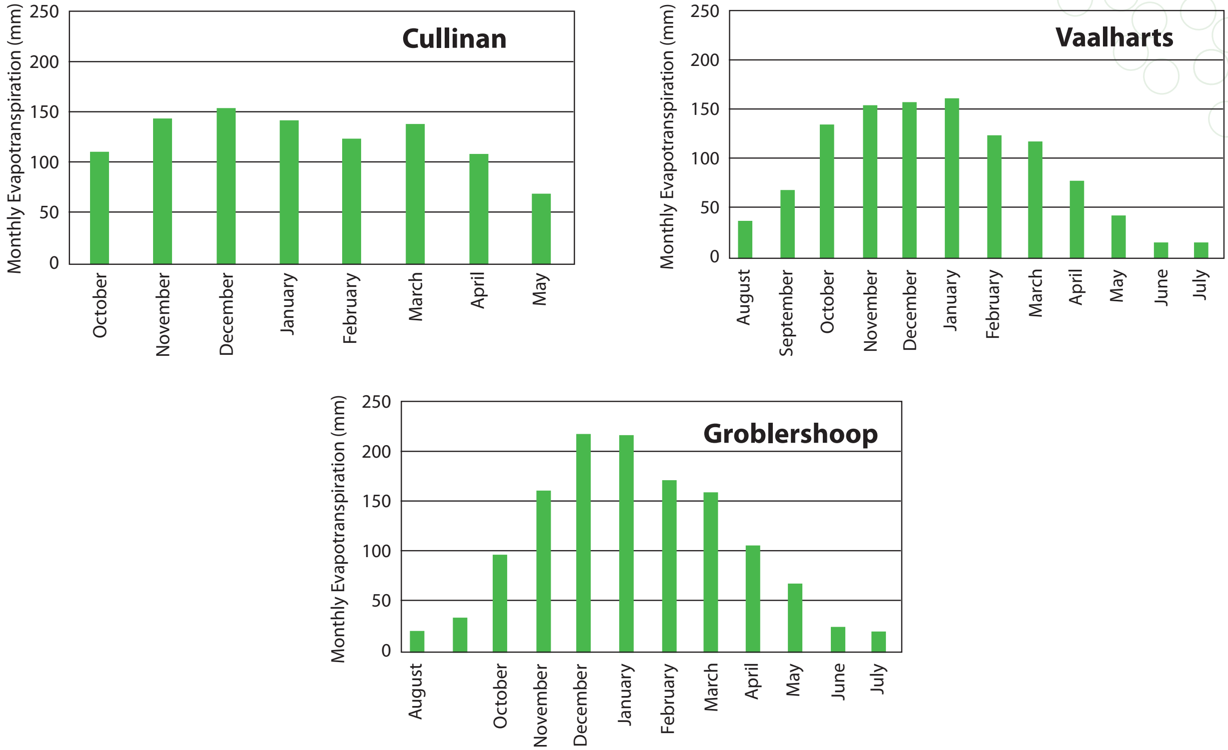
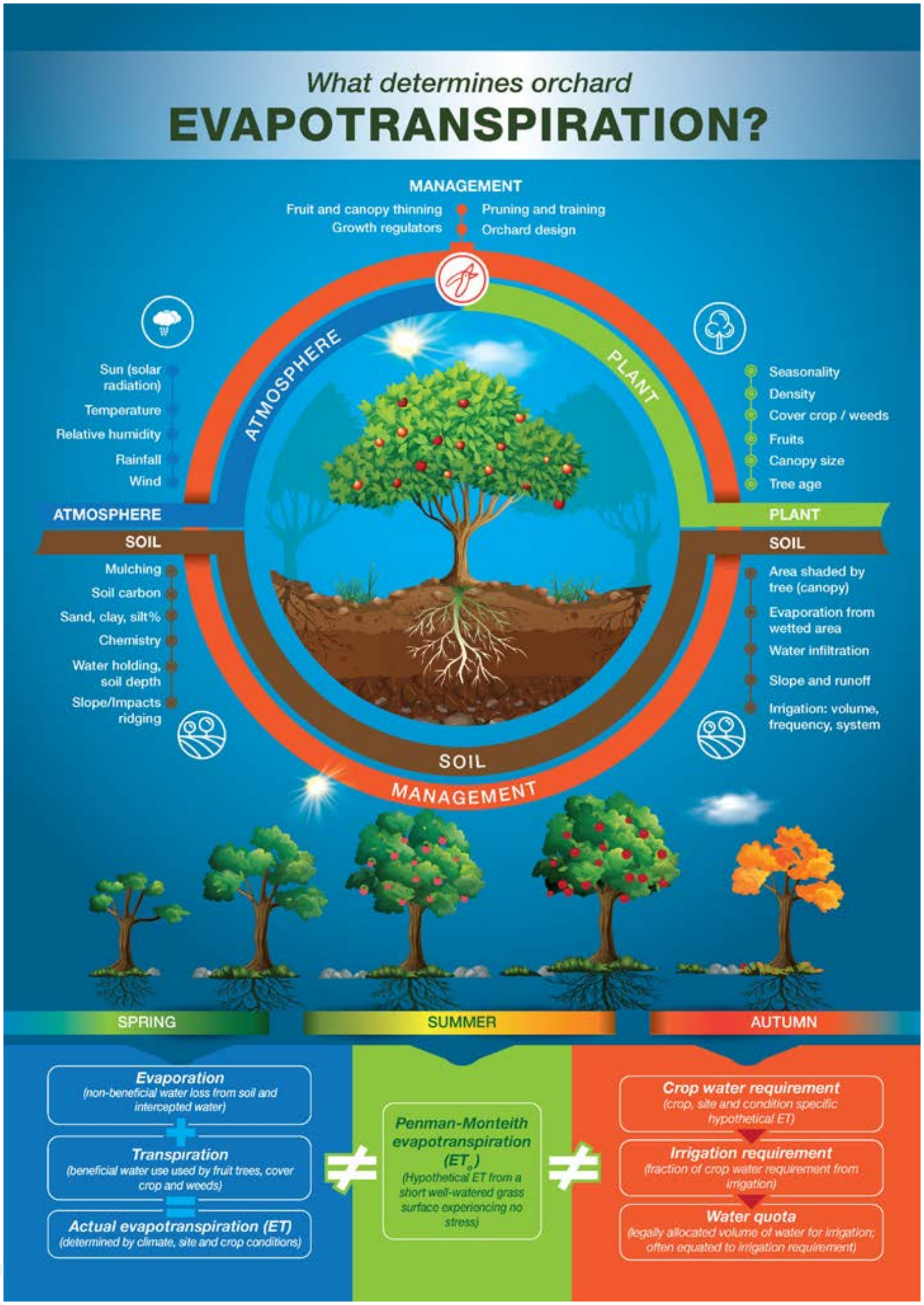


Figure 10. Monthly water use (evapotranspiration) of three mature pecan orchards growing in three different climates. No water stress was detected in these orchards during measurements. Details of the orchards are provided above.

While absolute values are required for water licenses purposes and irrigation planning, requiring the need for average and maximum values, it is clear that water use of an orchard varies quite considerably from season to season and from region to region. This means that irrigation volumes in any two seasons should not be identical and scheduling according to a calendar can result in inefficiencies. A number of factors impact seasonal water use, as summarised below, and these need to be considered, especially for irrigation scheduling throughout a season. Weather conditions is the first factor that explains differences across regions. Evapotranspiration is higher in Groblershoop than Vaalharts and Cullinan, as it is hotter and drier. This is evident when comparing ET_o across regions. The second factor is canopy size, which differs from orchard to orchard and from year to year as a result of pruning strategies.

3.2 Factors determining orchard evapotranspiration

Factors determining orchard evapotranspiration are summarised in the infographic below. The infographic covers the soil, plant atmosphere continuum and the impact of management practices. A number of important definitions are also provided in the infographic. While originally prepared for pome fruit, it applies equally to pecan orchards.



Graphic from Jarmain et al. Report to Hortgro Science (Pome and Stone fruit water use)

3.2.1 Soil water availability

Trees get their water from the soil and any factor which impacts soil water availability will impact the ability of the tree to extract water (and nutrients) from the soil. Understanding factors that impact soil water availability is therefore critical to good irrigation management. Soil is complex and consists of varying proportions of rock particles and organic matter making up the solid matter, the soil solution and air occupying pores (Figure 11).

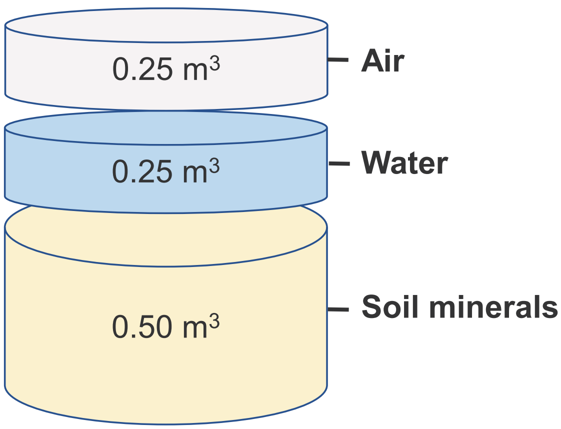


Figure 11. Soil constituents in a known volume of soil. All the components total 100%. Since volumetric water content (VWC) equals the volume of water divided by the total volume of soil, the VWC in this example would be 25%.

Transpiration of trees and evaporation from the soil is dependent on available soil water. Too little water will lead to a soil water deficit stress, whilst too much water can also lead to a stress as a result of anaerobic conditions (reduced oxygen availability) developing in a waterlogged soil. How can a grower determine if the soil has too little or too much water in it? Soil texture is key to understanding the availability of water in the soil for plants. Soil texture is determined by the ratio of sand to silt to clay as illustrated in the soil texture triangle in Figure 11 (Figure 12).

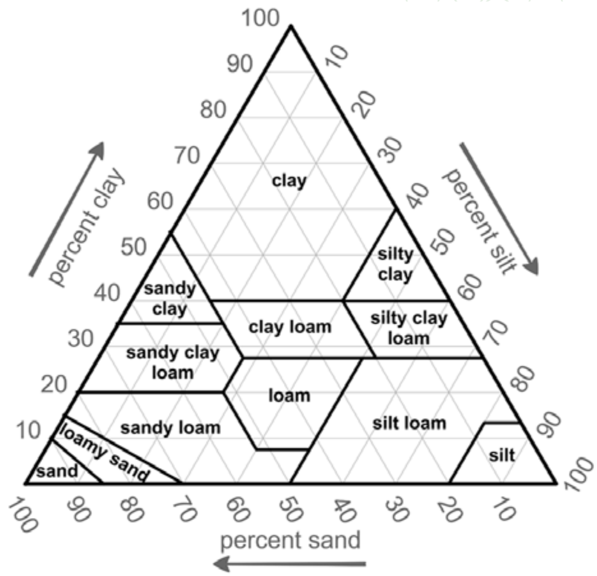


Figure 12. Soil texture triangle.

Clay soils are compact and are often poorly drained and aerated, but due to large internal surface areas these soils can store large volumes of water and minerals (high cation exchange capacity). Sandy soils are loose, well drained and well aerated, but have limited storage capacity for water and minerals. Loam soils are intermediate with respect to drainage, aeration and water and mineral storage capabilities. In general, soils with a high clay content have higher water and mineral storage capacity than sandy soils, but have lower aeration required for good root growth and functioning. As a result, the clay fraction is often an important indicator of whether the soil will be suitable for plant growth. The presence of a large amount of organic matter in the soil will increase the water holding capacity and cation exchange capacity. Increasing organic matter in a sandy soil will have a positive effect on profile water holding capacity. Increasing organic matter content from 0.2 to 5.4% more than doubles the water holding capacity of a sandy soil from 0.05 to 0.12 (v/v).

