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Transpiration of Irrigated Tahiti Acid Lime Trees with Different Canopy Leaf Areas, Reference Evapotranspiration and Water Balance for Precision Irrigation Schemes

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ABSTRACT

Regardless of the canopy leaf area, daily normalized transpiration (per unit leaf area) of irrigated Tahiti acid lime trees were equivalent to the normalized reference evapotranspiration (per unit of grass leaf area). Normalized transpiration represented about 1/3 of the reference evapotranspiration (ETo) during the growing season. Such coefficient represents the inverse of the leaf area of a hypothetical reference surface. Tree phenology disturbed substantially such relationship during the physiological rest of autumn/winter when photoperiod was short and minimum temperature was below 15°C. Normalized transpiration was nearly constant (≈ 0.4 L m^{-2} leaf d^{-1}) and independent of ETo during the rest period. However, once the tree was physiologically prepared to bloom (late winter/early spring) minimum temperature was not a limiting factor to the transpiration. Large canopy leaf area (99 m^2) did play a major role reducing drastically the normalized transpiration during summer days with high atmospheric demand (minimum relative humidity below 50%; maximum vapor pressure deficit above 2 kPa). During such days transpiration was reduced by 30 to 40% indicating that the shallow root system was not able to uptake soil water fast enough to supply the large transpiration surface under high demand. Conversely, a small tree (3 m^2 of leaf area) did not show any transpiration restriction. This is an indication that a pruning or topping program would reduce the growth of the transpiring area to keep a potential transpiration rate. An individualized soil water balance approach for precision irrigation schemes is presented.

Keywords: citrus, fraction p, minimum temperature, rootzone depth, vapor pressure deficit

INTRODUCTION

Shortages of stored and available fresh water world-wide and the costs of irrigation are leading to an emphasis on development of methods that minimize water use in large commercial orchards. Worldwide growers are embracing technology and riding the knowledge wave as they seek to develop sustainable production systems (Fernández *et al*. 2008). Improving irrigation management of fruit trees is of paramount importance in optimizing the use of limited resources (Fereres and Evans 2006). Precision irrigation in orchards evolved with the possibility of spatially variable delivery of water by automated and electronically controlled microsystems (Coates *et al*. 2006). The electronic technology has the potential to control the amount of water applied to each tree and an individualized soil water balance can be used to determine the moment to start the irrigation. Such customized irrigation system wets a restricted portion of the soil surface around a tree minimizing the soil evaporation from the non-wetted area (Bielorai 1982). Consequently, under restricted irrigation most of the lost water is through the tree transpiration, which is the amount used in the tree physiological processes, or the green water.

Several techniques are available for detecting the water needs of trees and some of the main advantages and disadvantages of different irrigation scheduling approaches are discussed by Jones (2004). Most of them require sophisticated or complex equipment, are labor intensive and not suitable for commercial use in large orchards, do not indicate the amount of water to be applied (Jones 2004), and are applied only to the monitored trees.

Precision irrigation requires the knowledge of the water used by each individual tree as well as its location in the field on real-time. An improved understanding of the tree transpiration on a daily basis can be used to enhance the precision of irrigation scheduling in orchards. It is also aimed at minimizing leaching of water and nutrients below the root zone, to avoid any potential water stress, and is crucial for improvement of irrigation management (Cohen 1991; Fares and Alva 1999). The amount of water to be applied and the time of irrigation are determined by the water balance of the soil around each tree. Soil water holding capacity depends on the physical properties of the soil and spatial variability is not unusual for most commercial orchards.

In nearly homogeneous tree size orchards it has been assumed that all trees transpire at the same rate. However, this can be an ill-assumption if the trees leaf areas vary spatially; consequently, some trees can receive either more or less water than needed resulting in a loss of productivity (Coates *et al*. 2006). Spatial variability of leaf area was reported in young acid lime trees (Silva *et al*. 2003). From a practical viewpoint an irrigation scheme should encompass the spatial variability of soil and plants within the orchard (Fernández *et al*. 2008).

