Irrigation Management in Olive

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Summary

Three main questions have to be answered for optimizing irrigation: how much, when and how. The last one, dealing with the design and characteristics of the irrigation system, is not addressed in this work; just to remark that localised irrigation is the best solution for most olive orchards, and that drippers are usually more convenient than microsprinklers. The second question cannot be properly answered without taking into account the time evolution of the crop water needs, which bring us to the first question: the optimum irrigation amount (IA) for our olive orchard. This work starts with an overview of the crop coefficient approach for calculating the required IA to replace the crop water needs, from the FAO recommendations to recent improvements that reduce the empiricism of the involved coefficients. At this point, aspects on the irrigation both of young and highly density orchards are commented. Deficit irrigation strategies are then discussed, with a comparison between regulated deficit irrigation and partial rootzone drying, plus a mention to old practices such as supplementary or complementary irrigation, that could be adequate in some cases; the section ends with practical considerations on the soil volume wetted by irrigation. An overview on the most promising techniques for scheduling irrigation occupies the rest of this work; most attention is dedicated to those based on plant measurements, namely plant water potential, sap flow and trunk diameter variations. Finally, the potential of thermal sensing combined with plant measurements for scheduling irrigation in commercial orchards is outlined.

Olive water requirements

The FAO coefficient approach. Determining the crop evapotranspiration (ET_c) for non-limited available water in the soil is crucial for calculating IA. Likely, that of the crop coefficient recommended by the FAO (Allen et al., 1998) is the most widely used approach for determining ET_c. This is calculated from the potential evapotranspiration (ET_o) in the area, a coefficient K_c called the crop coefficient and a coefficient K_r related to the percentage of ground covered by the crop: $ET_c = K_c K_r ET_o$.

The most widely accepted methods for determining ET_o are based on the use either of the evaporation tank or automatic weather stations for recording the variables required for calculating ET_o from a combination equation appropriate for the area. Details on the use of the evaporation tanks are given in the FAO Monograph 56 (Allen et al., 1998), available at http://www.fao.org/docrep/X0490E/X0490E00.htm. Evaporation tanks are cheap, easy to use, require little training and give reasonably good estimates of ET_o, provided they are correctly located and managed. Their main limitation is that they have to be frequently attended, although automatisms for replacing and recording the water lost by evaporation are available. There is a variety of reliable and relatively cheap weather stations in the market. Any of these, together with a standard computer provided with appropriate software (the REF-ET Reference Evapotranspiration Software, by Allen et al., 2002, is available at http://www.kimberly.uidaho.edu/ref-et/) allows the user to obtain reliable and frequent estimations of ET_o with a minimum effort.

The main limitation of the FAO method comes from the empirical character of the K_c and K_r coefficients: both of them depend on the orchard conditions, which means that published values from the literature (Orgaz and Fereres, 2004; Fernández et al., 2006a) can rarely be extrapolated to orchards different from those for which were obtained. Rather, the orchardist must find the correct values to each orchard, which may take one whole season in mature orchards and yearly adjustments in young orchards. Values of the K coefficients, determined by Fernández et al. (2006a) for a mature orchard in Seville, southwest Spain, are given in Table 1.

Latest advances on the coefficient approach. Testi et al. (2006) and Orgaz et al. (2006) have proposed a model of olive water requirements, which estimates transpiration (E_p) and soil evaporation (E_s) separately, and a new crop coefficient $K_c = ET_c/ET_o$, calculated as the sum of three main components: tree transpiration (K_p), evaporation from the soil (K_{s1}) and evaporation from the areas wetted by the emitters (K_{s2}). A fourth component can be added, accounting for evaporation of the water intercepted by the canopy (K_{pd}). The model by Testi et al. (2006) is a more mechanistic approach than that of the FAO method, since it takes into account main soil, weather and plant conditions. The method by Orgaz et al. (2006) is supposed to improve the precision of the IA calculation in olive orchards: in atypical years, average IA values can be corrected by re-applying the method at the end of the month, after knowing the actual rainfall and ET_o values. Values of the K coefficients, determined by Orgaz et al. (2006) for a mature orchard in Cordoba, southern Spain, are given in Table 2.

Water balance. Determining the components of the water balance equation in the olive orchard is a suitable approach for estimating the fractions of the supplied water used by the crop, stored in the soil or lost by drainage and runoff. Palomo et al. (2002) used this approach for two years and three water treatments, in a mature 'Manzanilla' olive orchard. The information obtained was useful not only to quantify the crop water needs, but also to evaluate water losses by drainage, which is important to evaluate the environmental impact of fertigation and to evaluate the irrigation management. This is, however, a labour and time consuming approach, mostly used with research purposes rather than for optimizing crop water use in commercial orchards.