Soil structure and pore spaces depend on particle size and how the basic particles are assembled into aggregates (Figure 13). Sandy soils typically have larger pore spaces than clay soils, due to the differences in particle sizes. Aggregates form in the presence of root exudates and organic colloids (humus – organic matter that can not decompose further) that are produced by soil microorganisms – these compounds act like glue. In clay soils the formation of stable aggregates is important for increased pore space, which will aid in infiltration and drainage and aeration in the soil. Through root exudates plants are able to encourage the formation of soil aggregates thereby altering the soil hydraulic properties.

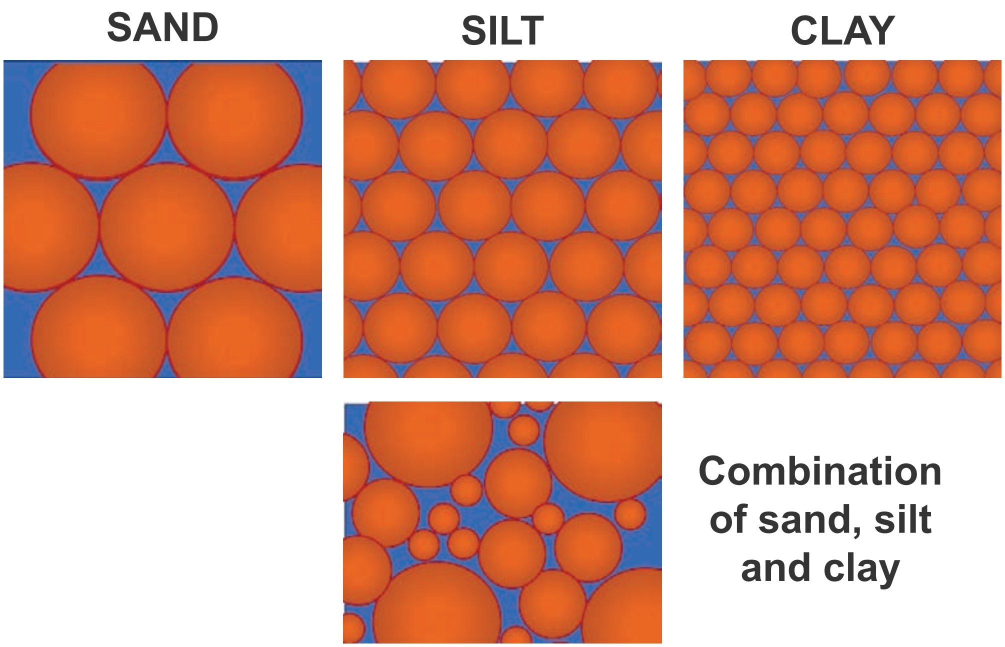


Figure 13. Variation in particle sizes and how this impacts pore space in a soil. Also note the varying surface area around different sized particles – the smaller the particles the greater the overall surface area.

Factors which impact soil structure of clay soils and break up aggregation can reduce infiltration, drainage and aeration considerably. Traffic over the soil (e.g. tractors and vehicles) and cultivating the soil when wet can result in ***soil compaction***. In arid regions irrigation with alkali water (as a result of carbonates and bicarbonates) can result in flocculation (precipitation) of soils. This all results in a reduction in the bulk density of soils, which is defined as the dry mass of soil divided by its volume. As a result, water infiltration and aeration are impacted in these soils.

In order to understand the relationship between soil water content and the water available for plant uptake, it is important to define soil water content and soil matric potential.

Gravimetric soil water content (w) is the mass of water per mass of soil (grams water per grams of soil). It is a parameter that can be measured directly and is the primary method for measuring soil water content. It can be determined experimentally by taking a sample of soil and weighing it immediately (wet mass - M_{wet}) and then drying it and determining the dry mass (M_{dry}) of the soil. It can then be calculated as:

$$w = \frac{M_{wet} - M_{dry}}{M_{dry}}$$

Volumetric water content (VWC or θ) is the volume of water per total volume of soil. It is very similar to gravimetric water, but is rather reported on a volume basis. This is the value often used by growers to schedule irrigation using capacitance probes. It is calculated as:

$$\theta = \frac{V_{water}}{V_{soil}}$$

Gravimetric and volumetric water content are linked by bulk density (ρ_b), where

$$\theta = w \times \rho_b$$

Therefore, if you can determine gravimetric water content experimentally, you are able to determine volumetric water content if you know the bulk density. Bulk density is the dry mass of the soil divided by the volume.

Soil water potential (Ψ_{soil}) depends on three main components varying in importance:

$$\Psi_{soil} = \Psi_m + \Psi_s + \Psi_g$$

Where Ψ_m is the matric potential of the soil produced by capillary and surface-binding forces, Ψ_s represents the osmotic potential produced by solutes in the soil water and Ψ_g represents the gravitational forces operating on soil water, which is important for drainage. Matric potential is the most significant component in the soil, because it relates to water adhering to the soil surfaces. A water potential gradient is the driving force for water flow in soil and soil water potential is the best indicator of plant available water. What this equation also tells us, is that when salts are added to the soil, the osmotic potential of the soil drops, which in turn lowers the total soil water potential. The accumulation of salts can therefore make it more difficult for roots to extract water from the soil.

Figure 14 shows soil water retention curves for different textured soils. It clearly demonstrates the relationship between soil water content and soil matric potential. The availability of water in a soil depends on the volume of water stored in the soil and its relationship to soil water potential. This will depend on the soil texture and the size of the pore spaces.

The vastly different soil water contents are clearly seen for the different soil textures at the same matric potential. This information is important for setting refill points for irrigation when using instruments such as tensiometers, which measure soil matric potential. In a sandy soil there is very little water in the soil at a matric potential of approximately -1 bar or -100 kPa, whilst in a clay soil there is still water available at -1 bar or -100 kPa. The refill point is therefore set at a higher value for sandy soils than clay soils. In addition, it can be seen that even though there is 20% (volume basis) of water available in a clay soil at -16 bar (-1600 kPa) this water is not available to plants.

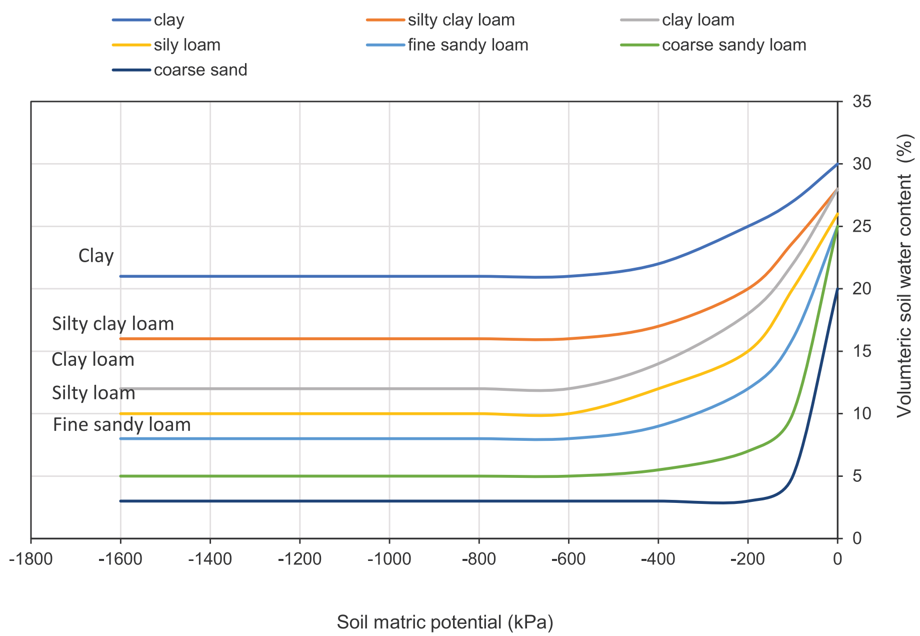


Figure 14. Soil water retention curves for different textured soils.

Knowing soil water content values of field capacity, permanent wilting point and as a result plant available water for the soils in a pecan orchard is very important for scheduling irrigation using soil water measurements. Volumetric water content at each point depends on soil texture, however, soil matric potential values for these points are more consistent, with permanent wilting point often depending on how well a plant can extract water from a drying soil.

Capillary pores are small pores (pores of between 30 – 60 µm or less) that can hold water against the force of gravity. This determines the ***field capacity*** of a soil or the amount of water retained in the soil following irrigation or rain. Capillary water is of the utmost importance to plants, as this is where plants access most of their water from. These small pores or capillaries generate very negative pressures (large suction tension). Very small pores (< 0.2 µm) hold water very tightly and it is very difficult for plants to extract water from these pores. Non-capillary pore space is the fraction of the soil volume from which water drains by gravity. This is the pore space that is critical for aeration in the soil required for root growth.

Almost 50% of any soil volume is pore space, but the ratio of capillary to non-capillary pore space will differ between soils, depending on the texture and the degree of compaction. A long history of cultivation can damage soil structure and result in a decrease in the non-capillary pore space, resulting in reduced aeration.

A soil is saturated if all the soil pores fill with water and there is no air left in the soil. A saturated soil can be easily determined by taking a soil sample in your hands and squeezing it. If muddy water is squeezed out of the soil, then it is saturated. Field capacity is defined as the water content in the soil after the soil becomes saturated, followed by complete drainage as a result of gravity. It is also referred to as the drained upper limit or upper storage limit. In most soils this point is between -10 and -30 kPa (-0.01 to -0.03 MPa) (Figure 15). The lowest water potential at which a plant can access water from a soil is referred to at the permanent wilting point (PWP or lower storage limit), because it is at this point that a plant will start to wilt due to a loss of turgor. In between the permanent wilting point and field capacity lies the plant available water. Irrigation is often set to occur close to ***50% depletion*** of plant available water. At a soil water content below this point plants typically start to experience a soil water deficit stress.

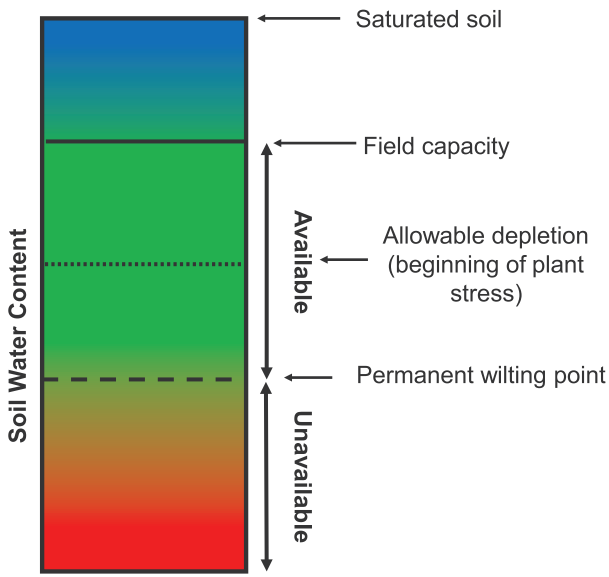


Figure 15. Soil water content from saturated to dry in relation to optimal levels for plant growth.

