GUIDELINES FOR IRRIGATION of JAPANESE PLUM

HORTGRO
Growing Fruit IQ
science

WATER RESEARCH COMMISSION

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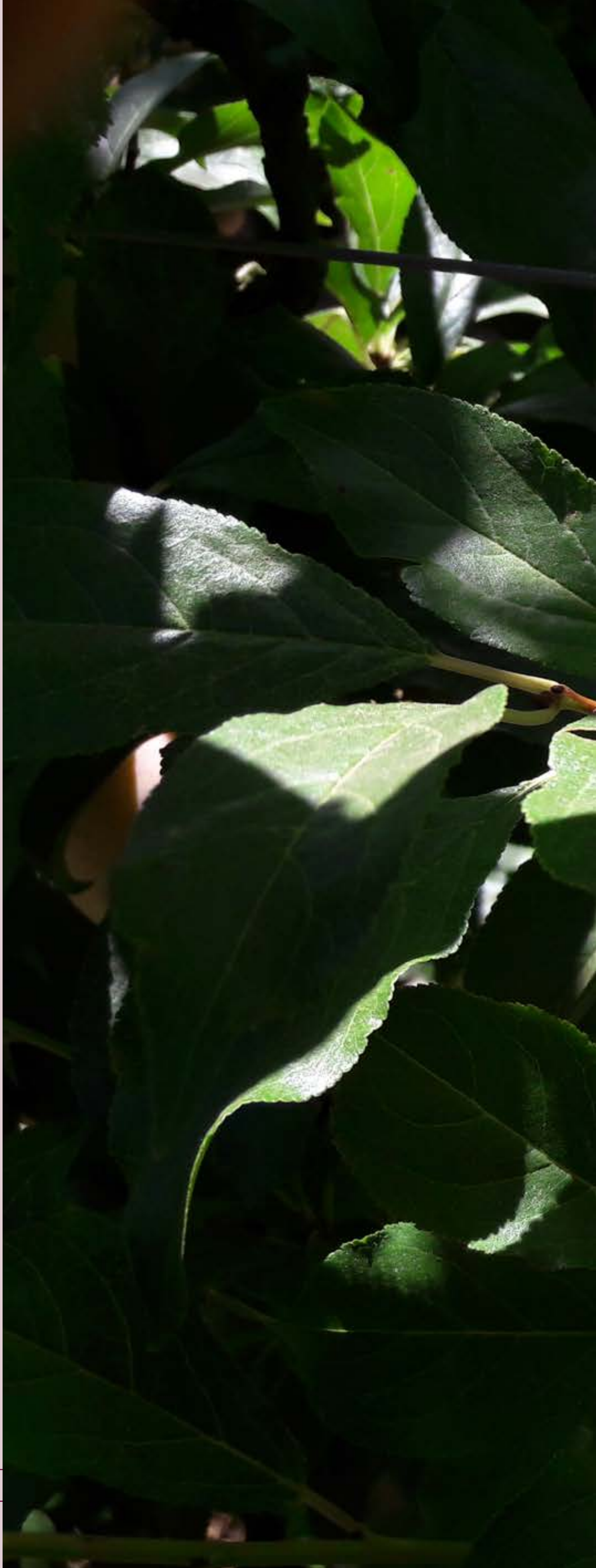
INTRODUCTION

In order to achieve maximum production potential of Japanese plums and use water efficiently, farmers need to know the crop water requirements, the type of soil and optimal cultivation and management practices to be applied in each orchard. Understanding these relationships will make a difference between success and failure in the production, yield and economics of fruit production.

Irrigation is even more critical in high-density orchards, where the economic success depends on obtaining high yields after a few years to be able to repay the investment costs. Farming under irrigation is a pre-requisite to obtain high fruit yields in plum orchards in the Western Cape. Recent increases in cost of energy and constraints due to loadshedding have also influenced the irrigation practice. Proper irrigation management to reduce energy costs and to rotate irrigations around loadshedding times has become even more critical.

Irrigation water requirements of plums depend on the following factors:

- The type of crop cultivar (early-, mid- or late-maturing varieties)
- Crop production practices
- The rooting depth
- The type of soil, soil hydraulic and water storage properties
- Rainfall and evapotranspiration (climate)
- Irrigation method
- Irrigation management and scheduling



TYPE OF CROP AND CULTIVAR

Japanese plum cultivars have a broad maturity/harvest time that spans from very early (November) to very late (April). Table 1 summarises maturity times for plum cultivars, based on information obtained from different sources and experience. Due to the sensitivity of plums to water stress during the reproductive stage (flowering, early fruit set/first rapid fruit growth and final fruit swell/second rapid fruit growth), the irrigation season in late-maturing varieties is maintained for an extended period as fruit growth needs to be sustained in order to achieve high yields (stage I and stage III). Crop water requirements need to be satisfied in full during these stages. As vegetative growth continues after harvest in both early- and late-maturing cultivars, irrigation needs to be sustained during off-season to prevent desiccation of trees and reduce carry-over effects in the next season. However, most farmers irrigate half of the water requirements or less during off-season.

Table 1. Maturity time of selected Japanese plum cultivars

Cultivar	Maturity	Weeks	Dates
African Delight®	Mid/Late	6-9	5 February – 5 March
African Rose®	Very Early	45-49	1 November – 10 December
Afri Gold	Mid	3-5	15 January – 5 February
Angeleno® (Suplum6)	Mid/Late	6-9	5 February – 5 March
Applum	Mid/Late	6-9	5 February – 5 March
August Yummy	Mid/Late	6-9	5 February – 5 March
Black Diamond® (Suplum11)	Early	50-2	10 December - 15 January
Black Giant	Mid/Late	6-9	5 February – 5 March
Black Splendor	Early	50-2	10 December - 15 January
Fall Fiesta	Late	10-14	5 March – 10 April
Flavor Fall	Very Late	>14	After 10 April
Flavor King	Mid	3-5	15 January – 5 February
Flavor Star	Mid	3-5	15 January – 5 February
Fortune	Early	50-2	10 December - 15 January
Honey Punch	Mid	3-5	15 January – 5 February
Lady Red	Early	50-2	10 December - 15 January
Laetitia	Mid	3-5	15 January – 5 February
Larry Anne	Mid	3-5	15 January – 5 February
Pioneer	Very Early	45-49	1 November – 10 December
Polaris	Mid	3-5	15 January – 5 February
Purple Majesty	Very Early	45-49	1 November – 10 December
Red Diamond	Early	50-2	10 December - 15 January
Red Giant	Late	10-14	5 March – 10 April