Average irrigation requirements. Average ET_c and IA values for mature olive orchards in areas with ET_o ranging from 1000 to 1400 mm year^{-1} are given in Table 3. For average weather conditions in the Mediterranean basin ($ET_o \approx 1200$ mm year^{-1}, rainfall ≈ 500 mm year^{-1}) and mature olive orchards with 100-300 trees ha^{-1} and localised irrigation, maximum potential ET_c could be 6000-7000 m^3 ha^{-1} year^{-1}, from which 3000-4000 m^3 ha^{-1} must be applied by irrigation. These are average figures, being necessary to adjust IA for each orchard depending on plant density, canopy volume and characteristics of the irrigation system, among other factors.

Figures given above do not apply either to young orchards or orchards with super high tree density. Little research has been made in these kinds of orchards. For young orchards, Pastor (2005) suggests using the model by Testi et al. (2006) for deriving appropriate crop coefficient values. From E_p estimations in mature orchards with localised irrigation and enough IA to replace the crop water needs (Fernández and

Moreno, 1999; Fernández et al., 2006a), the average E_p value for the whole irrigation season could be of 1.5 L m^{-2} day^{-1} (m^{-2} refers to square meter of leaf, one side), being peak values greater than 2 L m^{-2} day^{-1}. This applies also to young plants (Natali et al., 1991; Gómez del Campo, personal communication), which may help to estimate IA in young orchards.

The only peer review works we have found on irrigation management in super high density orchards are those by Grattan et al. (2006) and Berenguer et al. (2006), carried out in a 'Arbequina I-18' 1700 trees ha^{-1} (1.5 m × 3.9 m) orchard in California. At the beginning of the two year experiment (2002-2003), trees were 30 months old. They used the FAO coefficient approach mentioned above, with $K_c = 0.75$ for the whole season and K_r varying from 0.72 to 1.0, depending upon canopy size of trees under different water treatments. Average ET_o and rainfall in the area were 1330 mm and 533 mm, respectively. Under these conditions, ET_c for the irrigation season (May to October) was close to 6000 m^3 ha^{-1}. The authors found that the IA that maximized production amounted to 70-75% of ET_c, and that 33-40% of ET_c was enough to maximize oil quality.

Water losses by soil evaporation. Annual E_s can be quite high in olive orchards. Testi et al. (2006) determined E_s to be 40% of the annual ET_c in a typically Mediterranean traditional olive orchard (100 trees ha^{-1} at 10 m × 10 m spacing), and 35% in an intensive orchard (300 trees ha^{-1} and individual tree canopy volume of 50 m^3). For the two mentioned cases, annual E_s from the ground spots wetted by the emitters amounted to 11 and 10%, respectively. The model developed by Díaz-Espejo et al. (2004) can also help to estimate E_s in olive orchards with localised irrigation. These and other considerations (see the section on partial rootzone drying) must be taken into account both when evaluating the convenience of using an underground irrigation system and when deciding the number of emitters per tree.

Modelling. Continuous improvements on the understanding of the soil-plant-atmosphere relationships in olive orchards are leading to models that can be used as tools for optimizing irrigation. This is the case of the photosynthesis model for olive leaves published by Diaz-Espejo et al. (2006); combined with a model of radiation transfer through the canopy, it could predict the response of the whole-tree carbon assimilation to water stress. Now, the use of these highly mechanistic models to optimise production and the use of irrigation water in commercial orchards is limited by the required number of parameters and variables –some of them difficult to measure. A more practical approach is to use models in which some inputs are estimated from measurements of related variables made in the orchard in which are going to be applied. A good example is that of Green et al. (2002).

Deficit irrigation

Water for irrigation is scarce in most olive orchards. Therefore, the orchardist is very often bound to apply a deficit irrigation (DI) approach. The aim is to applied IA below the crop water needs but in a rational way, to keep the crop performance as close as possible to its maximum potential. The old practice of applying just one or very few irrigation events on the dry season has been called *supplementary* or *complementary* irrigation. *Sustained DI* is when a reduced percentage of ET_c is applied all throughout the irrigation season. *Low frequency DI* is when the soil is left to dry until the readily available water is consumed; then the soil is irrigated to field capacity and left to dry again. Details on these DI strategies can be found in Fernández and Moreno (1999), Orgaz and Fereres (2004) and Pastor (2005). Among the most widely used DI approaches are the *regulated deficit irrigation* (RDI) and the *partial rootzone drying* (PRD). Deficit irrigation strategies are not recommended for young orchards, since conditions for the trees reaching maturity as soon as possible must be favoured.