Volumetric water content at field capacity varies with soil texture (Figure 16), with field capacity in a sandy soil being at a considerably lower soil water content than a clay soil. At field capacity the volumetric soil water content may be 40% for a clay soil, but only 15% for a sandy soil. This again clearly shows the impact of particle size. The PWP is also much higher in clay soils than sandy soils, as in clay soils there are a number of very small pores which hold water very tightly. Permanent wilting point varies between -1000 to -8000 kPa (-1.0 to -8.0 MPa). A permanent wilting point of -1500 kPa (-1.5 MPa) is common for most herbaceous species. Permanent wilting point will differ between species depending on how well the plant can extract water from a drying soil. Also note how plant available water differs between different textured soils – it is typically higher in clay soils than sandy soils.

The importance of understanding the relationship between volumetric water content, soil matric potential and plant available water is demonstrated in Figure 17. Despite a higher volumetric water content in the clay soil than the sandy soil, the matric potential was very close to permanent wilting point in the clay soil. If only volumetric water content was measured without considering soil texture it is likely that only the sandy soil would have been irrigated. Measuring soil matric potential is therefore a good indicator of plant available water irrespective of soil texture (soil water measurements are discussed in section 4.1).

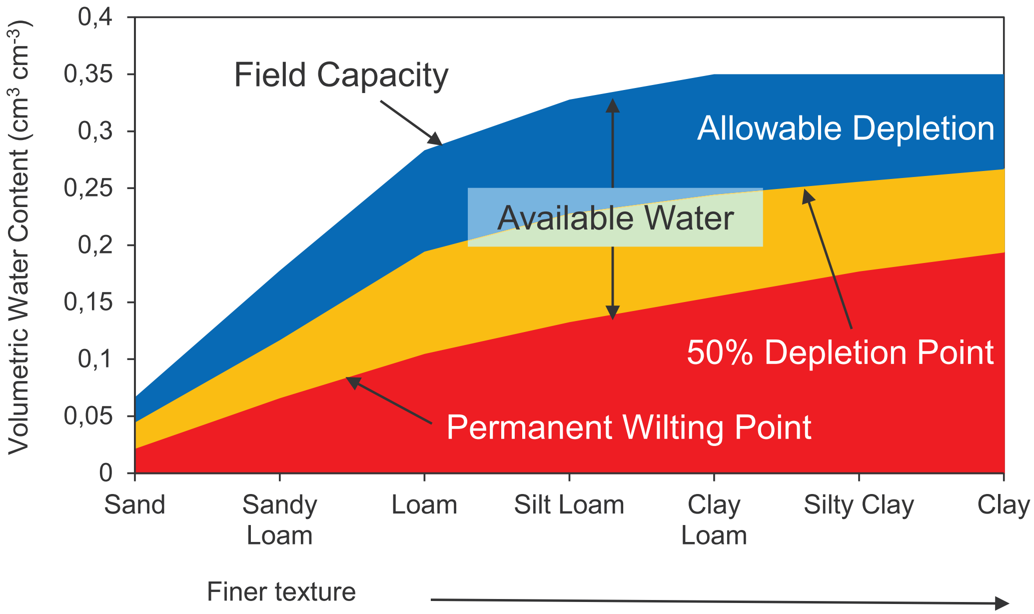


Figure 16. Field capacity (upper storage limit), plant available water and permanent wilting point (lower storage limit) for soils with varying textures. Note how volumetric water content for each point differ with soil texture.

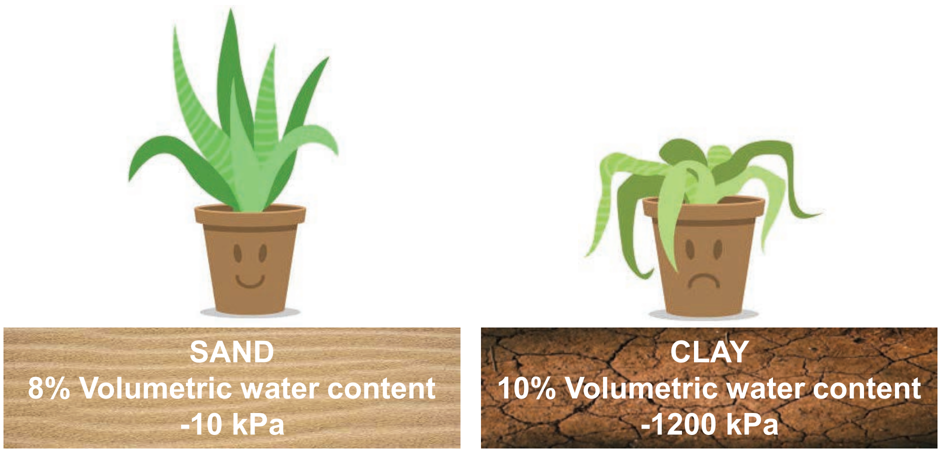


Figure 17 The relationship between volumetric water content and soil matric potential (kPa) for a sand and clay soil and the impact on plant water status.

3.2.2 Weather conditions

The impact of weather conditions on atmospheric evaporative demand and therefore tree water use is well summarised in the Penman-Monteith equation, which is used to determine reference evapotranspiration (ET_o) from weather variables. Typically, ET_o represents evapotranspiration from a hypothetical short grass surface, which is well watered and grown under optimal conditions. The equation uses variables measured by an automatic weather station and includes solar radiation, air temperature (T_a), vapour pressure deficit (VPD; e_s-e_a) and windspeed (u_2). Typically, water use will be higher on hot and dry days, with high windspeeds and lowest on cool and humid days, with low windspeeds. Net radiation (R_n) and soil heat flux (G) are calculated from solar radiation measurements. Δ is the slope of the vapour pressure curve (shows the relationship between temperature and vapour pressure, which is the tendency of water to become vapour) and γ is the psychrometric constant (relates the partial pressure of water in air to air temperature) (Allen et al., 1998).

Reference evapotranspiration (ET_o, mm day^{-1}) is estimated using the Penman-Monteith (FAO-56) equation (Allen et al., 1998) as follows:

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{T_a + 273} u_2\,(e_s - e_s)}{\Delta + \gamma\,(1 + 0.34\,u_2)}$$

As ET_o increases the evaporative demand increases and the water potential gradient for water loss out of the leaf increases. In theory, if leaves can supply the volume of water demanded by the atmosphere, the transpiration rate should increase at a similar rate to the increase in ET_o. However, although transpiration of pecan trees increases in hot and dry conditions, this increase is not always at the same rate and as it gets even hotter and drier (as indicated by increasing VPD or dryness of the air) transpiration rates start to plateau (Figure 18). As a result, pecan trees do not use more and more water as it gets hotter and drier. When scheduling irrigation based on weather data this needs to be kept in mind.

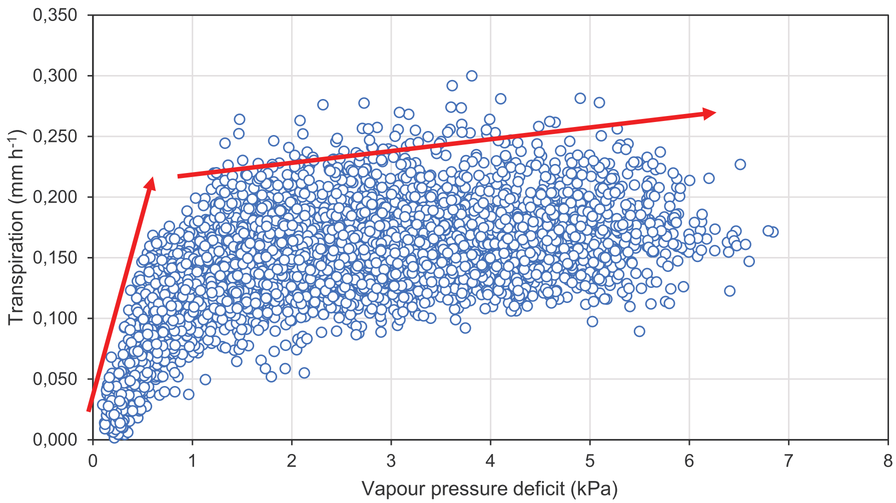


Figure 18. The relationship between hourly transpiration and vapour pressure deficit for 'Wichita' trees in Groblershoop.

3.2.3 Tree factors

3.2.3.1 Canopy size – tree age, seasonal changes, pruning and cover crops

The size of the transpiring canopy plays a big role in determining tree transpiration rates. An analysis of 9 seasons of transpiration data from two cultivars, in two orchards in two regions shows a clear relationship between maximum canopy cover in a season and total seasonal transpiration (Figure 19). The variation in seasonal total transpiration in the same orchard was as a result of changes in maximum canopy cover from one season to the next due to tree growth and pruning. The differences in canopy cover as a result of pruning strategy in an orchard is clearly seen in Figure 20. Not all trees in this orchard will use the same amount of water, and this needs to be kept in mind when scheduling – where do I put probes to show maximum extraction rates, so the bigger trees are not under irrigated? Prevailing weather conditions in each season also impacted seasonal transpiration.

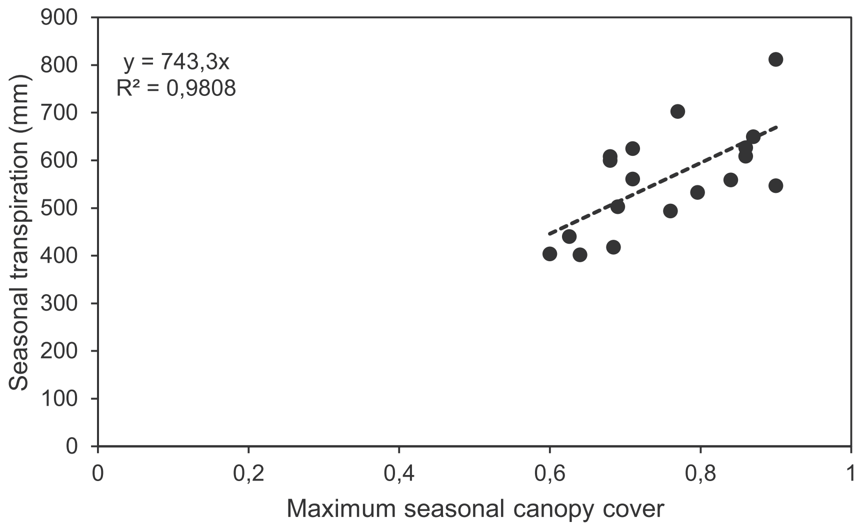


Figure 19. The relationship between maximum canopy cover for a season and seasonal transpiration for 'Wichita' and 'Choctaw' trees in Vaalharts and Groblershoop.

Figure 20. The impact of a four-year pruning cycle on canopy size is clearly visible in this orchard. This will impact seasonal evapotranspiration from an orchard.

Transpiration from cover crops will also contribute to orchard ET, and an orchard with vegetation between rows will have higher ET than clean cultivated orchards. The water use of the cover crop is very difficult to measure and there is little information on this water use in literature. The water use of the cover crop will be impacted by whether the vegetation is mown, how much vegetation is in the orchard (width of vegetated strip and density of the vegetation) the degree of shading of the vegetation by the canopy (the canopy cover) and how much water this vegetation receives via irrigation and rainfall. If full surface irrigation is practiced in an orchard, then vegetation between rows will make a contribution to total orchard ET and this needs to be taken into account when irrigating.