Tree water use depends heavily on the weather conditions, on its leaf area (i.e., the effective transpiring surface) and on its phenology, and the objectives of this chapter are threefold. First, it will be discussed an empirical relationship between irrigated individual orchard tree transpiration (sap flow) and the reference evapotranspiration taking into account the tree leaf area (Fuchs *et al*. 1987; Cohen 1991; Pereira *et al*. 2006). Transpirations of Tahiti (*Citrus latifolia* Tan.) acid lime trees with 5 different leaf areas are included to discuss some effects of the canopy size. Second, an analysis of the effects of air temperature, relative humidity and solar radiation on the tree transpiration is presented to show the effects of the phenology of the citrus trees on

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water use and irrigations. To avoid unnecessary irrigations the citrus phenology has to be considered mainly in regions where the winter is not too intense but a rest period is necessary in order to have the trees prepared for the next blooming season. Third, it is presented a general concept of the individual tree soil water balance to improve an automated precision irrigation scheme.

MATERIALS AND METHODS

In order to detect the effect of the leaf area and phenology on the water use sap flows were measured in five "Tahiti" acid lime trees grafted on "Swingle" (*Poncirus trifoliata* L.) citrumelo rootstock with very distinctive leaf areas (i.e., A = 3, 48, 64, 87 and 99 m^2) along the year. The experimental orchard was located in Piracicaba, São Paulo, Brazil (22° 42′ S, 48° 39′ W, 511 masl) on a Rhodic Kandiudalf clay texture soil with 5% slope (Alves Jr *et al*. 2007). Tree spacing was 7 × 4 m with drip irrigation (4 emitters with 4 L h^{-1} discharge rate) and the orchard floor was kept clean during the experiments to avoid competition for the soil water. Total annual rainfall for the region is about 1 257 mm with a cool and dry winter (June to September) and irrigation was used to assure that soil water was not a limiting factor to the transpiration. Sap flows were measured using the heat balance technique and integrated throughout the day to have the daily transpiration (Baker and van Bavel 1987).

Daily reference evapotranspiration was estimated by the parameterization scheme of the Penman-Monteith approach as described in Allen *et al*. (1998). Weather inputs were taken from a nearby automatic weather station over a grass surface.

Graphical and simple statistical analyses were used to compare measured and estimated daily sap flows, and also to detect the effects of the weather elements upon the tree water use.

RESULTS AND DISCUSSION

It is intuitive that as the size of the transpiring area increases the water use has to increase proportionally in the same weather conditions, if soil water is not a limiting factor as expected in frequently irrigated orchards. One way to analyze the effects of the environmental conditions on the water use by trees with different leaf areas is to normalize the tree transpiration on a unit leaf area basis. Normalized transpiration tends to eliminate (or minimize) the effect of the tree size and the water use is reduced to a common scale allowing a better understanding of the effects of the weather elements. The goodness of such approach can be checked comparing sap flows per unit leaf area (S/A) measured simultaneously in two irrigated trees during a sequence of 23 rainless days (**Fig. 1**). During this experiment one tree (T1) had a total leaf area of 87 m^2 while in the other (T2) it amounted to 64 m^2. It was assumed that the leaf areas did not change substantially during these days.