The olive tree is a parsimonious water consumer well adapted to xeric conditions. It's mechanisms for drought tolerance (Fernández and Moreno, 1999; Connor 2005; Connor and Fereres, 2005) make the species to be particularly suitable for DI. Moriana et al. (2003) showed that the relation between olive ET and yield is curvilinear, and not linear as for other fruit tree species. This means that optimum IA in olive could be less than that needed for a maximum ET_c, which agrees with results from Patumi et al. (2002) and Tognetti et al. (2005), among others. Benefits of DI on oil quality have been already mentioned. The orchardist must keep in mind, however, that any DI strategy may reduce the crop performance in subsequent years.

The success of complementary irrigation, sustained DI or low frequency ID depends on the soil water holding capacity, which must be characterized before any of these strategies is applied. Assuming that the readily available water (RAW) in a soil is about 75% of the total available water (AW) (Orgaz and Fereres, 2004), the value of RAW in a loam soil (θ_{fc} = 0.28 m^3 m^{-3} and θ_{wp} = 0.11 m^3 m^{-3}, being θ_{fc} and θ_{wp} the volumetric soil water content at field capacity and permanent wilting point, respectively) where the root depth is 1.3 m, will amount to 44% of the IA needed to irrigate the trees to 100% of ET_c. It is also true that the mentioned percentage of AW normally accepted as a threshold for soil water deficit for olive, could be too high, as discussed at the end of this work.

Regulated deficit irrigation (RDI). This is one of the most widely adopted DI strategies, based on supplying some 100% of ET_c when the crop is less tolerant to water stress and a reduced percentage (30% is quite common) for the rest of the season. For the whole season, IA reductions of about 50% of ET_c are easily achieved (Fernández et al., 2006a). A detailed knowledge on the tree physiology is crucial for the success of RDI. Currently, in fact, many studies on RDI are oriented to better establish the periods for IA reduction. See Girona (2001) for details on this irrigation strategy.

Partial rootzone drying (PRD). This is a relatively new DI approach –first paper on PRD was that of Dry et al. (1996). The aim is to irrigate with similar IAs than in RDI but achieving a greater crop performance. This is achieved by irrigating half of the rootzone while the other half is kept under drying soil, alternating irrigation from one half to the other every 2-3 weeks. In theory, this triggers a root-to-shoot signalling mechanism that induces stomata closure and improves water use efficiency. On the other hand, the irrigation system for PRD is more expensive than for a traditional localised irrigation system, since two laterals per tree row are required, and the management is more complicated. Wahbi et al. (2005) and Centritto et al. (2005) published the first pieces of work in which PRD was applied to olive, more precisely to mature 'Picholine marocaine' olive trees. Although IA amounted to 50% only of the control treatment irrigated on both sides with 100% of ET_c, relative water content and photosynthetic capacity were similar in both treatments, and yield was reduced in 15-20% only, with the same yield quality. Unfortunately they did not have a companion RDI treatment, so doubts remain on whether similar benefits could have been obtained with RDI. We have recently published an experiment in which 50% of ET_c was supplied by irrigation to mature 'Manzanilla' trees following both and RDI and a PRD approach

(Fernández et al., 2006a). Results were compared to those from a control treatment in which a traditional localised irrigation to 100% of ET_c was applied to similar trees. After analysing stomatal conductance (g_s, mol m^{-2} s^{-1}), net CO_2 assimilation (*A*), stem water potential (Ψ_{stem}, MPa) and sap flow in main roots, trunk and main branches (*Q*, L m^{-2} day^{-1}), we found no agronomical advantages on PRD as compared to RDI.

The use of the PRD technique in fruit tree orchards is certainly controversial: while different crop responses have been observed with container-grown plants of different species, little, if any, responses have been obtained under commercial-scale conditions. This may be due to the variability of water distribution in the rootzone of mature fruit trees (Naor, 2006). In olive, Fernández et al. (2003), found that conventional localised irrigation in both sides of the trees curtailed water consumption of mature 'Manzanilla' trees on up to 37%, as compared to the water amounts consumed by the same trees when the whole rootzone was wetted by pond irrigation. They suggested that a root-signalling phenomena already occurs in trees in which localised irrigation wets a portion of the rootzone only, even if both sides are simultaneously wetted. This may explains results like those by Pastor (2005), who registered a fruit yield of 70 kg $tree^{-1}$ in olive trees irrigated with two drippers, and 82 kg $tree^{-1}$ in similar trees irrigated with the same amount of water but with eight drippers.