Determining canopy cover

Fractional canopy cover can be defined as the fraction of the ground surface allocated to the tree which is covered by the canopy. A fractional canopy cover of 0.5 in a pecan orchard planted at 10 x 10 m spacing indicates that of the 100 m^2 allocated to the tree, 50 m^2 is covered by the canopy. This can be easily measured at solar noon by determining the area of the shadow that is cast on the soil by the tree divided by the area allocated to the tree in the orchard. All that is required is a tape measure.

Fractional canopy cover as viewed from above a pecan tree

RGB images using a drone can also be used to easily determine canopy cover with software applications such as Canopeo (https://canopeoapp.com/#/login).

3.2.3.2 Physiological control of transpiration

Importantly, it is not just the size of the tree and the prevailing weather conditions that determine tree transpiration volumes. In many tree species there is some form of regulation of transpiration that occurs because a tree is not just a pipe transporting water from the soil to the atmosphere (Figure 22). This is what is observed in Figure 18. Water has to be taken up into the root and this rate is determined by the anatomy of the root and the total length of roots. The water then moves through the xylem to the leaves and, depending on the structure of the xylem and size of xylem vessels, this water encounters different levels of resistances. Finally, when reaching the leaves, water needs move out the xylem – the veins of the leaves – to the point of exit which are the stomata.

Water encounters numerous resistances within this pathway and if the rate of supply to the leaf cannot match the demand from the atmosphere (how hot and dry it is) the stomata start to close to regulate the rate at which water exits the leaves to balance how quickly water is able to enter the leaf. In this way, stomata act as pressure regulators keeping leaf water potential within safe limits for the plant. The rate at which water is transported to leaves from the roots will determine if supply to the leaves can match demand from the atmosphere and if stomata stay open.

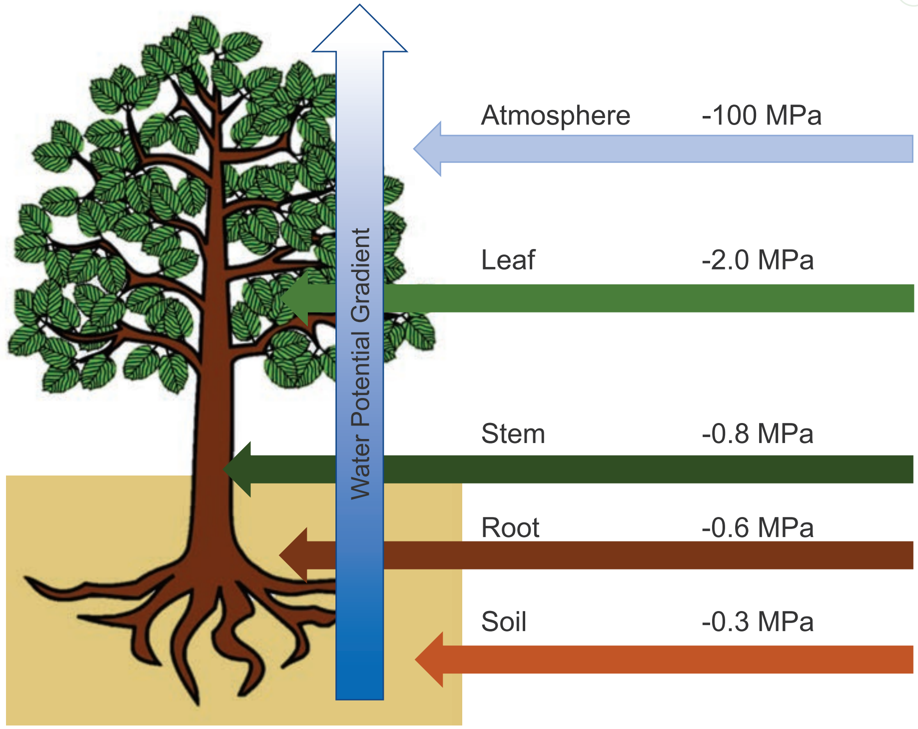


Figure 21. The flow path of water through a tree, with associated typical water potentials, which determines the gradient for water movement through the tree. Water will move from less negative to more negative water potentials.

3.2.4 Factors driving soil evaporation

Soil evaporation rates are determined by the amount of energy reaching the orchard floor (mainly solar radiation but windspeed and VPD at the surface also play a role) and the amount of water in the top soil layer. As a result, the amount of soil shaded by the pecan trees (Figure 23) and the area wet by irrigation and rainfall, and the frequency thereof, determine evaporation rates from an orchard (Figure 24). If soil is frequently wet by irrigation or rainfall then evaporation will occur at a rate that is dictated by prevailing weather conditions, however, if there is an interval between rain and irrigation events, then the top soil will dry out and the limited water available in the top soil layer will reduce evaporation rates.

As canopy cover is fairly low in young orchards, with little shade cast over the area wet by irrigation, evaporation rates can be high and the biggest proportion of ET. Significant water savings in young orchards can be made by reducing evaporation (non-beneficial consumptive water use). The wetted area can be reduced by blocking drippers far away from the tree or using a micro-sprinkler with a smaller radius. The rate of evaporation can be reduced by using a mulch.

Figure 22. Distribution of solar radiation on the orchard floor in an orchard in 1) Vaalharts (left) and 2) Groblershoop (right).

Figure 23. 1) Left: A drip irrigated orchard where only a small area of soil is both wet by the irrigation and exposed to solar radiation, as opposed to 2) Right: a full surface micro-sprinkler irrigated orchard where a large proportion of the area exposed to solar radiation is wet by irrigation. The light grey circles indicate the wetting pattern from irrigation in the exposed area.

3.2.5 Transpiration of understorey vegetation

Transpiration by understory vegetation can also be considered to be non-beneficial consumptive water use, especially if this vegetation receives water from irrigation. Transpiration from this vegetation with contribute to the total ET of the orchard. As a result, orchards with a cover crop will have higher water use than clean cultivated orchards.

It is very difficult to predict the amount of water used by the cover crop, but volumes will depend on the density of the cover, the amount of water received by the cover crop and the energy received by the cover crop. Cover crops are often seen as very beneficial in orchards for a number of reasons. In this case the argument has been made that transpiration from the cover crop should be viewed as beneficial consumptive water use.


04

MANAGING AND SCHEDULING IRRIGATION IN PECAN ORCHARDS

Irrigation scheduling involves applying the correct amount of water at the correct time. In order to do this accurately the application rate of the system needs to be known (mm/h^{-1}) and the distribution uniformity. Keeping good records of irrigation volumes throughout a season is critical for good irrigation management, as well as using an objective measure for deciding on when to trigger irrigation events and how long the event should be.

Pecan orchards in the summer rainfall regions of South Africa will have a rather dry soil profile at the start of spring as a result of dry winters, whilst those in the winter rainfall regions will have a much wetter profile in spring. If possible, in summer rainfall areas, the soil water profile should be filled prior to the start of the season – start with a full 'bank balance'.

4.1 Soil water measurements

Determining the available water in the soil is very important for good irrigation management. The soil stores water (the amount depends on soil texture as explained in section 2.2.1) and this acts as a 'bank account'. Trees 'withdraw' water from this store and irrigation and rainfall 'deposit'" water into the soil. Keeping an account of the soil water balance is therefore important to determine when to irrigate and how much to irrigate. Soil water data can provide valuable feedback as to whether ET scheduling is accurate or not and whether the tree is getting the water it needs. Logging sensors make this process easier and provide useful information on the depletion of soil water by the tree and the replenishment by irrigation. If the soil is showing a drying trend at deeper depths, it is likely that there is under-irrigation, however, if deeper depths get wetter over time, then it is likely that there is over-irrigation. These sensors can act as a 'rudder', steering your irrigation scheduling based on weather in the right direction by allowing for small adjustments. All sensors mentioned below need to be installed correctly in order to provide accurate soil water information.

4.1.1 Soil water content

There are a number of tools available in South Africa to monitor volumetric soil water content continuously. Monitoring soil water content continuously can provide a much better understanding of what is happening in the soil, than a manual measurement every few days, such as with a neutron probe. The most popular continuous logging probes are capacitance probes, which provide a relative measure of volumetric soil water content. As these sensors only provide a relative value for soil water content, they need to be calibrated in order to provide an absolute value, if this is needed. However, for scheduling purposes a relative value can still be used to schedule irrigation events. This involves using experience to set re-fill points for a specific probe and soil combination. The advantage of the sensors is that most sensors have platforms that allow remote access to data on a phone or computer. This allows the data to be included in other software used for farm management. The major drawback of the sensors is often the cost. It is a point measurement and if a probe per soil type or irrigation block is required, then the cost can escalate quite quickly.

An example of capacitance probe data from a drip irrigated orchard (daily irrigation) is provided in Figure 24. Clear responses to irrigation events and the withholding of irrigation are evident.

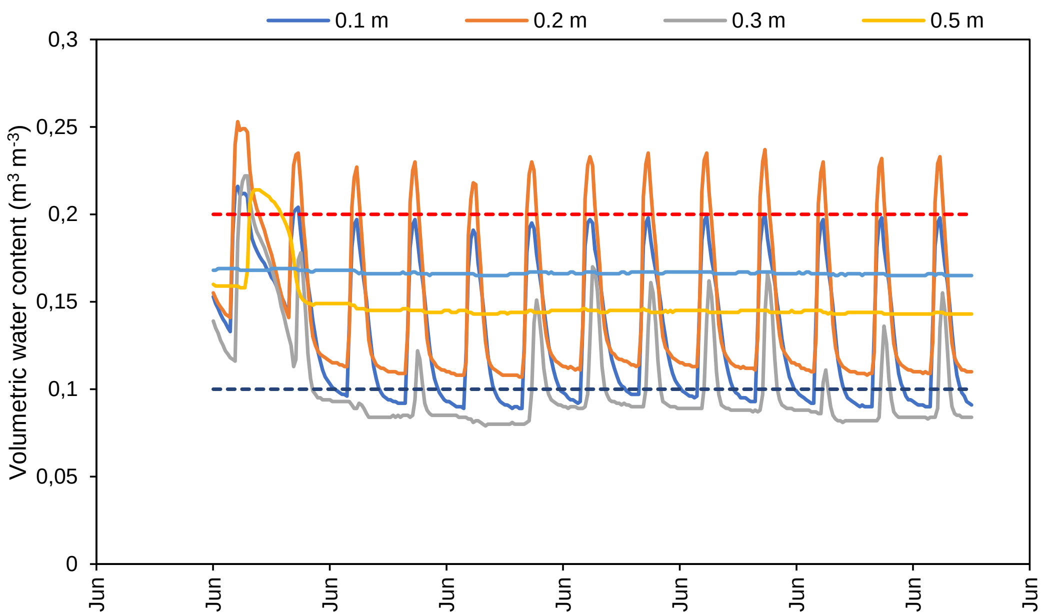


Figure 24. An example of data from a capacitance probe measuring volumetric water content (VWC), expressed as % field capacity (FC). Measurements were made at 100, 200, 300, 400, 600 and 800 mm in a drip irrigated orchard. Clear changes in VWC are evident with every irrigation event in the top 400 mm, with less clear changes at depth. A slight increase at 800 mm (dark blue line) noted over time suggested that irrigation exceeded crop evapotranspiration. Irrigation was stopped towards the end of August to dry out the profile and the reaction at all depths was evident. Data is from an irrigation trial by Tiaan Snyman. The green line is field capacity, the orange is the refill line (set by the grower) and the red is the stress line. The step down in soil water content at the end of the period is tree water use – as withdrawal of soil water by the plant only occurs during the day.