Cultivar	Maturity	Weeks	Dates
Red Phoenix	Mid	3-5	15 January – 5 February
Ruby Crisp	Mid	3-5	15 January – 5 February
Ruby Crunch	Early	50-2	10 December - 15 January
Ruby Red	Early	50-2	10 December - 15 January
Ruby Star	Mid/Late	6-9	5 February – 5 March
Ruby Sun	Early	50-2	10 December - 15 January
Sapphire	Very Early	45-49	1 November – 10 December
Satin Gold	Mid	3-5	15 January – 5 February
September Yummy	Late	10-14	5 March – 10 April
Solar Eclipse	Early	50-2	10 December - 15 January
Songold	Mid	3-5	15 January – 5 February
Southern Belle	Mid	3-5	15 January – 5 February
Souvenir	Early	50-2	10 December - 15 January
Sun Breeze	Mid	3-5	15 January – 5 February
Sunkiss®	Early	50-2	10 December - 15 January
Sun Supreme	Mid	3-5	15 January – 5 February

Crop and irrigation water requirements also depend on crop management. High density and super high density orchards require more resources and irrigation water compared to less densely planted orchards, although this depends primarily on canopy growth and leaf area index. Higher evapotranspiration and crop coefficients in high density orchards result in higher crop water requirements. Trellising and pruning also affect crop water requirements. Whereas excessive vigour increases water use, pruning vegetative mass may reduce the crop water requirements, thanks to the reduction in transpiring leaf area and more biomass being accumulated into the fruits. Row orientation plays an important role in the optimal capture of radiation energy required for the photosynthesis process and therefore gas exchanges at leaf level. This may result in variations of evapotranspiration and crop water requirements.

Figure 1. Examples of cover crops in plum orchards in Wellington (top) and Robertson (left).

CROP PRODUCTION PRACTICES

Planting density

High density orchards are usually planted at 3.5 m x 1.0 m to 4 m x 1.5 m (averaging between 1,667 and 2,857 trees per ha).

Cover crops

The primary purpose of cover crops is to improve soil water holding capacity and soil fertility. As a result, they reduce soil moisture loss, soil erosion and provide nutrients to the main fruit crop. Tilling cover crops into the soil and allowing them to decompose improves organic matter levels and increases soil water holding capacity.

A variety of cover crops/grasses are used across plum orchards in the Western Cape (Figure 1). Clover and legumes are recommended to increase soil fertility and attract pollinators. In some instances, farmers prepare a small ditch in the middle between rows in order to accumulate and decompose organic matter residue from cover crops to increase organic matter and water holding capacity of the soil.

Mulching

Besides cover crops, mulching is another means of conserving water by providing a physical barrier to direct evaporation of water from the soil surface. It also moderates soil temperature, the effects of wind, it reduces the occurrence of weeds and contributes to the soil water holding capacity. Mulches can be natural, organic or plastic. A densely planted orchard canopy provides a form of natural mulching itself. Cover grass cuts provide residue mulch, as well as pruned branches and thinned fruits (Figure 2). Amongst organic mulching, one can use plant material, compost, sawdust and wood chips. Plastic mulches are very effective in reducing soil evaporation and weeds. Trees grow through holes in the plastic mulching sheets, so plastic mulches should be applied away from the trunk base.

Figure 2. Mulch applied from cover grass cuts residue (top), and from pruned branches and thinned fruits (bottom).

Shade nets

Shade nets protect fruits from sunburn and pests. A positive secondary effect of shade nets is reduction in tree water consumption, especially during periods of heat waves, because they increase relative humidity, reduce solar radiation, canopy temperature, wind and crop water requirements. They protect the fruits from direct radiation and sunburn, but they may enhance vegetative growth at the expense of yield (Malik, 2020). Shade nets require a support structure (metal or PVC) (Figure 3).

Figure 3. Cultivation of plums under shade nets.

Pruning

Pruning is a fundamental practice to diminish vegetative growth, enhance fruit production and reduce water consumption. Scholarly horticultural guidelines indicate that pruning can be done by thinning and cutting back shoots down to 25-50 cm. Shoots usually grow on two year old branches with a lifespan of 5-6 years. Thinning can be performed on 25-30% of shoots while cutting back 50-75% of them. Dead, infected and broken branches can be removed. Pruning is usually done a month after bloom (October-November). However, frequent pruning (e.g. monthly) is also practiced in high density plum orchards in the Western Cape as this appears to improve yield quantity and quality.

ROOTING DEPTH

The root system is used by plants to take up soil water and nutrient resources. A deeper root system allows plants to explore a larger volume of soil for resources. Plant available water (PAW) is defined as the difference between soil water content at field capacity FC and permanent wilting point (PWP) times the rooting depth (RD):

PAW = (FC – PWP) x RD

PAW is generally expressed in units of mm of water. Not all PAW is readily available to plants. Optimal growth and transpiration can be maintained up to a certain allowable soil water depletion level (threshold), corresponding to readily extractable water (REW) (Figure 4). Beyond this threshold, plant water stress occurs. This can be described and quantified with a water stress index Ks, which is a proxy for the ratio of actual to potential transpiration (T/TP) or actual to maximum dry matter assimilation (DM/DMmax) (see Y-axis in Figure 4).

If soil water content is maintained in the REW range through irrigation (between FC and the threshold), plant transpiration and biomass production depend only on weather conditions and available solar radiation energy (***atmospheric demand limited*** section in Figure 4). If soil water content is depleted beyond the threshold, plant transpiration and biomass production decline and they are said to be ***soil water supply limited***. The threshold soil water content may fluctuate.

On a sunny, hot day, the soil water content needs to be higher than on a cloudy, cold day, for the root water uptake to keep up with the atmospheric evaporative demand and sustain plant transpiration. If too much water occurs in the soil, such as under water-logging conditions, plant symptoms similar to water stress occur due to lack of oxygen, with associated reduction in transpiration and biomass accumulation (Figure 4). The aim of irrigation management is to maintain soil water content within the REW range.