Irrigation scheduling

There is a need for a more accurate scheduling of water application in olive orchards: first, because of the increasing demand from competing water consumers; second, because of the increasing demand for quality, which, in the case of orchards for oil production, may require an accurate scheduling with IAs lower than those required for full irrigation. The techniques for estimating ET_c mentioned above are, in some cases, too coarse. Consequently, increasing efforts are being put into the development of new techniques for a more precise irrigation in olive orchards. Basically, water supplies in the orchard can be scheduled from the soil water status, from the atmospheric demand or from plant-based measurements. Among the last ones, leaf or stem water potential, trunk diameter variations and sap flow records are being evaluated by several research groups. Main advantage of plant-based indicators is that the tree is used as a biosensor which responses to the soil water status, the plant characteristics and the atmospheric demand. Irrigation scheduling based on the atmospheric demand has been considered in the first part of this work, so it is not considered here. Finally, infrared thermography is becoming a promising tool to account for orchard variability. Comparisons among different techniques for irrigation scheduling have been made by Fereres et al. (2003), Jones (2004) and Naor (2006).

Scheduling irrigation from soil water measurements. There is a variety of instruments for measuring θ and soil matric potential (*h*, MPa). Measurements of any of these variables, together with an adequate hydrodynamic characterization of the soil orchard, can be useful to monitor the soil water status for scheduling irrigation. Some of the sensors available in the market (see review by Fernández et al., 2000), although not very precise, are relatively unexpensive and can be easily automated. Main limitations of this approach are the high number of sensors that may be required to have representative measurements, and the fact that neither physiological features of the plant nor the atmospheric demand are taken into account.

Irrigation scheduling from plant water potential. Measurements of leaf water potential (Ψ_{leaf}, MPa) to monitor the response of the tree water status to irrigation have been widely used, with interesting practical results. Fernández et al. (1997) found -0.46 MPa to be a constant average predawn value of Ψ_{leaf}, for relative extractable water (REW, see Granier et al. 1987 for details) varying between 1 and 0.4. This agrees with previous results from a variety of woody species suggesting that a predawn value of leaf water potential of -0.05 MPa can be consider as a threshold for satisfactory water recovery at night. In recent years, the findings by Shackel et al. (2000) have been widely adopted and the stem water potential (Ψ_{stem}, MPa), less sensitive to atmospheric variability, is preferred to Ψ_{leaf}. More precisely, Ψ_{stem} measurements at midday are recommended for the control of water supply in olive orchards.

The technique has several limitations. First, measurements have to be manually made, which is labour consuming and restricts the number of replications. Second, there are uncertainties on the thresholds to be used. From measurements in central Spain, midday Ψ_{stem} values of -1.2 MPa for an "off" year and -1.4 MPa for an "on" year are recommended as thresholds for irrigating mature olive orchards (Moriana, personal communication). Despite of those relatively mild water stress levels, water savings amounted to 50% of ET_c. In any case, threshold values have to be adjusted depending on the location and orchard characteristics. The isohidric character of the olive tree (the tree is able to keep relatively constant Ψ values despite of significant differences on environmental conditions) may limit the performance of the technique under certain weather conditions. It is known that shoot growth and, especially, g_s are more sensitive to water stress than Ψ (Figure 2).

Irrigation scheduling from trunk diameter variations. Continuous monitoring of trunk diameter changes by linear variable displacement transducers (LVDT sensors) for assessing the tree response to irrigation water deficits has been evaluated for a variety of fruit tree species. The fundamentals of the technique are described by Goldhamer and Fereres (2001). In young olive trees, results are difficult to interpret due to the influence of trunk growth (Moriana and Fereres, 2002). In mature 'Manzanilla' trees, Moreno et al. (2006) obtained maximum daily trunk shrinkage baselines and reference values for use in irrigation scheduling. Most recent results by Moreno et al. (unpublished) indicate that the technique may be suitable for scheduling irrigation when a deficit irrigation approach is applied. Whether it has or not the required resolution for scheduling high frequency irrigation is still being evaluated. Details related to this question are given in the next section.

Irrigation scheduling from sap flow measurements. Both olive water consumption and the dynamics of transpiration and water uptake by main roots can be estimated from sap flow measurements (Fernández et al., 2006a, 2006c). The potential of this indicator for irrigation scheduling in olive was outlined by Fernández et al. (2001). Comparisons between sap flow and trunk diameter readings, as water stress indicators in fruit trees, and between these two variables and more traditional water stress indicators such us leaf or stem water potential and stomatal conductance, have been carried out by Ortuño et al. (2006) and Intrigliolo and Castel (2006), among others.

