

F. Orgaz · L. Testi · F.J. Villalobos · E. Fereres

Water requirements of olive orchards—II: determination of crop coefficients for irrigation scheduling

Published online: 26 October 2005
© Springer-Verlag 2005

Abstract Intensification of olive cultivation by shifting a tree crop that was traditionally rain fed to irrigated conditions, calls for improved knowledge of tree water requirements as an input for precise irrigation scheduling. Because olive is an evergreen tree crop grown in areas of substantial rainfall, the estimation of crop evapotranspiration (ET) of orchards that vary widely in canopy cover, should be preferably partitioned into its evaporation and transpiration components. A simple, functional method to estimate olive ET using crop coefficients ($K_c = ET/ET_0$) based on a minimum of parameters is preferred for practical purposes. We developed functional relationships for calculating the crop coefficient, K_c , for a given month of the year in any type of olive orchard, and thus its water requirements once the reference ET (ET_0) is known. The method calculates the monthly K_c as the sum of four components: tree transpiration (K_p), direct evaporation of the water intercepted by the canopy (K_{pd}), evaporation from the soil (K_{s1}) and evaporation from the areas wetted by the emitters (K_{s2}). The expression used to calculate K_p requires knowledge of tree density and canopy volume. Other parameters needed for the calculation of the K_c 's include the ET_0 , the fraction of the soil surface wetted by the emitters and irrigation interval. The functional equations for K_p , K_{pd} , K_{s1} and K_{s2} were fitted to mean monthly values obtained by

averaging 20-year outputs of the daily time step model of Testi et al. (this issue), that was used to simulate 124 different orchard scenarios.

Introduction

The expansion of permanent irrigation systems in orchard crops has changed the focus of irrigation scheduling, from determining irrigation timing to quantifying irrigation amounts. Crop water requirements (evapotranspiration, ET) are thus the essential information for scheduling irrigations in orchards. Past efforts at determining water requirements have been concentrated on the major herbaceous crops and to a much lesser extent, on tree crops and vines. For example, what has constituted the state-of-the-art method in quantifying crop water requirements, the FAO approach (Doorenbos and Pruitt 1977), has been extremely successful worldwide because it has a good level of precision combined with ease of use and transferability to farmers. However, the specific information on tree crops that it contains, is based on relatively few research reports. Even the recent revision of Allen et al. (1998), while improving the estimation of the reference evapotranspiration (ET_0), has not added much new information on crop coefficients (K_c) for perennial crops to that originally published by Doorenbos and Pruitt (1977).

There are some fundamental differences between the K_c of herbaceous crops and that of trees: in the first case, the K_c varies only seasonally, its variation is linked to easily detectable phenological stages, and is well defined by the initial, maximum and final values. The K_c of deciduous trees, also varies seasonally, but is affected by additional factors such as canopy architecture, tree density, pruning practices, crop load, irrigation method, and soil surface management (Fereres and Goldhamer 1990). Furthermore, even in mature, intensive orchards, full ground cover is never reached due to horticultural

Communicated by E. Christen

F. Orgaz · L. Testi (✉) · F.J. Villalobos · E. Fereres
Instituto de Agricultura Sostenible, CSIC,
Apartado 4084, 14080 Cordoba, Spain
E-mail: ag2lucac@uco.es
Tel.: +34-957-499231
Fax: +34-957-499252

F.J. Villalobos · E. Fereres
Dep. Agronomía, Univ. Córdoba, Apartado 3048,
14080 Córdoba, Spain

reasons, so that K_c is always influenced by soil wetness to some extent. A maximum or a “full cover” K_c , while useful in herbaceous crops, is not a precise and unique number in orchards.

Olive groves share the complexities in the determination of K_c with all other tree crops, with some additional difficulties. Olive is an evergreen species that is active throughout the year, thus requiring a longer irrigation season than deciduous tree species, especially after dry winters. Additionally, olive farming is experiencing structural changes leading to a heterogeneous mosaic of olive groves with a wide range of ground cover (Testi et al., this issue), due to local restrictions in management, water availability and variable age. If the information on tree crops water use is meagre, it is more so for the olive because the practice of irrigation, despite its present popularity, has a short history in this species. The information available is derived from relatively crude estimates of seasonal evapotranspiration (ET) or from ET measurements taken over short time periods (Orgaz and Fereres 1999). Goldhamer et al. (1994) used variable rates of applied irrigation combined with measurements of tree water status to infer a seasonal K_c value between 0.65 and 0.75 for a mature table olive orchard in Madera County (California). Allen et al. (1998) recommend, for a mature orchard (40–60% ground cover), K_c values of 0.65 for an initial period and of 0.70 for the rest of the year. Adjustment of the K_c of mature tree canopies to immature stands has been done empirically in the past. Keller and Karmeli (1974) proposed an equation that adjusted water use rates to low canopy cover for design purposes. Fereres and Goldhamer (1990) gave an empirical relationship between percent ground cover and percent mature orchard ET, measured in almond trees in California. It is not known whether such relationships apply to other crops and climates. In all cases of low tree canopy cover, the K_c is strongly affected by conditions that influence evaporation from the soil surface (E_s) (Ritchie 1972; Villalobos et al. 2000). Recently, Testi et al. (2004) proposed a simple linear relation between the olive ground cover (and Leaf Area Index) and the average K_c of the summer months, valid for ground cover fractions up to 0.25, along with its variation when wet surface soil spots are present. However, this relation does not apply outside a rainless summer, and the contribution to E_s from the drip system depends on the surface area and location of the wet spots and is not scalable.