4.2.1 Soil matric potential

Soil matric potential provides an indication of how tightly water is held in the soil and how difficult it is for plants to extract water from the soil. As soil water content declines, the water is held more tightly in the soil and it becomes harder for a plant to extract the water. This measure often provides a better indication of whether or not plants are experiencing a water deficit stress. Instruments to determine soil matric potential include tensiometers and granular matrix sensors (such as gypsum blocks, Watermark sensors and Chameleon sensors). More advanced sensors are available but they are more costly (such as those from the Meter Group).

Tensiometers are often used in orchards for irrigation scheduling, as they provide valuable information on soil water availability at a relatively low cost. Although logging models are available, these are more expensive and as a result manual tensiometers are mostly used, which require someone to manually read the pressure gauge. Tensiometers have a measurement limit of -80 kPa and if this value is exceeded the tensiometer will require refilling, as the water column within the tensiometer would have been broken at these tensions. Maintenance is therefore an important aspect to ensure tensiometers read correctly and continuously. Tensiometers in pairs, one in the root zone and one below the root zone, can provide valuable information about when to irrigate and when to stop irrigating (Figure 25). A similar set-up can be used with the granular matrix sensors, such as the Watermark sensors, which can be read with a handheld logger.

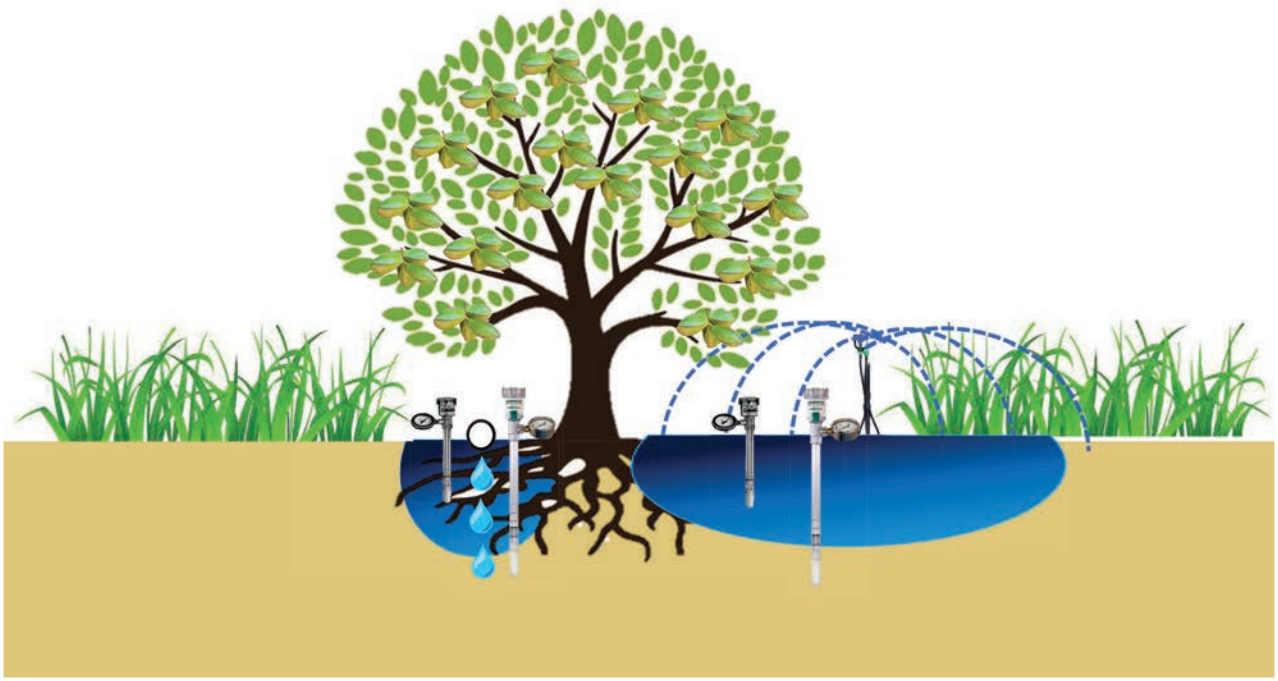


Figure 25. Placement of tensiometers within and below the root zone to trigger irrigation events and to monitor the depth of irrigation. The shallow tensiometer indicates when irrigation should start and the deep indicates when irrigation should stop.

A fairly inexpensive matric potential sensor – the Chameleon sensor – has recently been developed for a wide range of applications (Figure 26). It is called a Chameleon sensor as soil water tension is measured with colours and the sensor's 'colour' changes to match the surrounding soil. Full details of these sensors can be found at the Virtual Irrigation Academy. Each sensor array consists of three sensors, which can be buried at different depths depending on the crop and the type of irrigation system used. When a sensor is 'blue' soil tension lies between 0 and -20 kPa, which means the soil is wet and water is moving within the soil profile. Irrigation is not recommended under these conditions, as leaching of fertilizer is possible. Green indicates a moist soil and lies between -22 and -50 kPa. This indicates sufficient water within the soil profile but water is not moving within the profile. When the sensors is red, soil tension has fallen below -50 kPa and the soil is dry. Irrigation is recommended. It is designed to be a learning tool, that allows growers to learn from measurements and adjust irrigation accordingly.

Figure 26 Chameleon soil water sensors and wifi reader for determining soil matric potential at three different depths.

4.1.3 Placement of soil water sensors

The number of sensors required depends on the uniformity of the soil in an orchard. Usually only one probe will be required for an irrigation block, but if there are soil textural changes within a block then one sensor per major soil type should be considered. This is because of the different soil water holding capacities of different soil textures, which impacts plant available water. A soil survey prior to planting will help identify how to divide the farm into irrigation blocks based on soil texture and soil types.

The placement of the sensor relative to the tree and the irrigation system (either a dripper or the micro sprinkler) is not an easy decision, as the distribution of water and roots varies within the root zone. The aim is to place the probe in an area that represents average soil water content that the tree is experiencing and where water uptake by roots is taking place. Profile pits will help to decide where the active root zone is and some gravimetric soil water sampling can help establish where average soil water content is found relative to the irrigation system (Figure 27). The probe should not be placed in the wettest area, as this can give the impression that there is always sufficient water in the soil. If the sensor is too far from the emitter, it can also appear as if the soil is always dry. This can easily lead to under- or over-irrigation. Knowledge of water distribution by a micro-sprinkler and water movement in the soil under a dripper is therefore very important for determining where to place the sensor (see section 2.4 and It is also important to keep in mind that for drip systems, the drip line moves and if the drip line is not secured in place relative to the sensor, what is being measured can change and this could impact scheduling.

When using this data to schedule irrigation it is important to note that sensors provide point measurements and may not represent what is happening in the entire orchard. It is important to have 'boots in the orchard' to check system uniformity. Taking soil samples at various depths and doing soil feel tests across the orchard are very important.

Figure 27. Profile pits in pecan orchards which aid in the determination of rooting depth and wetting patterns from irrigation. Knowing where the roots are and the wetting patterns from irrigation allows the determination of the best place to measure soil water with a capacitance probe or tensiometer.

4.2 Plant water status

In order to move water through a plant, a pressure gradient is required. The water at the top of a plant develops a large tension and this tension ***pulls*** water through the plant. This xylem tension required to pull water from the soil develops in leaves as a consequence of transpiration. Leaves open their stomata at the start of a day to allow CO_2 entry into the leaf for photosynthesis, as a result of stomata opening water vapour diffuses out of the leaf through the stomata. This causes water to evaporate from the surface of cells in the leaf and as a result the water potential (Ψ) of the leaf starts to decrease. This creates a gradient in water potential that causes water to flow towards the sites of evaporation. The gradient in water potential or tension depends on the balance between the available soil water and the rate at which water is transpired from the leaves. As soil water is depleted, more tension develops in the plant to maintain the gradient between the soil and the leaf. This drop in water potential (becoming more negative) can indicate a developing water deficit stress. It is a drop as the values are always negative and are typically measured in units of pressure such as megapascals (MPa) or bars.

This tension can be measured in a severed leaf (removed from the plant) using a pressure chamber (Figure 28) and applying a pressure to the leaf. The pressure required to force water out of the petiole of the severed leaf equals the leaf water potential and this value is read on a gauge on the pressure chamber. There are two main methods for determining tree water status using water potential measurements, that can then be compared to thresholds for the same measurement for the crop to decide if irrigation is necessary or not. Measurements can be made on leaves before dawn and at this time leaf water potential provides an indication of soil water potential, as just before dawn the tree water is in equilibrium with the soil matric potential. Alternatively, measurements can be made at midday on leaves that have been placed in a foil covered plastic bag for at least 30 min prior to measurement, to allow the leaf to come into equilibrium with the xylem in the stem – these measurements are referred to as midday stem water potential. Work done in New Mexico, USA, determined that pecan trees are considered well-watered when midday stem water potential is between –0.40 and –0.85 MPa, moderately stressed between –0.90 to –1.45 MPa and severely stressed between –1.5 and –2.0 MPa (Othman et al., 2014). From a stress trial conducted in the orchard at the University of Pretoria, a corresponding predawn leaf water potential of -0.45 MPa was found to indicate the onset of mild stress.

The advantage of this method is that it is an integrated measure of the whole root zone and not a point measure as for a soil water measurement. The disadvantage is that it is a manual method and requires an experienced operator to get consistent results. The instrument is also fairly expensive and requires a pressurised cylinder to pressurise the chamber. In addition, although it can provide good information on when to irrigate to avoid tree stress, this measure provides no information on how much to irrigate.

Figure 28. A Scholander pressure chamber used for determining leaf water potential.

4.3 Estimating orchard water use

4.3.1 Crop coefficient approaches

Orchard evapotranspiration can be calculated by multiplying reference evapotranspiration (ET_o) by a crop coefficient (K_c).

$$ET = K_c \times ET_o$$

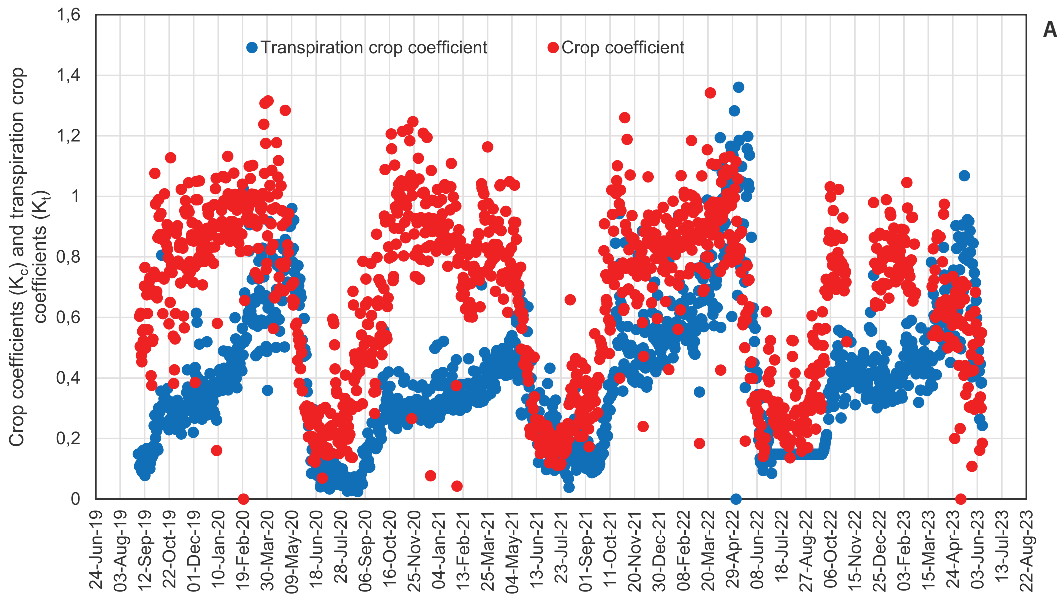
ET_o accounts for weather variability, whilst the K_c accounts for differences in the crop (including canopy cover) and the irrigation system. K_c values account for both transpiration from the crop and evaporation from the soil. K_c values can be adjusted for different orchards based on location and canopy size to derive orchard specific ET.