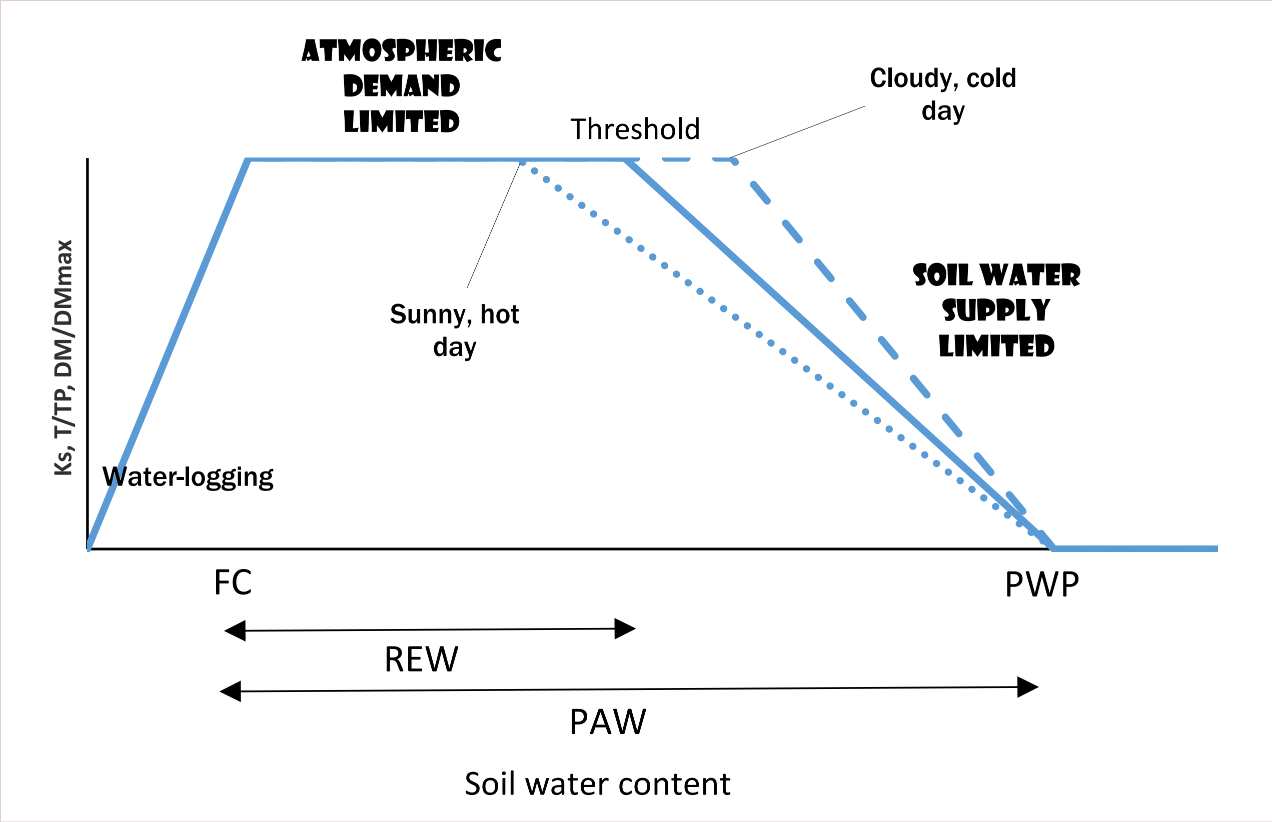


Figure 4. Schematic of the atmospheric demand-soil water supply limited transpiration.

Root development in hedgerow tree orchards does not occur across the entire row cross-section, but only up to a certain distance from the rows. For this reason, the effective root depth and volume need to be determined and managed so that trees can be supplied with the correct amounts of water through localized irrigation.

In adult plum trees, the root system usually reaches depths of about 1 m, but most roots are concentrated in the top 30-40 cm as demonstrated in Figure 5. Roots are likely to spread about 1 m on both sides of the row. The recommended soil volume to be managed is therefore 1 m (depth) x 2 m (width).

Figure 5. Root depth distribution in a Fortune (left) and African Delight (right) plum orchard.

SOIL

The most important soil characteristics for irrigation of high density plum orchards are the soil depth, soil texture, infiltration rate, soil water holding capacity and their variability. Along with soil properties, the topography, climatic conditions, local traditions and skills, the availability and quality of water supply as well as the supporting infrastructure play important roles in irrigated agriculture (Fonteh, 2017).

Plums prefer deep, well-drained and highly water-retentive soils. Soils in the Western Cape are inherently shallow, with texture generally ranging from sandy loam to clay loam. Due to their relatively high water holding capacity, such soils are suitable for cultivation of Japanese plums. In some instances, soils are too shallow (≈40 cm) to support the bulk of the root system of plums, generally about 1 m deep. Some farms practice cultivation in ridges to increase the available soil depth explored by the root system (Figure 6).

This practice proved to be successful both in terms of increasing water holding capacity of the soil profile, nutrients uptake and in reducing competition for resources between individual densely planted trees. However, non-beneficial water loss through soil evaporation may increase from the ridge slopes that are exposed to solar radiation energy.

Figure 6. Plum cultivation on ridges at Wellington (Western Cape).

Due to their hydraulic characteristics, different soils have different infiltration rates. This affects the selection of irrigation method (drip-, micro-jets, surface irrigation etc.) and the irrigation management. Irrigation water application rates should be lower than soils' infiltration rates to avoid water losses via overland flow. This is one of the reasons that the preferred irrigation methods make use of drippers and micro-jets that wet only a portion of the soil surface in the orchard along tree rows. Irrigation drippers and micro-jets provide low water application rates and ensure a more efficient utilisation of water resources. The wetted bulb below the wetted area spreads in a shallower and broader pattern in heavier soils compared to sandy soils, covering a substantial volume of soil where the root system is usually well-developed.