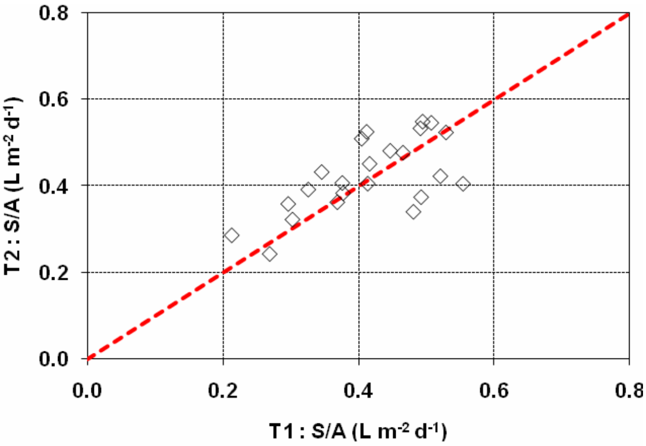

Fig. 1 Comparison of simultaneous sap flow per unit leaf area (*S/A*) for two irrigated Tahiti acid lime citrus trees with different leaf areas during 23 rainless days (T1 = 87 m^2; T2 = 64 m^2).

It became obvious that the normalized transpiration for trees of different canopy sizes have similar values as the scattered points were very close to the equal values line (1:1). Consequently, all relationships determined by the weather elements have the potential to be unique and not tree specific, and points with significant deviations can be used to understand possible environmental and phenological effects.

Tree transpiration and the reference evapotranspiration

It is very common in irrigation projects to relate daily tree water use with a reference evapotranspiration (*ETo*) through some empirical crop coefficient for adjustments to the local orchard conditions. Even though this approach is universally used as a conversion of *ETo* taken from regional weather stations for precision irrigation schemes Fuchs *et al*. (1987) indicated that its application needs judicious evaluations including leaf area index L. Such alternative was applied by Cohen (1991) to determine the transpiration of 17-year-old irrigated grapefruit trees in orchard near Bet Dagan, Israel, throughout the irrigation season. With data taken from selected days during the summer the average daily transpiration (T, mm d^{-1}) of two trees irrigated every 3 days was a fixed proportion of *ETo* (mm d^{-1}), i.e., $T = 0.281\ ETo\ L$ ($R^2 = 0.962$), and L (= 5.5 m^2 leaf m^{-2} ground) was the average leaf area index for the two trees. Consequently, the product 0.281 L (= 1.54) is the crop coefficient for the two trees and it is much larger than the values recommended in irrigation manuals and reports.

Dimensionally it can be seen that the ratio T/L represents the daily amount of water transpired per unit leaf area of the tree (i.e., mm d^{-1}/ [m^2 leaf m^{-2} ground] = L m^{-2} leaf d^{-1} = S/A). As discussed above the normalized irrigated tree transpiration becomes independent of the tree size and results from different trees tend to merge in a unique relationship of *ETo*. Indeed, analysis with data from apples, olives, walnut trees, and grapevines orchards in New Zealand indicate that the regression coefficients of such empirical relationship varied in a very narrow range between 0.346 and 0.355 (Pereira *et al*. 2006). Even though such values are a little higher than Cohen's 0.281 (1991) they confirm that about one third of *ETo* is a reliable estimate of the normalized tree transpiration.

Pereira *et al*. (2006) proposed that the irrigated tree normalized transpiration is equal to the normalized *ETo*, i.e., $T/L = ETo/L_o$, and L_o is the leaf area index of the reference surface. The reference surface was defined as a hypothetical grass field with constant L_o = 2.88 (Allen *et al*. 1998). Therefore, theoretically the relationship becomes $T/L = 0.347\ ETo$. The reliability of the calculations rests on good knowledge of tree leaf area and this approach could have a greater impact on the use of computer-based tools for scheduling irrigation (Fernández *et al*. 2008).

Fig. 2 displays the relationship between T/L and *ETo* for Tahiti acid lime trees with leaf areas varying from 3 to 99 m^2. During the summer (January and February) and early spring (August) days the relationship had a regression coefficient of 0.34 (± 0.05; $R^2 = 0.76$, n = 29). Summer is the local rain season and it is difficult to take representative sap flow measurements for days of low *ETo* due to rainfall interruptions; consequently, only a few days with reliable data is included in the present analysis, but the results confirm the one third relationship described above.