Whilst crop coefficients have been determined for pecan orchards in the USA and an orchard in South Africa, these regions have shorter seasons than the Northern Cape production region, meaning that these K_c values would not be accurate for other regions in South Africa. As a result, SAPPA and the WRC funded research on water use in this region. In order to show the season to season variation and general shape of the K_c and transpiration crop coefficient curves (K_t) daily data is presented in Figure 29.

A crop coefficient can be split into a transpiration crop coefficient (K_t) and evaporation coefficient (K_e) in order to estimate transpiration and evaporation separately, known as the dual crop coefficient approach. This can be a big advantage in younger orchards when canopy cover is less than 80% and evaporation is an important component of orchard evapotranspiration. It is also important when different irrigation systems are used which impact soil evaporation. In this case a K_c can be calculated as follows:

$$K_c = K_t + K_e$$

More details of K_t and K_e values for pecans can be obtained from the authors of this guide.



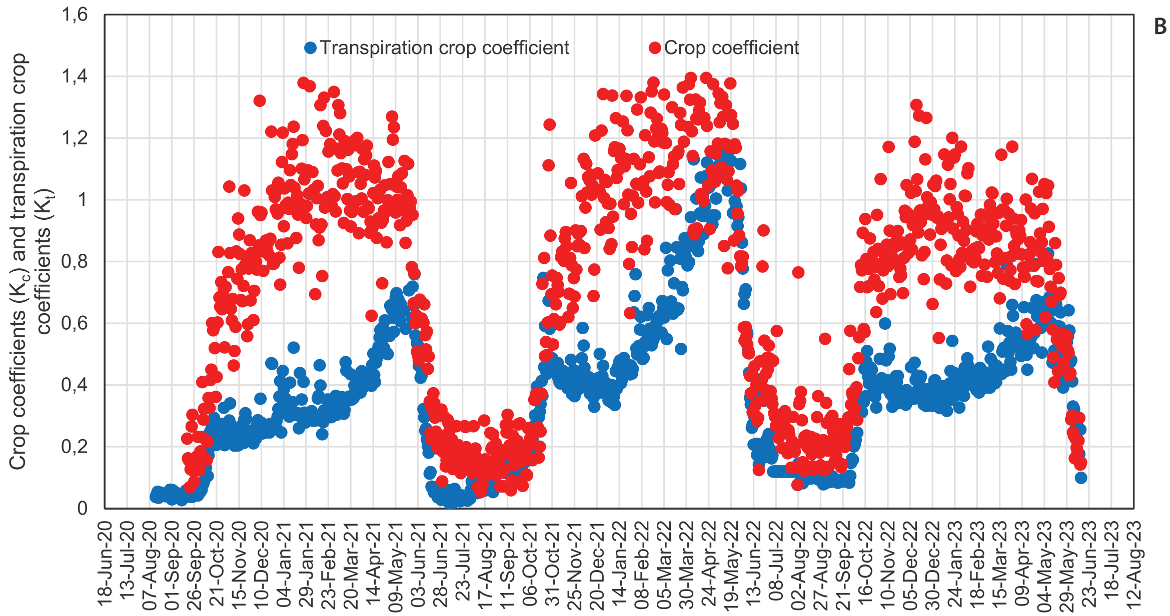


Figure 29. Daily crop coefficients (Kc) and transpiration crop coefficients (Kt) for A) 4 seasons in Vaalharts and B) 3 seasons in Groblershoop.

In order to try and make these values easily applicable to orchards in the cooler and hotter production regions of South Africa, average monthly K_c values are provided for Cullinan (Gauteng) and Vaalharts and Groblershoop (Table 3 and Table 4). These can be used for general irrigation planning on a seasonal and monthly basis. For more detailed planning biweekly K_c values have been provided for Vaalharts and Groblershoop (Table 5).

Table 3. Average monthly crop coefficients (K_c), daily reference evapotranspiration (ET_o) and calculated daily evapotranspiration (ET) for mature orchards in Vaalharts (micro-sprinkler irrigated) and Groblershoop (drip irrigated). Canopy cover <80%

	Vaalharts*			Groblershoop#		
	K_c	ET_o	ET	K_c	ET_o	ET
Aug	0.39	3.18	1.24	0.19	3.42	0.66
Sep	0.50	5.00	2.53	0.20	5.13	1.03
Oct	0.80	5.60	4.47	0.52	6.03	3.12
Nov	0.78	6.29	4.91	0.78	7.17	5.59
Dec	0.83	6.23	5.18	0.96	7.42	7.13

	Vaalharts*			Groblershoop[#]		
	K_c	ET_o	ET	K_c	ET_o	ET
Jan	0.86	6.18	5.32	1.01	7.16	7.22
Feb	0.84	5.24	4.38	1.02	6.05	6.16
Mar	0.85	4.50	3.83	1.05	4.79	5.03
Apr	0.82	3.21	2.65	0.99	3.55	3.53
May	0.61	2.39	1.44	0.92	2.36	2.18
Jun	0.29	2.06	0.60	0.38	1.99	0.75
Jul	0.24	2.44	0.57	0.24	2.57	0.61

*5 seasons of data

[#]4 seasons of data

Table 4. Average monthly crop coefficients (K_c), daily reference evapotranspiration (ET_o) and calculated daily evapotranspiration (ET) for Cullinan (micro-sprinkler irrigated). Canopy cover >80%

	Cullinan*		
	K_c	ET_o	ET
Oct	0.73	4.04	2.95
Nov	0.97	4.76	4.63
Dec	1.02	4.91	4.99
Jan	1.03	4.51	4.64
Feb	0.94	4.59	4.31
Mar	1.09	4.14	4.53
Apr	1.31	3.33	4.37
May	0.96	2.27	2.17

*3 seasons of data

Table 5. Average biweekly crop coefficients (K_c), daily reference evapotranspiration (ET_o) and calculated daily evapotranspiration (ET) for mature orchards in Vaalharts (micro-sprinkler irrigated) and Groblershoop (drip irrigated). Canopy cover <80%.

	Vaalharts*			Groblershoop[#]		
	K_c	ET_o	ET	K_c	ET_o	ET
Aug 1-15	0.35	2.83	0.99	0.22	2.92	0.65
Aug 16-31	0.39	3.34	1.29	0.17	3.48	0.59
Sept 1-15	0.42	4.02	1.68	0.20	4.33	0.87

	Vaalharts*			Groblershoop#		
	K_c	ET_o	ET	K_c	ET_o	ET
Sept 16-30	0.50	5.19	2.61	0.21	5.38	1.12
Oct 1-15	0.71	5.47	3.87	0.29	5.64	1.66
Oct 16-31	0.82	5.41	4.46	0.51	6.31	3.20
Nov 1-15	0.81	6.00	4.84	0.76	6.38	4.82
Nov 16-30	0.88	6.45	5.69	0.77	7.31	5.66
Dec 1-15	0.84	6.26	5.23	0.87	7.44	6.48
Dec 16-31	0.84	6.14	5.16	0.98	7.46	7.31
Jan 1-15	0.85	6.18	5.23	0.99	7.26	7.17
Jan 16-31	0.87	6.25	5.43	1.00	7.00	7.02
Feb 1-15	0.82	5.48	4.51	1.03	6.55	6.71
Feb 16-28	0.80	5.17	4.15	1.02	5.85	5.99
Mar 1-15	0.84	4.76	4.00	1.05	5.28	5.53
Mar 16-31	0.85	4.21	3.58	1.05	4.64	4.87
Apr 1-15	0.86	3.57	3.08	1.04	4.06	4.21
Apr 16-30	0.79	2.98	2.36	0.97	3.33	3.24
May 1-15	0.82	2.51	2.05	1.02	2.66	2.70
May 16-31	0.60	2.29	1.38	0.87	2.26	1.96
June 1-15	0.42	2.06	0.86	0.51	2.03	1.04
June 16-30	0.29	2.11	0.61	0.37	1.85	0.69
July 1-15	0.28	2.15	0.60	0.27	2.45	0.67
July 16-31	0.29	2.56	0.75	0.21	2.59	0.54

4.3.1.1 Determining reference evapotranspiration (ET_o)

Reference evapotranspiration or ET_o is determined from weather station data (Figure 30). Solar radiation, air temperature, relative humidity and windspeed are all required for the calculation as detailed in section 2.2.21. There is a network of automatic weather stations in South Africa with various service providers which can be used or a weather station can be purchased for the farm. Some service providers also provide forecasted ET_o for a week and provide measured ET_o for each week. There are also some free weather services which provide ET_o estimates. This allows the determination of a schedule for the week ahead based on forecasted values. Scheduling according to weather data is very important as any two weeks are seldom the same and this impacts water use of the orchard. Rainfall is also measured at the weather station and this can be used to adjust irrigation volumes. An ET_o calculator is available online.

Figure 30. An automatic weather station installed over a short grass reference surface.

4.3.1.2 Determining canopy size

Canopy size can be estimated as fractional canopy cover as described in 3.2.3.

4.3.2 Comparison of water use for different irrigation systems

As discussed in section 3.2.4 (Factors driving soil evaporation) the irrigation system used in an orchard and the frequency of wetting has an impact on orchard evapotranspiration as a result of different rates of evaporation. In order to illustrate how evaporation rates differ between different irrigation systems, evaporation was estimated using a well-established model for the same orchard under drip, micro-sprinkler and flood irrigation from October to March (Figure 31). Typical irrigation scheduling adopted by the grower was used for the simulations.

Soil evaporation (E_s) under flood and sprinkler irrigation was almost twice as high as in the drip-irrigated orchard. This difference was most pronounced under medium canopy cover, when the fraction of wetted and exposed soil was high (October-November). However, as the canopy cover increased and the fraction of wetted and exposed soil decreased, the differences in E_s between the irrigation systems became less significant (December to February).

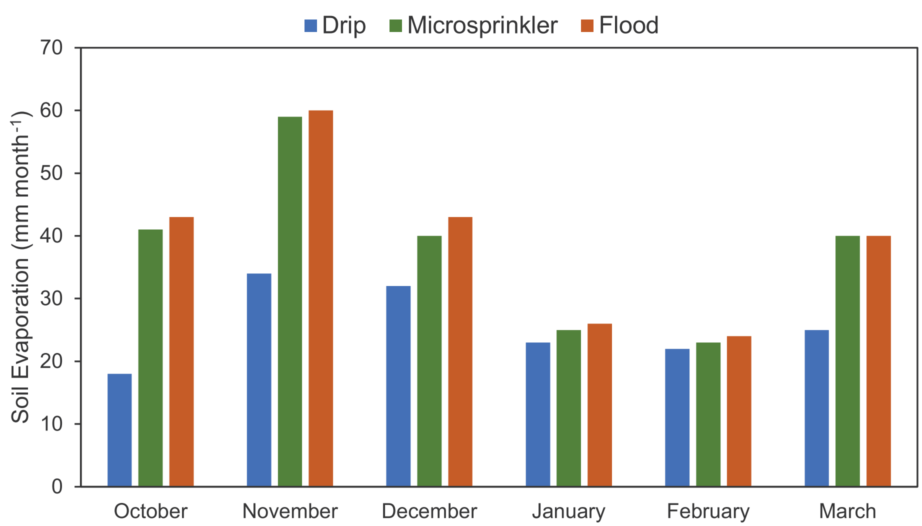


Figure 31. Monthly soil evaporation (mm month^{-1}) from a mature pecan orchard in Groblershoop irrigated with either drip or full surface micro-sprinklers or flood irrigated. Simulations were run from October to March and no rainfall was considered.