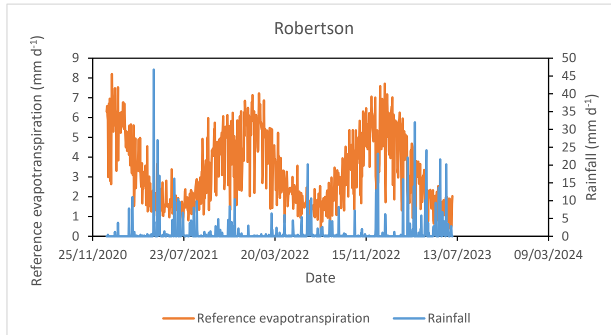
Soil hydraulic properties and water holding capacities are characterized by large spatial variability (horizontally and in depth). As a result, soil sampling and measurements require a substantial amount of replications in order to provide a reliable spatial representation of these soil properties. This applies both to laboratory analyses and the use of sensors for measuring and logging soil water content data in the field.

RAINFALL AND EVAPOTRANS-PIRATION DEMAND

Similarly to other deciduous fruit trees, plums require low temperatures in winter in order to induce a rest period that enhances flowering and growth in the following season. Climatic conditions are suitable for plums in the main production regions of the Western Cape, but only under irrigation. This is due to the Mediterranean winter rainfall climate that imposes the need for irrigation during the dry summer months.

The Klein Karoo receives between 175 and 300 mm/year of rainfall and it is shielded from cooling oceanic breezes. The production region in the Berg River catchment has higher summer temperatures, cooler winter temperatures, it is exposed seawards and it receives a long-term average rainfall of around 450 mm/year. Annual evapotranspirative demand is far higher than rainfall.

Figure 7 shows the reference grass evapotranspiration and rainfall recorded at Robertson (Klein Karoo) and Wellington (Berg River catchment). Plums also prefer sunny and aerated locations, whilst the occurrence of frost in the Western Cape production regions is improbable. However, rainy or windy conditions during flowering may cause poor fruit set.



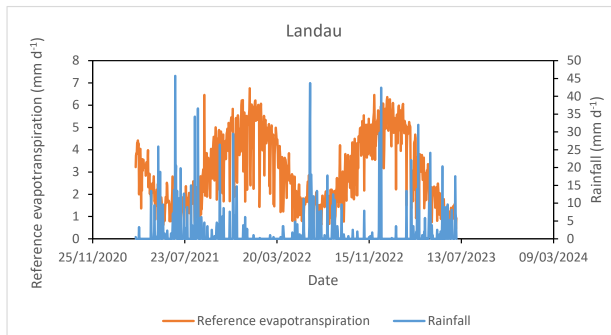


Figure 7. Reference grass evapotranspiration and rainfall at Robertson (Klein Karoo) and Landau in the vicinity of Wellington from 2021 to 2023 (Agricultural Research Council).

IRRIGATION METHOD

Due to the high water requirements, high level of investment and water shortages in the Western Cape, micro-irrigation of plums is practiced with micro-jets and drip-irrigation (Figure 8). These irrigation methods provide the highest irrigation efficiency at field scale (≈90%) and the most manageable and flexible systems to replenish soil water targeting the root system, as well as to remedy heat waves on large commercial farms with a large number of orchard blocks. In addition, they don't require too much labour, they are beneficial to control weeds and they reduce the risk of pests and diseases because they don't wet the foliage (FAO, 2007).

Drip-irrigation is generally operated in two lateral lines per tree row with emitters spaced 0.5 m apart and discharge rates of 2.0-2.5 L/h. Operating pressure is 3 b or less. On some farms, a third drip-irrigation line is added. This is done to ensure sufficient discharge rates especially in deeper alluvial soil and to refill the sub-soil that may have dried out during the dry season; however, it has been shown to increase water use. Micro-jet irrigation is operated in one lateral per tree row with micro-jet spacing of 1 m, discharge rate of about 30 L/h and operating pressure of 3 b.

Orchard blocks of rectangular shape between 0.2 and 3 ha are suitable for both drip and micro-jet irrigation, with slopes <5%. Lateral lengths of 100 m or less are recommended to ensure uniform pressure and water distribution, although self-compensating pressure drippers are available on the market. Any type of soil texture is suitable. For micro-jet infiltration, low soil infiltration rate may not be suitable (<6 mm/h).

For drip-irrigation, there are some requirements in terms of irrigation water quality. To reduce the risk of emitter clogging, salinity and toxicity, pH should be close to neutral (6.5-8.4), Langelier Index <+0.2 to reduce scaling or encrustation, TDS should be less than 2,000 mg/L, SAR <12, RSC < 1.25 meq/L and B <0.9 mg/L (DWAF, 1996; Halder et al., 2012). A filter is essential. In addition to the above, for micro-jet irrigation, Cl should be <12 meq/L to avoid toxicity to the above-ground biomass. If well-managed, localised irrigations can mitigate the impact of soil salinity by flushing and accumulating salts at the border of the wetted area through frequent water applications.
Besides the crop and soil type, the choice of the irrigation method also depends on the farmers' experience and skills, capital and operational costs, capacity in maintaining equipment (e.g. pumps, laterals, emitters, fertigation, filters etc.) and many other criteria. Drip-irrigation is generally preferred by farmers because it is easier to perform fertigation, it is more localised targeting the root system and more efficient in terms of non-beneficial water losses (no evaporation from sprayers and reduced evaporation from the soil surface). The estimated size of the wetting radius (or radius of the wetting bulb) is ≈1 m in loamy and clayey soils suitable to plum cultivation. On the other hand, micro-jet irrigation is preferred to create a cool micro-climate through short high-intensity water pulses that may reduce sunburn and preserve fruit quality. Short-duration pulse or mist irrigation may also be applied during the hottest hours of the day in the case of heat waves.

Although research data showed that micro-jets use on average 9% more water than drip irrigation, exceptions were recorded and a blanket approach cannot be used when selecting an irrigation method, but rather a case-by-case approach is advised which takes into account the root distribution, soil texture and planting density among other factors. The choice of the irrigation method also depends on the design, irrigation scheduling, farm operations, orchard management practices etc. Micro-sprinkler systems use more water, however, the shallow and wide wetting pattern is more conducive to optimal tree water status (meeting the plant's water demand by adequately wetting the root zone) compared to the narrow and deep wetting pattern observed under drip irrigation systems, which leaves the trees more prone to water stress. Therefore, the solution lies in the design and implementation of precision irrigation technologies which strike a balance between reducing water consumption (maximizing water use efficiency) and maintaining fruit yield and quality.