In a recent work, Fernández et al. (2006b) designed and tested an irrigation controller for fruit tree orchards, named as CRP (C*ontrolador de* R*iego de la* P*lantación*). It was designed to adjust IA daily to the water consumed by the trees on the previous day, keeping the soil around field capacity all throughout the irrigation period. The device calculates IA automatically, from sap flow readings in the trunk of trees irrigated to cover the crop water needs, considered as normally irrigated trees (NI trees), relative to similar measurements made in overirrigated trees (OI trees), used as reference trees. More precisely, every day the CRP calculates the transpiration ratio between both types of trees (E_{pNI}/E_{pOI}), and adjusts the IA for the next day as follows: if $(E_{pNI}/E_{pOI})_{DOY} \cong (E_{pNI}/E_{pOI})_{DOY-1}$, being DOY day of the year, the IA applied on the current day could have been either enough to cover the water needs of the NI trees or too high; therefore, the IA of the next day is reduced. If $(E_{pNI}/E_{pOI})_{DOY} \neq (E_{pNI}/E_{pOI})_{DOY-1}$, the CRP assumes the IA applied on the current day was not enough to cover the demand of the NI trees, and increases the IA of the next day. This protocol is repeated every day of the irrigation period.

The CRP was tested in the summer of 2006, in a 'Manzanilla' olive orchard with daily localised irrigation. Unexpectedly, the E_{pNI}/E_{pOI} ratio remained constant for 50 days after the beginning of the irrigation period, and, consequently, the CRP applied decreasing IAs for all that period (Figure 3). An explanation to this apparently striking result was found when analysing data from θ and Ψ_{stem} measurements in the orchard: despite of a significant decrease on the REW values, from 0.8 at the beginning of the irrigation period to around 0.5 on day 50, midday values of Ψ_{stem} remained relatively constant during all that period. This agrees both with the findings by Fernández et al. (1997) mentioned above and with the well known high capacity of the olive tree for taken up water from drying soils (Xiloyannis et al., 1996). From days 50 to 58, E_{pNI}/E_{pOI} decreased from about 1.7 to 0.7, in agreement with a decrease of midday Ψ_{stem} from -0.81 MPa to -1.76 MPa. After the mentioned decrease on the E_{pNI}/E_{pOI} ratio, we ordered the CRP to apply a 100 L tree^{-1} recovery irrigation on day 62 after the start of the irrigation period (Figure 3), and left afterwards the device to calculate IA as programmed. In some 10 days of overirrigation, both REW and midday Ψ_{stem} recovered to original values, and reduced IAs were supplied again. These results suggest that both the drought tolerance of the olive tree and the soil water holding capacity may limit the capability of an automatic irrigation controller based on sap flow measurements for scheduling high frequency irrigation. The CRP, however, could be useful for applying a DI strategy, since it was able to detect the time at which the water stress of the trees increased. Results of Fig. 3 also suggest that an acceptable threshold for soil water depletion could be around 50% of AW, rather than the usually recommended 75%, at least for our variety and soil conditions.

Infrared thermography. This technique has some disadvantages that must be overcame before becoming widely adopted by growers. Thus, being capable to detect the right time for irrigation, does not indicate the amount of water need it. In addition, is still expensive, and image analysis requires sophisticated software. On the other hand, however, the technique allows to characterize variability within the orchard due to both differences in soil and crop conditions and problems with the irrigation system; it performs well in hot and dry conditions, typical for most olive orchards; and it is suitable for large cropped areas. These advantages makes infrared thermography, combined with measurements at the orchard level, to be considered by many as the most promising approach for irrigating commercial orchards in a rational way.

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Table 1. Crop evapotranspiration (ET_c) for an olive orchard with 30-year-old 'Manzanilla de Sevilla' trees planted at 7 m × 5 m close to Seville, southern Spain, with 1.5 leaf area index and 34% of the ground covered by the crop. Average potential evapotranspiration (ET_o) in the area was estimated with the FAO56 Penman-Monteith equation and 30 year (1971-2000) of weather records. K_c = crop coefficient; K_r = coefficient related to the percentage of ground covered by the crop.