It is worth noting that the large tree with 99 m^2 of leaf area did show a sequence of 5 days with drastically reduced transpiration under high evapotranspirative demand (T1 HD: $ETo > 5$ mm d^{-1}). The regression coefficients for the 5 days varied from 0.19 to 0.26, and were not included in the regression line fit shown above. Cohen (1991) also reported a drop in this coefficient for days with extremely high evaporative demands. During the 5 days the normalized tree transpiration was almost constant and about 1.1 L m^{-2} leaf d^{-1} but well below the 1.6 to 1.9 L m^{-2} leaf d^{-1} predicted by

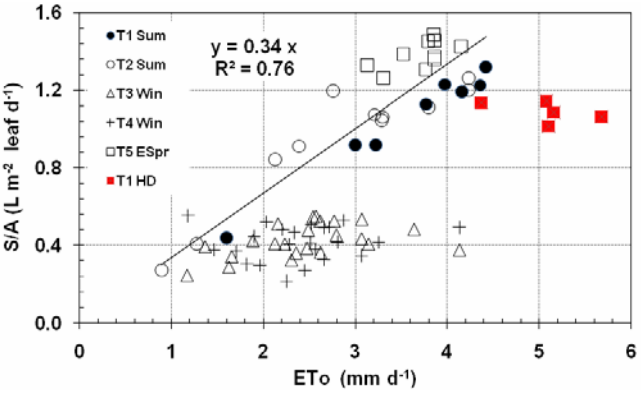

Fig. 2 Transpiration per unit leaf area (*S/A*) versus daily reference evapotranspiration (*ETo*) for 5 Tahiti acid lime citrus trees with different leaf areas (A1 = 99 m^2; A2 = 48 m^2; A3 = 64 m^2; A4 = 87 m^2; A5 = 3 m^2). T1 HD = tree 1 during days with high evapotranspirative demand.

the statistical relationship for the corresponding *ETo* values. In the 5 days the incoming solar radiation (S_R) varied from 26 to 31 MJ m^{-2} d^{-1}, with afternoon temperatures between 29 and 33°C, and vapor pressure deficit of 3 to 4 kPa. Even though the volume of water transpired was very large and amounted to 100–113 L d^{-1} it represented only 60 to 70% of the predicted potential demand for the period (160 to 190 L d^{-1}). It is here inferred that the shallow citrus tree root system was not able to supply the leaf canopy with the required amount of water during these 5 days.

The amount of water effectively transpired by the tree with leaf area of 99 m^2 during the 5 days (533 L) would be enough to supply the needs of the 48 m^2 tree (62 L d^{-1}) for at least one week. Therefore, a pruning or topping program can be used to control the growth of the transpiring surface to reduce significantly the irrigation necessary to keep the potential transpiration of the orchard during peak of water requirement.

It is interesting to note that during the winter (dry season) measurements taken during 44 days in two other trees with different leaf areas (A3 = 64 m^2; A4 = 87 m^2) did not show any relationship with *ETo* up to 4 mm d^{-1}. In fact, the normalized transpiration was almost constant, very low and equal to 0.4 L m^{-2} of leaf d^{-1}. The corresponding incoming solar radiation varied from 6 to 17 MJ m^{-2} d^{-1} and it was in the normal range for the season. This is an indication that tree phenology has also to be taken into consideration when designing citrus irrigation systems. During days with short photoperiods (autumn and winter) the citrus trees have a reduced metabolism and ETo (or S_R) is not a good indicator of transpiration. These results substantiate the recommendation that irrigation can be suppressed for 4 to 5 weeks to favor the flowering induction by a not too intense soil water deficit during the low temperature season (Reuther 1977; Doorenbos and Kassam 1979; Southwick and Davenport 1986; Davies and Albrigo 1994; Iglesias *et al.* 2007; Prado *et al.* 2007).