Figure 8. Drip irrigation (left) and micro-jet irrigation in plum orchards.

IRRIGATION MANAGEMENT AND SCHEDULING

Operation and maintenance programmes for irrigation of plum orchards include the collection of the following information:

- Climatic data (rainfall, solar radiation, temperature, relative humidity, wind speed and reference evapotranspiration)
- Irrigation design data, infrastructure and equipment (water availability and allocation, water withdrawal, storage, pumping, distribution networks)
- Irrigation water quality
- Monitoring of plant conditions
- Irrigation and cropping calendars

- Programmes for dates and areas to be irrigated (water distribution and rotational schedules)
- Plans for the maintenance of irrigation schemes
- Labour availability

Maintenance of the irrigation system involves periodic servicing of pumps, filters, injectors of fertigation. This is usually done off-season (April to August) and it should ensure a high water use efficiency at the irrigation scheme level.

Irrigation water use efficiency (WUE) is commonly defined as:

$$WUE = \frac{Water\ consumed\ for\ the\ intended\ use}{Water\ abstracted/delivered}$$

and expressed in %. WUE in the storage and distribution system can drop down to 50% or less if the irrigation system is not maintained properly (half or more of the water abstracted does not reach the intended use). This may be due primarily to water evaporation from storage facilities (dams and reservoirs), linear water losses along canals or conveyance pipes, as well as pipe and fittings leakages. Maintenance of the infrastructure is therefore imperative to reduce water losses.

Extensive use of maps is made on commercial plum farms in order to get an overview of topography, contour lines, soil type and properties, block arrangements and dimensions, cultivars, age, height, planting density and row orientation of orchards, water sources and distribution system, farm roads and buildings.

In recent times, loadshedding has affected normal operations of pumps and irrigation management needed to be adapted to avoid power cuts and preserve water pumps by switching them off and on before and after load-shedding schedules. Many farms are considering the use of alternative non-renewable energy sources such as solar energy.

For irrigation management, soil type and soil properties need to be established:

- Soil forms and horizons
- Soil texture
- Permeability and drainage
- Soil depth and water holding capacity
- Soil fertility
- Chemical properties to identify potential salinity, alkalinity and toxicity problems

Soil available and readily extractable water need to be determined based on soil properties and rooting depth. Rooting depth is often limited due to the shallow soils in the Western Cape.

- Irrigation scheduling (when and how much to irrigate) makes use of a variety of methods:
- Gravimetric measurement of soil water content consists in sampling soil from the root zone and drying it in an oven to determine the soil water content. Experienced farmers may also use the "look and feel" method by feeling soil moisture through the fingers.
- Atmospheric measurements are based on the crop coefficient method described in the next section. Researchers use micrometeorological stations to measure the energy balance fluxes above the orchard canopy (Bowen ratio, eddy covariance etc.).
- Plant-based irrigation scheduling methods make use of sap flow measurements, indicators of water stress such as leaf/stem water potential, stomatal conductance, dendrometers to measure tree trunk diameters, canopy temperature measurements and remote sensing of vegetation with satellite or drone imagery. Experienced farmers may spot visually symptoms of plant water stress by observing wilting, curling or falling leaves, reduced growth and canopy cover; however, these symptoms are visible only at an advanced stage of water stress.
- Soil-based methods make use of the soil water balance and they rely on the measurement of soil water content or soil water potential with instruments and sensors such as tensiometers, electrical resistance blocks, capacitance and time domain reflectometry probes.

Common frequencies of drip- and micro-jet irrigation on Western Cape farms is daily to every three days in the absence of rainfall, depending on the crop stage.

Irrigation scheduling services in the Western Cape are provided by a large community of consultants and suppliers of equipment. The irrigation scheduling service provision usually consists of soil water content devices or sensors (neutron probes, soil capacitance sensors, time domain reflectometry) coupled with remote data acquisition and Internet platforms. Examples of such systems are Motorola, DFM, Irrigator and Irricon. FruitLook (FruitLook, https://fruitlook.co.za/ accessed on 3 May 2023) also provides irrigation scheduling services based on satellite data acquisition.

CROP COEFFICIENTS OF PLUMS

The growth curve of Japanese plum in the Western Cape follows the pattern in Figure 9 and it can be approximated with the four-stage FAO crop coefficients for crop water requirements: initial, development, mid-stage and late stage (Allen et al., 1998; Pereira et al., 2021). The onset of shooting marks the end of the initial and beginning of the development stage in September. It coincides with the beginning of the irrigation season, the timing of which depends on rainfall. Full development occurs in mid-October when the mid-stage begins and it lasts until after maturity and harvest, depending on the cultivar. After harvest, irrigations are reduced, however trees continue to grow although they shed leaves until June. The dormancy period is between June and September. As temperate cover crops/grasses are planted in many orchards between the rows, the crop coefficient may remain fairly high during winter dormancy.

Crop water requirements (ETc), or the amount of water to be replenished in the soil due to evapotranspiration losses, are calculated with the following equation:

ETc = Kc ETo

where ETo is the reference evapotranspiration calculated with the Penman-Monteith equation and depending on weather data solely, and Kc is the crop coefficient describing the crop characteristics. As crop coefficients may vary from orchard to orchard depending on climate and crop management practices (planting density, row spacing, cultivar, area wetted by irrigation), the crop coefficient is split into two components:

ETc = (Kcb + Ke) ETo

where Kcb is the basal crop coefficient related to transpiration (beneficial water consumption) and Ke is the component related to non-beneficial water consumption (commonly soil evaporation).

Recommended FAO basal crop coefficients (Kcb) based on experimental data are summarised in Table 2. As orchard-specific crop coefficients can be calculated from canopy cover (f_c) and leaf area index (LAI), typically measured values of f_c and LAI are also reported in Table 2. These values, however, depend on crop management and pruning.

Figure 9. Trends of FAO crop coefficient in plum orchards during different growth stages and months of the year.

Table 2. Recommended value ranges of FAO basal crop coefficients (Kcb) for growth stages, typical values of canopy cover (f_c) and Leaf Area Index (LAI), and crop height of Japanese plums in the Western Cape.