Month	K_c	K_r	$K_c \times K_r$	ET_o (mm/month)	ET_c (mm/month)	ET_c	ET_c (L/tree/day)
Jan	1.16	0.7	0.81	28.73	23.27	605 (mm/yr)	26.27
Feb	1.06	0.7	0.74	42.05	31.11		38.89
Mar	0.88	0.7	0.62	76.46	47.10		53.18
Apr	0.84	0.7	0.59	98.31	57.81	↑	67.44
May	0.76	0.7	0.53	134.48	71.54	357	80.77
Jun	0.70	0.7	0.49	153.83	75.38	(mm/irrigation	87.94
Jul	0.63	0.7	0.44	176.56	77.86	season)	87.91
Aug	0.63	0.7	0.44	164.48	72.54		81.90
Sep	0.72	0.7	0.50	118.28	59.62	↓	69.55
Oct	0.77	0.7	0.54	72.18	38.91		43.93
Nov	1.07	0.7	0.75	39.03	29.27		34.15
Dec	1.14	0.7	0.80	26.14	20.91		23.61

Table 2. Crop evapotranspiration (ET_c) for an olive orchard with mature 'Picual' trees planted at 10 m × 10 m close to Cordoba, southern Spain, with 10,500 m^3 ha^{-1} canopy volume. K_p = coefficient related to tree transpiration; K_{s1} = coefficient related to soil evaporation; K_{s2} = coefficient related to evaporation from the soil surface wetted by the emitters. ET_o = potential evapotranspiration (After Orgaz and Pastor, 2005).

Month	K_p	K_{s1}	K_{s2}	K_c	ET_o (mm/month)	ET_c (mm/month)	ET_c
Jan	0.18	0.67	0.00	0.85	33.2	28.2	648 (mm/yr)
Feb	0.19	0.65	0.00	0.84	45.9	38.6	
Mar	0.20	0.40	0.00	0.60	87.1	52.4	
Apr	0.23	0.25	0.04	0.51	110.4	56.8	↑
May	0.27	0.13	0.03	0.43	154.1	66.8	402
Jun	0.32	0.05	0.03	0.40	169.5	67.3	(mm/irrigation
Jul	0.32	0.04	0.03	0.39	210.8	81.3	season)
Aug	0.31	0.05	0.03	0.38	182.3	70.1	
Sep	0.28	0.18	0.03	0.49	122.1	59.9	↓
Oct	0.31	0.38	0.04	0.73	80.6	58.8	
Nov	0.28	0.68	0.00	0.96	42.6	40.9	
Dec	0.18	0.72	0.00	0.90	29.8	26.9	

Table 3. Crop evapotranspiration (ET_c) in mature olive orchards with localised irrigation, in areas with different potential evapotranspiration (ET_o), and irrigation amounts (IA) required to replaced the crop water needs on the dry season.

Reported by	Orchard characteristics	ET_o (mm)	ET_c (mm)	IA (mm)
Dettori (1987)		1000	560	
"		1200	620	
Fereres (1995) & Villalobos et al. (1998)		1400	700-800	
Fernández et al. (1998)	'Manzanilla', 286 trees/ha, localised irrigation	1400	640	380
Palomo et al. (2002)	" "	1400	653	403
Orgaz and Fereres (2004)	100 trees/ha, localised irrigation	1400	588	327
Pastor (2005)	" "	1270	651	237
Tognetti et al. (2006)	'Frantoio' and 'Leccino' 555 trees/ha localised irrigation	1180	552	273

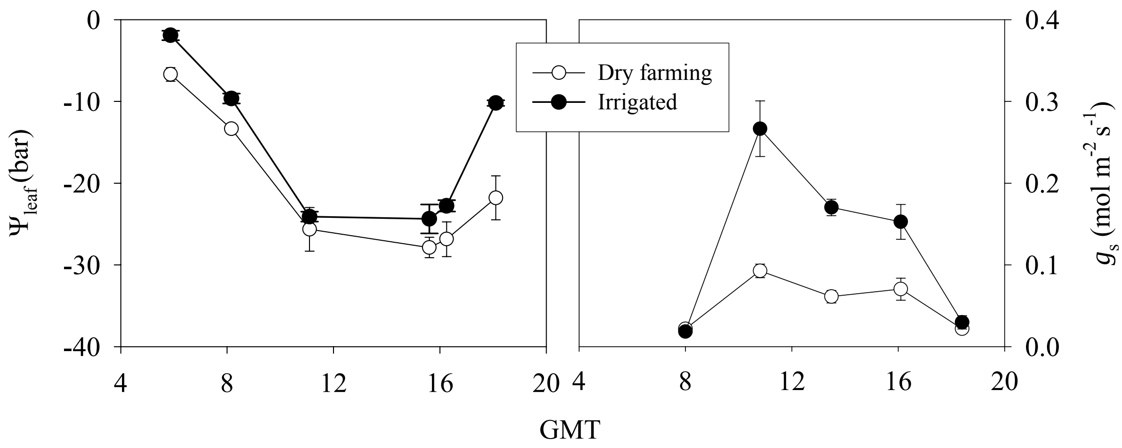

Figure 2. Diurnal evolution of leaf water potential (Ψ_{leaf}) and stomatal conductance (g_s) for leaves of pond irrigated and dry-farming trees of the olive orchard mentioned in Fig. 1. Measurements were in leaves of the current year, on a clear-sky day of August 2003. Each data point is the mean of 4 measurements for Ψ_{leaf} and 6 for g_s. Vertical bars indicate ± 1 SE. GMT = Greenwich mean time. (Measurements by A. Diaz-Espejo).