Normalized transpiration (in MJ m^{-2} d^{-1}) during the summer (January and February) and early spring (August) dissipated approximately 16% of S_R ($R^2 = 0.76$; n = 29) for $S_R < 26$ MJ m^{-2} d^{-1}. Considering the local long term relationship between weather station grass net radiation (R_N) and S_R (i.e., $R_N \approx 0.6\ S_R$) the transpiration consumed about ¼ R_N. This value confirmed the results reported by Pereira *et al.* (2007) with apples, olive and walnut trees. Obviously this approach does not apply during the winter when the citrus trees have a reduced metabolism.

An important climatological factor conditioning this lack of response of the tree transpiration to the *ETo* stimulus is the minimum temperature and it is discussed in the next section.

Effect of minimum temperature

Water uptake by the citrus root system is dependent on the soil temperature. Root hydraulic conductivity, which is a measure of the water uptake, increases considerably from 10 to 30°C (Syvertsen 1981; Wilcox and Davis 1981). Most citrus species make little or no shoot elongation and the root growth ceases when the soil or the air temperatures fall below about 15°C (Reuther 1977; Shalhevet and Levy 1990).

Fig. 3 displays the relationship between normalized transpiration and the corresponding daily minimum air temperature. The early spring/summer and the winter days do form very distinctive clusters of dispersion points. In fact, during the winter days of measurements (June/July) the minimum temperature was below 15°C for many days in a sequence and this might explain the results displayed for the *ETo*. Minimum temperature conditioned the tree transpiration when the photoperiod was decreasing. It is interesting to note that during the early spring days (August), with increasing photoperiod, the minimum temperature were also below the 15°C threshold but the tree was already at the beginning of the flowering period and the normalized transpiration was not affected by the minimum temperature. This is an indication that daily minimum temperature by itself is not a good indicator of orchard water use and the tree phenology plays a major role in controlling irrigations.

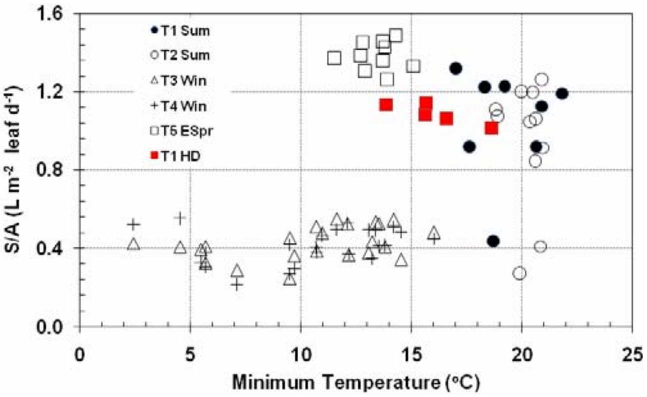

Fig. 3 Transpiration per unit leaf area (*S/A*) and daily minimum air temperature for 5 Tahiti acid lime citrus trees with different leaf areas (A1 = 99 m^2; A2 = 48 m^2; A3 = 64 m^2; A4 = 87 m^2; A5 = 3 m^2). T1 HD = tree 1 during days with high evapotranspirative demand.

Effect of atmospheric vapor pressure deficit

Leaf conductance in citrus is negatively associated with hourly midday atmospheric vapor pressure deficit even when soil moisture in the root zone is not a limiting factor (Cohen and Cohen 1983). Afternoon minimum relative humidity (*RH*) during the summer and early spring days did have a pronounced effect on the daily total tree transpiration (**Fig. 4**). During this period tree transpiration increased almost linearly as *RH* decreased down to 50%, but for *RH* below this threshold tree transpiration was nearly constant. This is an indication that under high evapotranspirative demand the citrus tree is not able to pump up the required water amount to maintain high transpiration rates. It became also clear that under high atmospheric demand for water the size of the tree leaf area plays also an important role as the transpirational restriction is more pronounced in the tree with 99 m^2 than in the much smaller one with 3 m^2.