Variable		Range values
Initial stage	f_c	0.34-0.59
	LAI	0.55-1.22
	Kcb	0.84-0.98
Mid-stage	f_c	0.82-0.91
	LAI	2.35-3.37
	Kcb	1.14-1.20
Crop height (m)		3.0-3.5

Basal crop coefficients for specific orchards and stages can be calculated from LAI and f_c using the method of Allen and Pereira (2009). The method of Allen and Pereira (2009) proved to be sufficiently robust to determine Kcb with the calculations summarized in Box 1. "Robust" implies that the calculated values of Kcb do not change dramatically as long as realistic input data are used in the calculations. As the calculations in Box 1 are quite lengthy, a spreadsheet calculator was compiled to determine Kcb for specific orchards as a function of LAI and f_c. The "***Kcb calculator***" spreadsheet is attached to this guidelines.

LAI and f_c can be measured with scientific instruments, such as the LAI2200 plant canopy analyser (manufactured by Li-Cor, Nebraska, USA), or obtained from sources that use satellite imagery, such as FruitLook (https://fruitlook.co.za/ accessed on 3 May 2023). For the user's convenience, a database of pictures of orchards taken at different stages of the season with corresponding LAI and f_c values was compiled. This is attached as Appendix 1 to these guidelines. The user can estimate the LAI and f_c by comparing the current look of the orchard to the pictures.

Finally, Kcb are plugged into the equation:

ETc = (Kcb + Ke) ETo

to calculate crop water requirements ETc for irrigation scheduling purposes. The reference evapotranspiration ETo is calculated with the Penman-Monteith equation (Allen et al., 1998):

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

R_n - Net radiation (MJ m^{-2} d^{-1})
G - Soil heat flux (MJ m^{-2} d^{-1})
(R_n – G) - Available energy at the land surface (MJ m^{-2} d^{-1})
Δ - Slope of the saturation vapour pressure-temperature curve (kPa °C^{-1})
T – Average daily temperature (°C)
u_2 – Average daily wind speed at 2 m height (m s^{-1})
e_s – Saturated vapour pressure (kPa)
e_a – Actual vapour pressure (kPa)
(e_s – e_a) – Vapour pressure deficit (kPa)

Many software packages exist for the caculation of ETo with the Penman-Monteith equation. However, the ETo values are usually supplied directly with weather station data, such as those managed by the Agricultural Research Council.
The crop coefficient related to soil evaporation (Ke) varies in time. It is high when the soil is wet (after rainfall or irrigation) and it reduces during a soil drying cycle. A procedure to calculate daily Ke is explained in the FAO56 Bulletin (Allen et al., 1998). However, for all practical purposes, the Ke coefficient is very small under drip- or micro-jet irrigation because the wetted portion of the ground is predominantly in the shade of tree rows. Rallo et al. (2021) recommended an indicative standard value of 0.05 for Ke for very high-density stone fruit trees.
In summary, the step-by-step procedure recommended to calculate the crop coefficients (Kcb and Ke) and crop water requirements ETc in high-density, fully-bearing irrigated plum orchards is outlined in Box 2. Irrigations should be scheduled to replenish ETc.

CALCULATION OF BASAL CROP COEFFICIENT (KCB) FROM LEAF AREA INDEX (LAI) AND CANOPY COVER (FC) USING THE METHOD OF ALLEN AND PEREIRA (2009).

For tree crops having grass or other ground cover, Kcb is calculated as follows:

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

$K_{cb\ cover}$ – Kcb of the ground cover in the absence of tree foliage
K_d – Canopy density coefficient
$K_{cb\ full}$ - Estimated Kcb during peak plant growth for conditions having nearly full ground cover (or LAI ≈ 3)

$K_{cb\ cover}$ is estimated to be 0.7, based on the value reported by Allen and Pereira (2009, in Table 4) for the initial stage of fruits (apricots, peaches, pears, plums, pecans) with no killing frost.

The K_d coefficient can be calculated as follows (Allen and Pereira, 2009):

$$K_d = 1 - e^{(-0.7\ LAI)}$$

LAI and f_c can be measured with the LAI-2200 plant canopy analyser and they are found to be quite stable during the season if the trees are pruned to the required canopy size. Average LAI is therefore used in the equation to calculate K_d.

$K_{cb\ full}$ is calculated according to the following equation (Allen and Pereira, 2009):

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

F_r - Downward adjustment ($F_r \leq 1.0$) if the species exhibits more stomatal control on transpiration than is typical of most annual agricultural crops

h – Crop height (m)

u_2 – Wind speed at 2 m height (m s^{-1})
RH_{min} – Minimum daily relative humidity (%)

Crop height can be easily measured in the field, whilst u_2 and RH_{min} can be obtained from weather stations. The adjustment F_r can be calculated as follows (Allen and Pereira, 2009):

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

Δ – Slope of the saturation vapour pressure-air temperature curve (kPa $°C^{-1}$)

γ – Psychrometric constant (kPa $°C^{-1}$)

r_l - Mean leaf resistance for the species (s m^{-1})

The slope of the saturation vapour pressure-air temperature curve can be calculated with equation:

$$\Delta = \frac{4098\left[0.6108\,exp\left(\frac{17.27\,T}{T+237.7}\right)\right]}{(T+237.3)^2}$$

where T is the daily average temperature in °C. The psychrometric constant is approximately 0.0665 kPa $°C^{-1}$ at standard atmospheric pressure. In the absence of measurements of stomatal resistance, r_l for plums is assumed to be 100 s m^{-1} resulting in $F_r = 1$.

STEP-BY-STEP PROCEDURE TO CALCULATE CROP WATER REQUIREMENTS IN IRRIGATED PLUM ORCHARDS:

1. Obtain **weather data** from a nearby weather station.
2. Consult the database of pictures of orchards at different stages of the season with corresponding values of **Leaf Area Index (LAI)** and **canopy cover (f_c)** (Appendix 1).
3. Use the Kcb calculator spreadsheet to calculate the **basal crop coefficient Kcb**.
4. Use 0.05 for the **soil evaporation coefficient Ke**.
5. Apply the formula to calculate crop water requirements in mm:

   ETc = (Ke + Kcb) ETo
6. Plan irrigations to replenish the calculated ETc.