When considering the impact of E_s on total orchard water use or ET, it is clear that ET was higher in orchards irrigated with micro-sprinklers or flood irrigated, due to higher evaporation rates. In drip irrigated orchards E_s was approximately 30% of total ET over the six-month period, whilst in micro-sprinkler and flood irrigated orchards E_s was closer to 40%. As a result, higher applied irrigation volumes are required for systems that wet a greater area of the orchard floor to replace the full ET requirements of the crop. When compared to drip, 25% more water needs to be applied in micro-sprinkler and flood irrigated pecan orchards. These values will differ between orchards depending on tree size, size of the wetted area, frequency of wetting and weather conditions, as discussed in section 3.2.4.

Table 6. Monthly soil evaporation and orchard evapotranspiration rates for a mature pecan orchard in Groblershoop irrigated with either drip or full surface micro-sprinklers or flood irrigated. Simulations were run from October to March and no rainfall was considered. Tree transpiration was considered equal for all irrigation system based on measurements of transpiration.

Month	Drip		Microsprinkler		Flood	
	E	ET	E	ET	E	ET
	(mm month^{-1})					
October	18	48	41	71	43	73
November	34	103	59	128	60	129
December	32	102	40	110	43	113
January	23	92	25	94	26	94
February	22	90	23	91	24	92
March	25	87	40	102	40	102
TOTAL	**154**	**522**	**228**	**596**	**236**	**603**

4.4 Leaving room for rain

Making the most of rainfall is a good strategy to reduce the reliance on irrigation over a season. In order to do this, there needs to be room in the soil profile for rain and the effective rainfall needs to be determined. Not all rain that falls can be used by the crop, as some rain is intercepted by the tree canopy (from where it evaporates), some runs off from the surface if rainfall is very heavy and some will percolate out the root zone if a lot of rain is received. Knowing if the profile is full or not after a rainfall event and when the water in the soil is depleted by the tree after rainfall is important for making the most of the rain. Monitoring soil water probes after rainfall events will help determine how full the profile is after rain and when it is depleted to a point when irrigation should resume.


05

BENCHMARKING CROP WATER PRODUCTIVITY

Water use indicators as defined by Fernández et al. (2020) were used in the study of pecan water use in the Northern Cape Province. Crop water productivity based on ET_c (WP_c, kg/m^3) or crop water productivity based on T (WP_T) and irrigation water productivity (WP_I, kg/m^3) can be calculated as:

$$WP_c = \frac{yield}{ET_c} \quad \text{or} \quad WP_T = \frac{yield}{T} \quad \text{or} \quad WP_I = \frac{yield}{IWU}$$

Where IWU is irrigation water applied. Economic crop water productivity (EWP_c, R/m^3) and economic irrigation water productivity (EWP_I, R/m^3) can calculated using the net margin as:

$$EWP_c = \frac{profit}{ET_c} \quad \text{or} \quad EWP_I = \frac{profit}{IWU}$$

Profit was calculated by subtracting total production costs from the gross profit per ha, based on commodity prices for each season from Profarmer (GWK). It is important to note that these values are season specific and change depending on average prices for pecans and input costs. These values presented in this guide are therefore only a rough guide to provide growers with some form of benchmark to aim towards. Values are for average water use (ET and T) and average yields for the region. The regions are presented separately due to the different climatic conditions, where Groblershoop is hotter and drier than Vaalharts.

Table 7. Average crop water productivity considering evapotranspiration (WP_c), transpiration (WP_T) and irrigation (WP_I) for Vaalharts and Groblershoop and average economic water productivity for both regions considering evapotranspiration (EWP_c) and irrigation (EWP_I)

	Vaalharts	Groblershoop
WP_C (kg m^{-3})	0.22	0.19
WP_T (kg m^{-3})	0.43	0.43
WP_I (kg m^{-3})	0.32	0.27
EWP_c (R m^{-3})	17.6	
EWP_I (R m^{-3})	34.6	

06

IMPACT OF WATER STRESS ON YIELD AND QUALITY

6.1 Definitions of water stress and plant responses to water stress

6.1.1 Water stress

A water deficit stress develops when water demand by the tree exceeds the water available in the soil, resulting in a decline in plant water status where normal plant functioning is affected. As water in the soil is depleted stomata start to close in order to prevent leaf water potential from dropping to a point where the water potential gradient in the plant is so high that embolisms form in the xylem (these are air bubbles that can stop water transport in xylem vessels). As a result of stomatal closure, photosynthesis declines and the ability of the plant to produce carbohydrate skeletons is reduced. Alternatively, if soils become waterlogged, the lack of oxygen in the soil results in reduced water uptake by roots, resulting in similar symptoms to a water deficit stress. Stomata will once again close, which impacts photosynthesis.

6.2 Sensitivity of phenological stages to water stress

An experiment has been running for 6 years in an experimental orchard at the University of Pretoria (Innovation Africa@UP) to determine the impact of a water deficit stress at different phenological stages on yield and quality (Figure 32). Whilst, stress could not be induced during every phenological stage in every season, when stress was imposed there were consistent impacts on yield and quality for each phenological stage.

The impacts on yield and quality at each stage can be summarised as follows:

Flowering and nut set:
Yield is reduced if a sustained stress occurs at this time. This is due to increased flower and nut drop at the stage, resulting in lower yield due to a fewer number of nuts on the tree. Although, there were fewer nuts, there was no increase in nut size, relative to a well-watered control. There were no other impacts on quality.

Nut sizing:
There was no impact on yield when stress was imposed during nut sizing. However, nut size was consistently reduced when stress was imposed during this stage. Stress therefore resulted in an increased number of smaller nuts.

Nut filling:
Stress during nut filling consistently resulted in reduced yields and quality, as a result of poorly filled nuts or pops. The percentage of wafers or air pockets was also higher when stress was induced during this period.

Shuck dehiscence:
The number of sticktights increased when stress was successfully implemented during shuck dehiscence. In some cases, these sticktights were poorly filled and in others they were well filled. Yield was not significantly impacted when a stress was imposed during this stage.

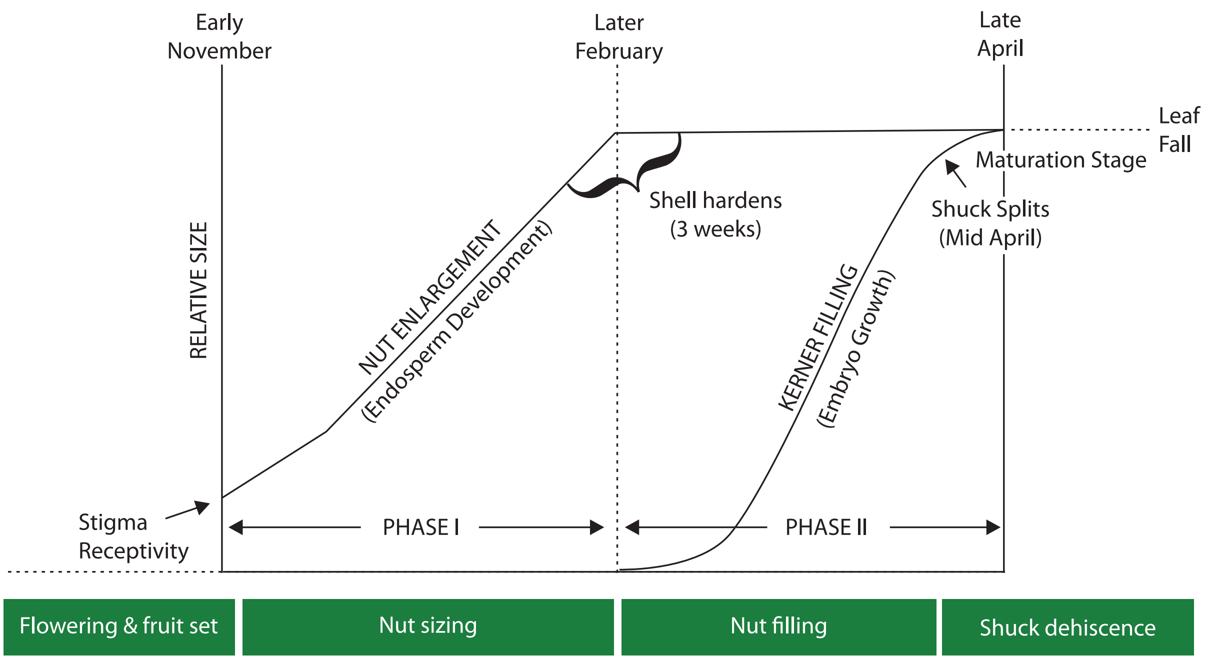


Figure 32. Pecan nut development (adapted from Herrera (1990)).

6.3 Opportunities to save water during a season

If water savings need to be made during the season due to reduced water allocations, usually due to drought, it may be possible to implement a mild deficit during nut sizing and shuck dehiscence with a minimal impact on yield and quality. Importantly, it should only be a mild stress. A severe stress could have more profound impacts on yield and quality at these stages. When implementing a mild stress, predawn or midday stem water potential measurements will help maintain stress within limits. Measurements of soil water content or soil matric potential will also assist in maintaining a slight stress.

Other water savings strategies can also be employed when allocations are reduced. These strategies include a mulch on the soil surface, limiting weed growth and keeping a cover crop short (to limit transpiration), limiting the wetted area from irrigation that is exposed to radiation (use drip systems or micro-sprinkler with a smaller radius) and making the most of any rainfall that occurs, considering that it may be a drought year.

07

CONCLUSIONS

The decision of when to irrigate and how much to irrigate to optimise yield per cubic meter of water applied is not easy and a number of factors need to be considered. These include prevailing weather conditions, canopy size and the distribution uniformity and delivery rate of the irrigation system. Using an objective means to schedule irrigation (weather forecasts and soil water probes) can lead to improved water management in orchards throughout a season. In addition, being quantitative (having water meters on irrigation lines) and keeping records is important as it allows adaptive learning to move towards better scheduling practices.

Choosing the best irrigation system to use depends on local conditions, quality of irrigation water and what system a grower is most comfortable with when it comes to scheduling. The success of the system will depend largely on the manner in which it is managed and maintained. Ensuring uniformity of the irrigation system throughout the orchard and over the whole season will be key to avoiding under and over-irrigation. However, if water losses need to be minimised then drip systems, which place water within the shaded area of a tree, may be a good option. Irrigation system design depends on maximum water requirements of the crop and for pecan orchards this needs to be considered for mature trees when first establishing an orchard. The questions that need to be asked are - Will my irrigation system provide sufficient water when my trees are mature and will I have enough water for all my trees when they are mature?