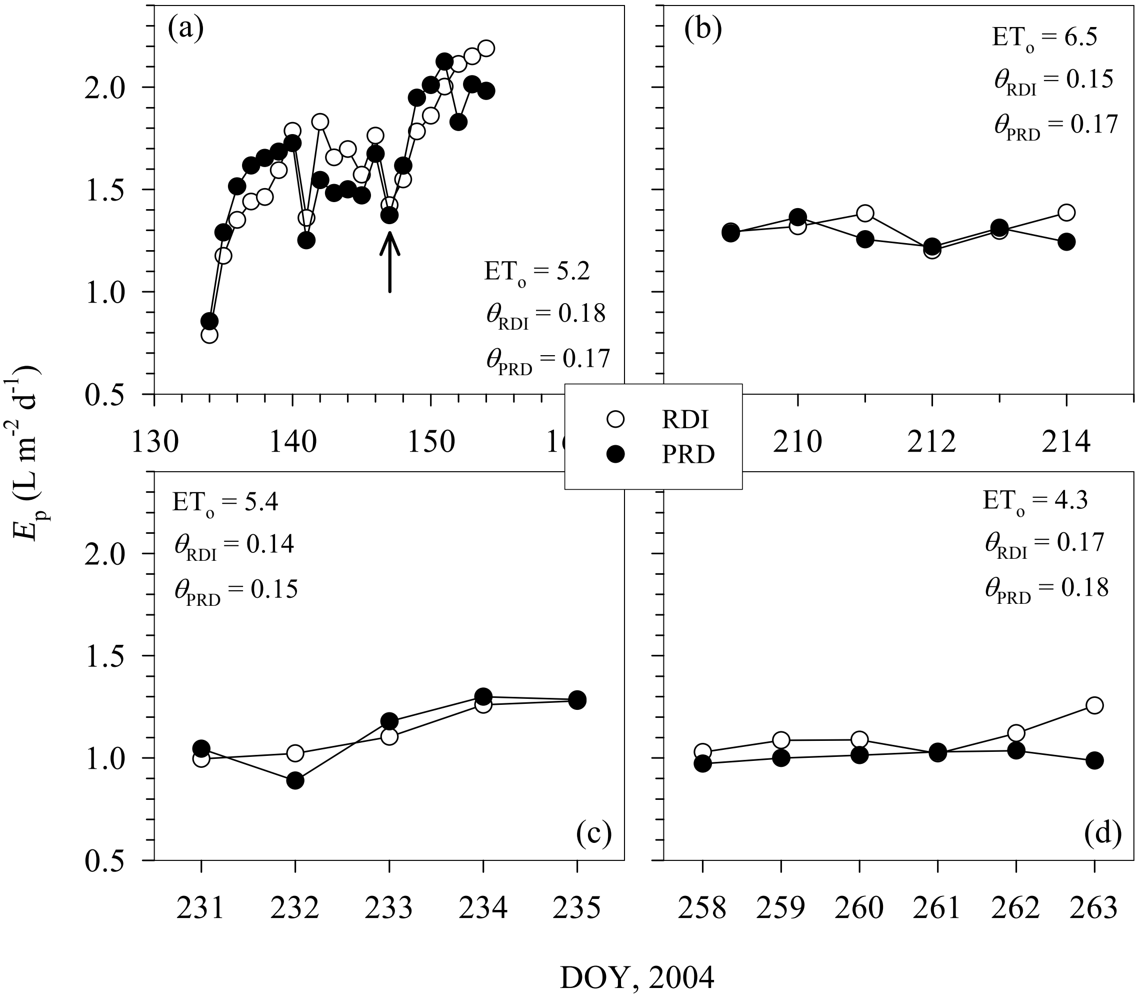

Figure 1.Values of daily transpiration per unit of leaf area (one side) (E_p) estimated from sap flow measurements made in two 36-year-old 'Manzanilla de Sevilla' trees, one under partial root zone drying (PRD) and the other under regulated deficit irrigation (RDI). Measurements were made at mid May (a), end of July (b), end of August (c) and mid September (d) 2004, in an olive orchard close to Seville, Spain, with the trees planted at 7 m × 5 m. The arrow in figure (a) shows the beginning of the irrigation treatments. Average data for each of the measurements periods on reference evapotranspiration (ET$_o$, mm) and volumetric water content (θ, m^3 m^{-3}) in the soil of both trees are also shown. For the PRD tree, θ values correspond to the wetted side. DOY = day of year. (After Fernández et al., 2006a).