Low minimum *RH* is associated with maximum vapor pressure deficit (*Da*) and the transpirational restriction did occur when *Da* was greater than 2 kPa (**Fig. 5**). Large *Da* induces an overall reduction in tree bulk water vapor conductance by stomata closure in the most exposed leaves to the incoming solar radiation. Leaf conductance of Shamouti orange (*Citrus sinensis* L. Osbeck) was negatively cor-

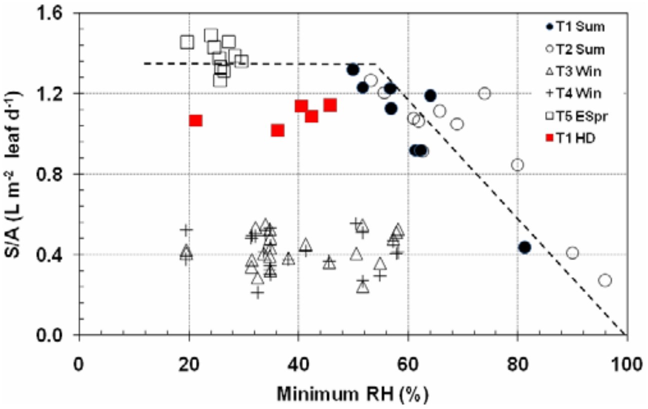

Fig. 4 Transpiration per unit leaf area (*S/A*) and daily minimum air relative humidity for 5 Tahiti acid lime citrus trees with different leaf areas (A1 = 99 m^2; A2 = 48 m^2; A3 = 64 m^2; A4 = 87 m^2; A5 = 3 m^2). T1 HD = tree 1 during days with high evapotranspirative demand.

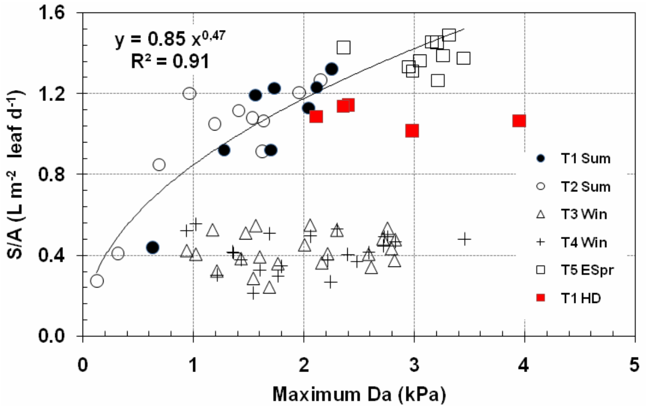

Fig. 5 Transpiration per unit leaf area (*S/A*) and daily maximum vapor pressure deficit (*Da*) for 5 Tahiti acid lime citrus trees with different leaf areas (A1 = 99 m^2; A2 = 48 m^2; A3 = 64 m^2; A4 = 87 m^2; A5 = 3 m^2). T1 HD = tree 1 during days with high evapotranspirative demand.

related with *Da* even when the soil moisture in the root zone was high (Cohen and Cohen 1983). *Da* was the dominant regulator of sweet orange (*Citrus sinensis* L. Osbeck) canopy transpiration as it explained about 80% of the variations in canopy conductance (Oguntunde *et al.* 2007).

Soil water balance for precision tree irrigation

Precision irrigation of orchard trees requires the knowledge of the time and the amount of water to be applied in each event for each tree. Such informations are only possible if a soil water balance for each tree is worked out in real-time and this is nowadays feasible with the present level of electronic and irrigation technologies. The soil works as an active reservoir for water that is taken up by the roots as required by the transpiration. The amount of water stored in the soil depends on the volume explored by the roots of each tree. Such volume is a direct function of the soil physical properties and of the size of root system. The size of the root system is taken into account by the definition of an effective depth of soil explored by the roots and by the surface area that contains most of them. Effective soil depth for irrigation control should contain between 75 and 85% of the roots. Such percentage figures are enough to avoid excessive water stresses between irrigation events and also to minimize leaching losses mainly in sandy soils.