Finally, there are a number of strategies that can be employed to save water in pecan orchards by limiting non-beneficial consumptive water use and non-consumptive water use. In addition, if a grower is faced with the situation where it will be impossible to schedule normally with the reduced allocation of water in a season, it may be possible to induce a slight stress during nut sizing and shuck dehiscence without a big impact on yield or quality. Stress during flowering and nut set and nut filling will reduce yield and quality.

Useful conversions

1 L per m^2 = 1 mm

1 m^3 = 1000 L

1 m^3 ha^{-1} = 0.1 mm, 1 mm = 10 m^3 ha^{-1}

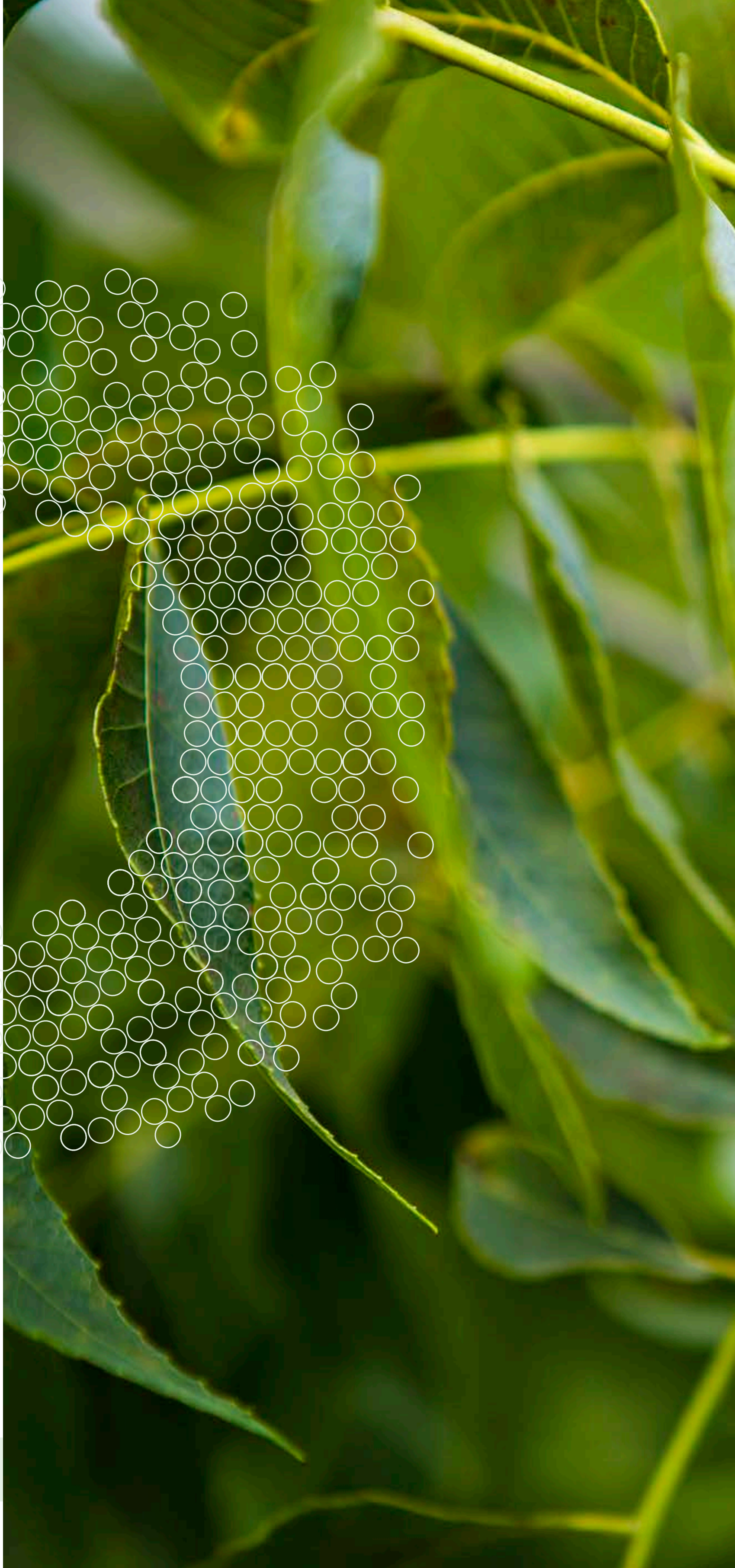
08

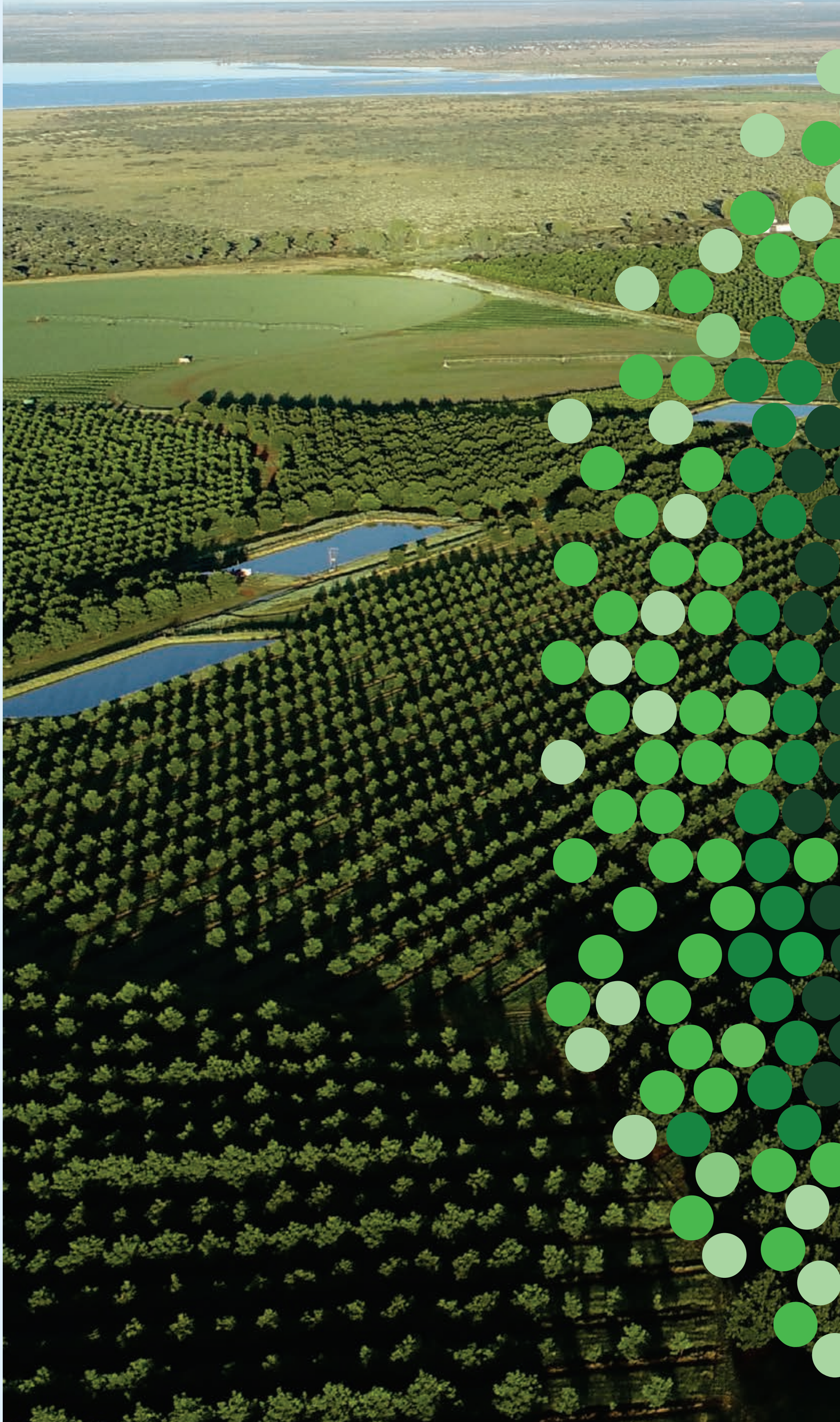
REFERENCES

- Fernández, J., Alcon, F., Diaz-Espejo, A., Hernandez-Santana, V. and Cuevas, M., 2020. Water use indicators and economic analysis for on-farm irrigation decision: A case study of a super high density olive tree orchard. *Agricultural Water Management*, 237: 106074.
- Herrera, E.A., 1990. Fruit Growth and Development of Ideal' and Western' Pecans. *Journal of the American Society for Horticultural Science*, 115(6): 915-923.
- Othman, Y., VanLeeuwen, D., Heerema, R. and Hilaire, R.S., 2014. Midday stem water potential values needed to maintain photosynthesis and leaf gas exchange established for pecan. *Journal of the American Society for Horticultural Science*, 139(5): 537-546.
- Perry, C., 2007. Efficient irrigation; inefficient communication; flawed recommendations. Irrigation and Drainage: *The Journal of the International Commission on Irrigation and Drainage*, 56(4): 367-378.
- Reinders, F., 2010. Standards and guidelines for improved efficiency of irrigation water use from dam wall release to root zone application. WRC Report no. TT 466/10
- Reinders, F.B., 2022. Irrigation water use efficiency: A water balance approach. *River*, 1(2): 142-148.

GLOSSARY	
Applied water	The amount of water applied to the orchard during a growing season. Typically, irrigation volumes but can also include rainfall.
Available soil water	That amount of water that lies between field capacity and permanent wilting point is the water that is available to the plant for uptake.
Capacitance probe	A device used to measure volumetric soil water content.
Crop water productivity	The yield from an orchard divided by either the 1) evapotranspiration 2) transpiration or 3) applied irrigation for that orchard (units kg/m^3).
Consumptive water use	The part of water applied to an orchard that is withdrawn and either evaporated, transpired or incorporated in the crop.
Crop coefficient (K_c)	Orchard evapotranspiration divided by reference evapotranspiration.
Economic water productivity	Rands earned from yield divided by either the 1) evapotranspiration 2) transpiration or 3) applied irrigation for that orchard (units R/m^3).
Field capacity	Water content in the soil after the soil becomes saturated, followed by complete drainage as a result of gravity.

GLOSSARY	
Fractional canopy cover	The fraction of the ground surface allocated to the tree which is covered by the canopy.
Evapotranspiration	The sum of water lost from the orchard through transpiration and evaporation from the soil surface (including transpiration from any vegetation on the orchard floor).
Evaporation	The release of water vapour from the soil surface.
Leaf water potential	Measure of plant water status determined with a pressure chamber. Measurements are either made predawn or on bagged leaves at midday.
Non consumptive water use	Water that is applied to the orchard that is not consumed and is lost to the orchard e.g. run off and deep percolation.
Orchard water balance	The net change in the available water in an orchard through changes in applied water and extraction of water.
Permanent wilting point	The lowest soil matric potential at which a plant can access water from a soil
Reference evapotranspiration (ET_o)	Evapotranspiration from a hypothetical well-watered short grass surface that is growing optimally. It is calculated from weather data.
Soil matric potential	The relative availability of water held in the soil profile for plant uptake. Indicates how much energy plants need to exert to extract water from the soil.
Soil texture	The percentage of clay, silt and sand in the soil. Soil texture has a key impact of soil water holding capacity, drainage, water infiltration and chemical properties.
Tensiometer	Device to measure soil matric potential.
Transpiration	The release of water vapour from plants, through stomata into the atmosphere
Transpiration crop coefficient (K_t)	Orchard transpiration divided by reference evapotranspiration.
Volumetric soil water content	Volume of water per total volume of soil





WATER
RESEARCH
COMMISSION