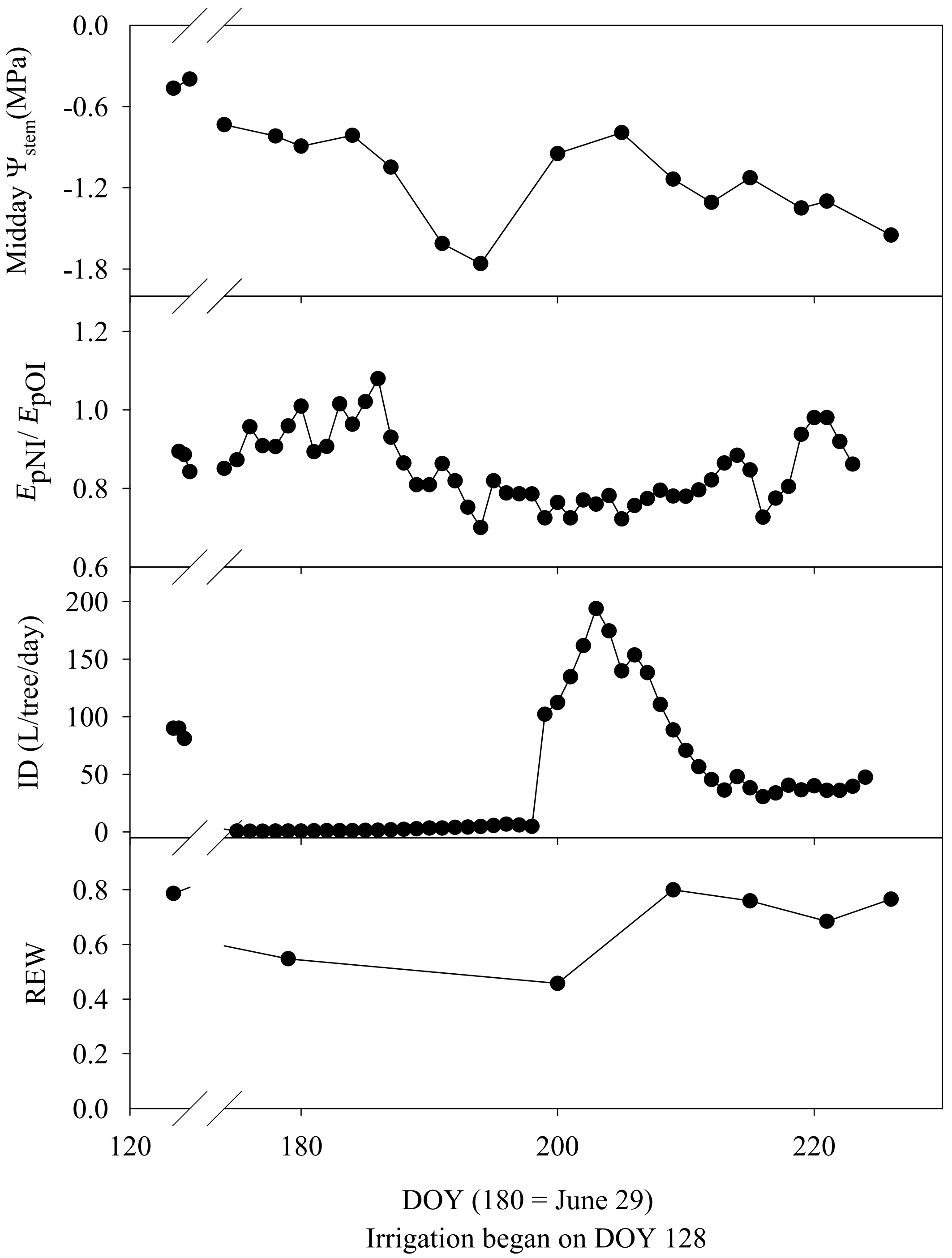

Figure 3. Daily values of the transpiration ratio between the normally irrigated and over irrigated trees (E_{pNI}/E_{pOI}) determined by the CRP in August 2006, during a field testing experiment made in the olive orchard mentioned in Fig. 1. Also shown are the daily irrigation doses (ID) calculated by the CRP, as well as the values of stem water potential (Ψ_{stem}) measured at midday in three representative trees (2 leaves per tree) and the relative extractable water (REW) calculated from eight soil water profiles measured in the rootzone of the three mentioned trees.