PLUM WATER STRESS

Knowledge on plant-water relations is fundamental in identifying the onset of water stress and for irrigation scheduling, i.e. deciding the timing and volume of irrigation. This is particularly important in intensive high-yielding plum orchards to sustain high productivity and secure stable income. Plums are anisohydric plants, i.e. they keep stomata open and transpire under water stress. This adaptation behaviour allows them to sustain photosynthesis and biomass accumulation during water stress, however at the risk of dehydrating. For this reason their water potential energy, notably in the stem, drops considerably during the hottest parts of the day. The midday stem water potential was often demonstrated to be a good indicator of water stress in plums, with a threshold value of -1.5 MPa (15 b) generally recommended in the literature.

The development stage is the period when high water consumption of plums commences in the year. Critical stages for water stress in plums are early fruit set, flower bud initiation and formation, and final fruit swell (2-4 weeks before harvest), when water shortages may result in small fruit or loss of fruit (stages I and III in Figure 10). The resulting recommendation (Torrecillas et al., 2018) is to regulate plant water stress to stage II of fruit development and the post-harvest stage to avoid impacts on fruit size (Figure 10). Midday stem water potential should be maintained >-0.7 MPa in stage I, >-1.5 MPa in stage II, >1.0 MPa in stage III and >-1.65 MPa at post-harvest. However, this may also depend on the water stress tolerance of the crop as some cultivars may be better adapted to drought conditions than others.

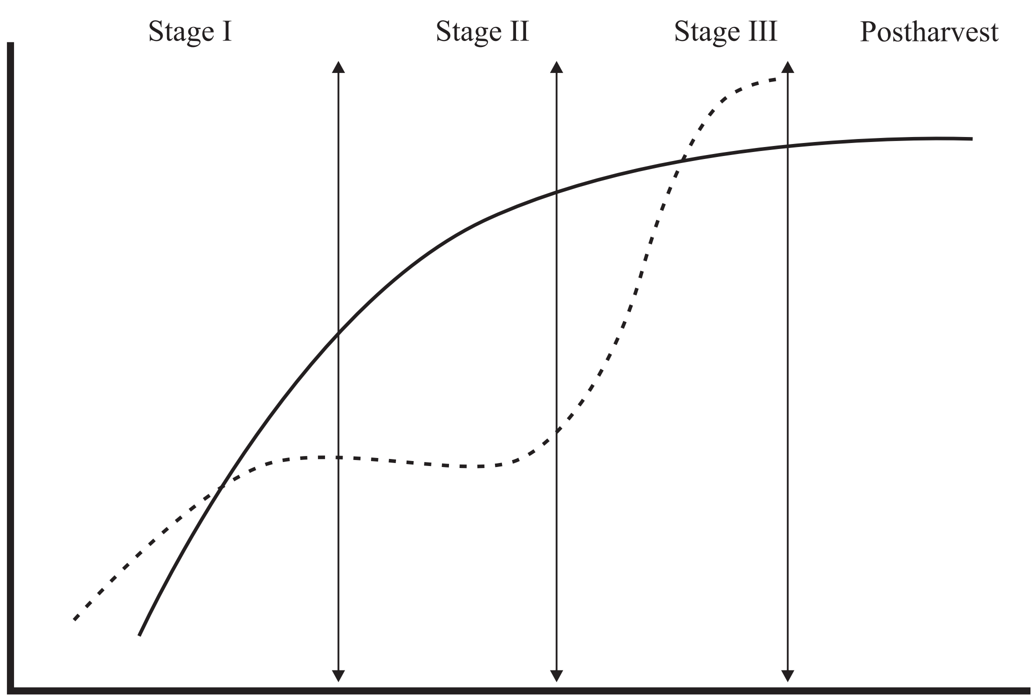


Figure 10. Developmental stages in plums from flowering to rest, where the solid line represents vegetative growth and the dashed line is the fruit growth (Torrecillas et al., 2018).

CROP WATER REQUIREMENTS AND PRODUCTIVITY

Estimated seasonal water consumption through evapotranspiration in Western Cape plum orchards depends mainly on climatic conditions and orchard management. Table 3 summarises typical annual crop water requirements in two climatic regions for the full year (from 1 September to 31 August of the following year).

Full-year crop water requirements are essential for water allocations as many orchards need to be irrigated after harvest, although at reduced rates, in order to avoid damage or death of trees due to drought and water stress, and to prevent carry-over effects to the next season. Crop water requirements are higher in Robertson than in Wellington because the atmospheric evaporative demand is higher (reference evapotranspiration).

Orchards with higher LAI exhibit higher crop water requirement. Yields are comparatively higher in Robertson because of more favourable climatic conditions, which also reflects in the higher crop water productivity, provided the orchards are high-density, fully-bearing and well-managed.

Table 3. Reference evapotranspiration, crop water requirements, yields and biophysical crop water productivity measured in early and late-maturing plum cultivars in two production regions of the Western Cape (full year).

Location and cultivar	Robertson (Klein Karoo)		Wellington	
	Late-maturing	Early-maturing	Late-maturing	Early-maturing
Reference evapotranspiration (mm)	1188-1214	1188-1214	1129-1196	1129-1196
Crop water requirement (mm)	1076-1267	1190-1285	958-1170	1094-1149
Yield (t ha^{-1})	51.0-52.0	39.8-42.0	32.0-36.0	28.4-37.9
Biophysical crop water productivity (kg m^{-3})	4.03-4.51	3.10-3.31	2.97-3.34	2.87-3.59

Considering maximum crop water requirements in Table 2 and reducing them by the average annual rainfall in Wellington and Robertson, the following maximum water allocations for plum irrigation are recommended:

- Wellington
    - Late-maturing cultivar (African Delight): 7,800 m^3 ha^{-1} (780 mm)
    - Early-maturing cultivar (Ruby Sun): 7,500 m^3 ha^{-1} (750 mm)
- Robertson
    - Late-maturing cultivar (African Delight): 10,000 m^3 ha^{-1} (1,000 mm)
    - Early-maturing cultivar (Fortune): 10,200 m^3 ha^{-1} (1,020 mm)

In view of water shortages, water costs and the need to maximize farm benefits, the productivity of water can be quantified as:

Biomass water productivity (kg m^{-3})

$$\boldsymbol{WP = \frac{kg\ biomass\ produced}{m^3\ of\ water\ used}}$$

As farmers are not interested in total biomass produced, water productivity can be more appropriately expressed as:

Biophysical (crop) water productivity (kg m^{-3})

$$CWP = \frac{kg\ yield\ produced}{m^3\ of\ water\ used}$$

Expected yields and biophysical water productivities of full-bearing, high-density plum trees are reported in Table 2 for two production regions in the Western Cape and early/late cultivars. Farmers may be even more interested in income or profit rather than total yields, so water productivity can be expressed as:

Economic water productivity (ZAR m^{-3})

$$EWP = \frac{Profit\ generated}{m^3\ of\ water\ used}$$

EWP is a particularly interesting indicator of productivity when farmers use reduced irrigation (deficit irrigation) to sacrifice some yield but get products of better quality, e.g. for the export market, resulting in more income/profit per unit water used ("more income per drop"). Deficit or regulated deficit irrigation are relatively novel strategies that need to be investigated for plums in South Africa through research.

IRRIGATION WATER QUALITY

An original reference document for assessing the fitness of water quality for agricultural use was the South African Water Quality Guidelines (DWAF, 1996). This document provides thresholds of water quality for agricultural use. Plum is considered a sensitive crop to salinity, according to the well-known Maas and Hoffman tables (Maas, 1990). Threshold values applicable to sensitive crops should therefore be applied to plums according to the South African Water Quality Guidelines (DWAF, 1996). Plum is also sensitive to B (0.5-1.0 mg/L) and foliar application of Cl (>175 mg/L) and Na (>115 mg/L) that may result in foliar injury (DWAF, 1996).

It has been recognised, however, that the approach of the South African Water Quality Guidelines based on conservative threshold values is too rigid for applications in agricultural irrigation, where water quality constituents and their effects on crops vary in time and space, and they can be managed. The old South African Water Quality Guidelines for agriculture have recently been reconsidered by du Plessis et al. (2017) and a risk approach has been recommended to determine water quality fitness for irrigation.

This was necessary firstly, because the fitness for use of a specific water implies different levels of acceptability and probability of risk occurrence. Secondly, the impacts of irrigation water quality is very site-specific so that generic rigid thresholds are not always applicable. For this purpose, Du Plessis et al. (2017) developed a Decision Support System (DSS) for evaluating the water quality fitness for irrigation based on the following suitability indicators categorized into impacts on soil quality, crop yield and quality, and irrigation equipment:

- Soil Quality
    - Root zone salinity
    - Soil permeability
    - Oxidizable carbon loading
    - Trace elements accumulation
- Crop Yield and Quality
    - Root zone effects
    - Leaf scorching when wetted
    - Contribution to NPK removal
    - Microbial contamination
    - Qualitative crop damage by atrazine
- Irrigation Equipment
    - Corrosion or scaling of equipment
    - Clogging of drippers

The DSS for the assessment of fitness of water quality for irrigation can be obtained from the published report of Du Plessis et al. (2017) and website https://www.nbsystems.co.za/downloads.html (accessed on 5 May 2023).

REFERENCES

- ALLEN RG and PEREIRA LS (2009) Estimating crop coefficients from fraction of ground cover and height. *Irrigation Science* **28** 17–34. DOI 10.1007/s00271-009-0182-z.
- ALLEN RG, PEREIRA LS, RAES D, SMITH M (1998) ***Crop evapotranspiration. FAO Irrigation and Drainage Paper 56***. Food and Agriculture Organization (FAO), Rome, Italy.
- DU PLESSIS M, ANNANDALE J, BENADE N, VAN DER LAAN M, JOOSTE S, DU PREEZ C, BARNARD J, RODDA N, DABROWSKI J, GENTHE B and NELL P (2017) ***Risk Based, Site-Specific, Irrigation Water Quality Guidelines: Volume 1. Description of Decision Support System***. Water Research Commission Report No. TT 727/17, Pretoria, South Africa.
- DWAF (1996) ***South African Water Quality Guidelines. Volume 4: Agricultural Water Use: Irrigation***, 2nd Ed., Department of Water Affairs and Forestry, Pretoria, South Africa.
- FAO (2007) ***Handbook of Pressurized Irrigation Techniques***. Food and Agriculture Organization (United Nations), Rome, Italy.
- FONTEH MF (2017) Guidelines for sustainable irrigation system design and management in sub-Saharan Africa. African Journal of Agricultural Research 12(20) 1747-1755. DOI 10.5897/AJAR2017.12343.
- HALDER S, SADHUKHAN S and VERMA R (2012) Adaptability of drip irrigation in coastal and hard rock terrain of West Bengal, India. International Ground Water Conference 2012, Aurangabad, Maharashtra, India.
- MAAS EV (1990) Crop Salt Tolerance. In: ***Agricultural Salinity Assessment and Management***, KK Tanjii (Ed.). ASCE Manuals and Reports on Engineering Practice No. 71. ASCE, New York, USA.
- MALIK N (2020) Shade net studies on two Japanese plum cultivars ***(Prunus salicina*** Lindl.). MSc Thesis, Stellenbosch University, South Africa.
- PEREIRA LS, PAREDES P, HUNSAKER DJ and LOPEZ-URREA R (2021) Updates and advances to the FAO56 crop water requirements method. ***Special Issue in Agricultural Water Management***. https://doi.org/10.1016/j.agwat.2020.106697
- RALLO G, PACO T, PAREDES P, PUIG-SIRERA A, MASSAI R, PROVENZANO G and PEREIRA LS (2021) Updated single and dual crop coefficients for tree and vine fruit crops. ***Agricultural Water Management***. https://doi.org/10.1016/j.agwat.2020.106645
- TORRECILLAS A, CORELL M, GALINDO A and PEREZ-LOPEZ D (2018) Agronomical effects of deficit irrigation in apricot, peach, and plum trees. In: I.F. Garcia-Tejero and V.H. Duran-Zuazo (eds.) ***Water Scarcity and Sustainable Agriculture in Semiarid Environment: Tools, Strategies and Challenges for Woody Crops***, Chapter 5, pp. 87-109. Elsevier-Academic Press, The Netherlands.

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