In summary, the ET of an olive orchard under localised irrigation has four basic components: (a) tree transpiration as a function of tree size and time of the year; (b) rainfall intercepted and directly evaporated from the foliage, function of ground cover and of the frequency of canopy wetting; (c) evaporation from the overall soil surface, which is a function (mainly) of the time averaged soil surface wetness of the whole orchard and of soil shading by the canopy; and, (d) evaporation from the areas wetted by the emitters, which would depend on the fraction of wetted soil surface and on

irrigation frequency. Variations in each component lead to a number of cases so large that cannot be quantified without the assistance of a simulation model. For practical purposes, however, what is needed is a simple approach to generate the K_c values.

We have used the daily time–step simulation model of Testi et al. (this issue) to calculate the above–mentioned components of the ET for a large number of olive orchards scenarios, obtaining daily values lasting 20 years for each scenario. We averaged these calculated values on a monthly basis, and used them to fit functional equations for calculating additively the monthly K_c of any type of olive orchard. The calculation method presented below is aimed at providing average monthly K_c values for practical irrigation scheduling of olive orchards.

Materials and methods

In our approach, the ET of an olive orchard results from combining soil evaporation (E_s) and tree canopy transpiration (E_p). If the olive is under localised irrigation, the evaporation from the emitter’s wet spots (E_{ws}) must also be taken into account. After a rainfall event, the water intercepted by the canopy evaporates directly into the atmosphere (E_{pd}); this water loss may be large during rainy periods.

In the calculation method that we propose here, the monthly K_c (non–dimensional) is defined as the sum of the ratios between the four components of ET mentioned above and the ET_0 :

$$K_c = \frac{ET}{ET_0} = \frac{E_p + E_{pd} + E_s + E_{ws}}{ET_0} \quad (1)$$

thus,

$$\begin{aligned} K_c &= \frac{E_p}{ET_0} + \frac{E_{pd}}{ET_0} + \frac{E_s}{ET_0} + \frac{E_{ws}}{ET_0} \\ &= K_p + K_{pd} + K_{s1}(1 - F_w) + K_{s2}(F_w) \end{aligned} \quad (2)$$

K_{s1} and K_{s2} applies to different parts of the soil surface: K_{s2} must be weighted to the fraction of soil that is wetted by the emitters (F_w), and K_{s1} to the fraction of soil that is independent to irrigation wetting ($1 - F_w$).

Scenario analysis

The monthly K_c calculation method presented in Eq. 2 and explained below in Eqs. 3 to 12, was derived from results obtained by simulating different scenarios with the detailed daily time–step model of olive ET of Testi et al. (this issue). A wide range of orchard scenarios was developed by varying tree density, tree canopy volume and the fraction wetted by the emitters, all within realistic limits, for a total number of 124 orchard cases. Tree densities varied from 100 to 400 trees ha^{-1} , canopy volume varied from 10 to 120 $m^3 tree^{-1}$ and the fraction

of soil wetted by emitters varied between 0 (case of subterranean drippers) and 0.15. The detailed features of the orchards used in the simulations are summarised in Table 1.

Every orchard scenario of Table 1 was simulated with the daily time step model for 20 years, using actual meteorological data collected in Cordoba, southern Spain, from 1983 to 2002; the climate of Cordoba is representative of the Mediterranean environment where most of European olive groves are located. The average rainfall and ET_0 registered in this period were 552 mm and 1,333 mm, respectively. The model provided separated outputs for each olive ET component, namely E_p , E_{pd} , E_s and E_{ws} , for each day of simulation (Testi et al., this issue). These 20 years of data were averaged for each month, and the K_c components were obtained as in Eq. 2, for each scenario and month. This generated K_c dataset included thus the effects of the characteristics of each orchard case, but did not include the meteorological variability among years. This dataset was then used to fit the empirical equations described below to calculate each K_c component.