Root distribution is strongly affected by the soil physical conditions and the excavation of 93 grapefruit trees in the Lower Rio Grande Valley (Texas, USA) showed that there is not a typical root system for citrus (Adriance and Hampton 1949). It is known that citrus trees in general have a moderately shallow and spreading rooting habit (Reuter 1977; Kriedemann and Barrs 1981). The horizontal spreading of the roots in orchards is limited by the spacing between the trees. In close spacing orchards each tree has its root system growth limited by the presence of its neighbor's roots competing for water and nutrients. An isolated tree has its roots spreading in all directions of a circular area around the trunk. But as the spacing decreases mainly along the planting line the circle becomes an oblong tending to a rectangular area. For precision irrigation the surface area appropriate for the individual soil water balance can be taken as that covered by tree canopy drip area.

It is also known that even for nearly identical soils the effective root depth varies with the irrigation frequency. Under frequent irrigations the root system tends to concentrate near the soil surface where the soil water is kept near field capacity most of the time. Root growth is also affected by the availability of nutrients and they tend to concentrate around the emitters under fertigations and the effective root depth was about 0.3 m for a 26-year-old grapefruit (*Citrus paradisi* MacFadyen) tree on sour orange (*C. aurantium* L.) rootstock (270 trees ha^{-1}) on two row raised beds (Zhang *et al.* 1996).

The amount of water (*AW*, in L) that can be stored in the effective root zone depth (Z_{EF}, in m) and the irrigated surface area around the tree (I_A, in m^2), between field capacity (*FC*, in m^3 water m^{-3} soil) and permanent wilting point (*PWP*, in m^3 water m^{-3} soil), can be computed as $AW = 1000\ (FC - PWP)\ Z_{EF}\ I_A$. Expressing the amount of water in liters instead of the conventional millimeters helps the dimensioning of the volume of water to be applied in each irrigation event, the number of and the rate of emitters, and also the size of the reservoir necessary to store the water required to supply the orchard during the irrigation season.

If the soil physical properties (*FC* and *PWP*) are not available for the site an alternative solution is to use the practical rule to determine *AW* as a function of the soil texture as recommended by the FAO irrigation and drainage paper 33 (Doorenbos and Kassam 1979). A soil with a heavy (clay) texture can store up to 200 L m^{-3}, while a light (sandy) texture holds only 60 L m^{-3}, and an intermediate texture is able to keep about 140 L m^{-3}. Roots systems adapt to the soil physical conditions and are deeper in light textured soils than in those with heavy structure compensating for the smaller water holding capacity. Therefore, Z_{EF} varies with the soil texture but *AW* is about the same if the horizontal spreadings of the roots are similar (same spacing).

For irrigation purposes only a fraction (*p*) of the total stored water should be considered as readily available water (*RAW*, in L). This concept of $RAW = p\ AW$ is a practical solution to simplify the water balance in large commercial orchards without any plant or soil indicator. For citrus orchards *p* is about 0.4 to 0.5 (Doorenbos and Kassam 1979; Allen *et al.* 1998).

Knowing that the soil is an active water reservoir and that the energy necessary to use its water increases exponentially as it dries, it is assumed that *RAW* is a storage threshold and water use below this limit reduces significantly tree growth and yield. Consequently, for precision irrigation the worksheet for the water balance of each tree should consider *RAW* and not *AW* to determine the time of irrigation. This way, when the water balance indicates that the remained stored water is not enough to supply another day with the present atmospheric demand then it is about time to trigger the irrigation system. The amount of water to be applied in each irrigation event is determined by the strategy planned (partial wetting, regulated deficit, partial root-zone drying, etc.) as described elsewhere (Bielorai 1982; Goodwin and Boland 2000; McCarthy 2000; Leib *et al.* 2006).

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