The transpiration component, K_p

Transpiration of olive groves is mainly controlled by their stomatal conductance (Villalobos et al. 2000). Olive stomatal conductance varies seasonally (Moriana et al. 2002) following a specific pattern, with lower values in spring and higher values in fall for similar environmental conditions (Testi et al. 2006). The underlying mechanisms for these variations are unknown; thus, K_p requires empirical adjustments.

Here, the K_p is calculated as:

$$K_p = Q_d F_1 F_2 \quad (3)$$

Q_d is the fraction of intercepted diffuse radiation (non-dimensional). This variable provides an appropriate scaling up of transpiration with tree size and density of foliage (Orgaz et al., submitted). Q_d is approximated by:

$$Q_d = 1 - e^{(-k_1 \cdot V_u)}, \quad (4)$$

where V_u is the canopy volume per unit ground area ($m^3 m^{-2}$) and k_1 is the coefficient of radiation attenuation which is given for olive groves by Orgaz et al. (submitted):

$$k_1 = 0.52 + 0.79 \cdot 10^{-3} D_p - 0.76 e^{-1.25 L_d} \quad (5)$$

D_p is the planting density (trees ha^{-1}), and L_d is the Leaf Area Density ($m^2 m^{-3}$) that varies with the canopy volume per unit surface (V_u):

$$L_d = 2 - \frac{0.8(V_u - 0.5)}{1.5} \quad (6)$$

within the range $1.2 < L_d < 2$.

F_1 and F_2 in Eq. 3 are empirical parameters obtained through equation fitting.

F_1 values change with D_p as:

$$F_1 = 0.72 \quad [D_p < 250 \text{ trees } ha^{-1}] \quad (7a)$$

$$F_1 = 0.66 \quad [D_p > 250 \text{ trees } ha^{-1}] \quad (7b)$$

while monthly F_2 values are given in Table 2.

The plant direct evaporation component, K_{pd}

During a rainfall event, part of the precipitation amount is intercepted by the canopy and is directly evaporated into the atmosphere—once the conditions are appropriate—without reaching the soil surface. When rainfall events are frequent (which is fairly common in the Mediterranean winters), the rate of direct evaporation from wetted trees leads to high K_c (Testi et al., this issue), although the absolute amount of water lost in this process is often small, due to the low evaporative demand.

The amount of water directly evaporated from an orchard in a given time is proportional to the size of the trees, and to the frequency of rainfall events. From the E_{pd} dataset generated by the daily model, we fitted the following equation that gives the K_{pd} for a month:

$$K_{pd} = 2.7 \frac{F_{gc} f_r}{ET_0}, \quad (8)$$

Table 1 Description of the scenarios simulated with the daily olive ET model (Testi et al., this issue) for the calibration of the monthly K_c calculation method

D_p (trees ha^{-1})	V_c (m^3 Tree $^{-1}$)	F_w (ratio)	Number of orchard types	Number of average monthly K_c 's
100	10–120 (12 cases)	0–0.15 (4 cases)	48	576
200	10–80 (8 cases)	0–0.15 (4 cases)	32	384
300	10–60 (6 cases)	0–0.15 (4 cases)	24	288
400	10–50 (5 cases)	0–0.15 (4 cases)	20	240
			124 (total)	1,488 (total)

Every run was a simulation of 20 years. The resulting 1,488 monthly K_c 's are the average of 20 K_c 's for every case and for each month, and do not include the meteorological variability among years. D_p , density of plantation; F_w , fraction of the soil wetted by the emitters; V_c , canopy volume

Table 2 Monthly values of the empirical coefficient, F_2 for the calculation of K_p (see Eq 3 in text)

Month	F_2
Jan	0.70
Feb	0.75
Mar	0.80
Apr	0.90
May	1.05
Jun	1.25
Jul	1.25
Aug	1.20
Sep	1.10
Oct	1.20
Nov	1.10
Dec	0.70

where F_{gc} is the ground cover fraction, ET_0 is expressed in $mm\ day^{-1}$ and f_r (dimensionless) is the fraction of rainy days in the month.

The general soil evaporation component, K_{s1}

The evaporation from the soil (E_s) after rainfall follows a two-stage process (Philip 1957). After a wetting event, E_s is limited only by the available energy at the soil surface (stage one) until the air-soil interface has dried up enough to reduce the soil hydraulic conductivity. From this point on (stage two), E_s is inversely related to the square root of time (Ritchie 1972). In an orchard, part of the incident radiation is intercepted by the canopy thus reducing the energy available for the first stage, without affecting the second stage. The E_s process in an olive orchard was modelled by Bonachela et al. (1999); when considered over a long period, E_s is a function of the frequency of the rainfall events (f_r) that brings the soil into stage one conditions, the ground cover fraction (F_{gc}) and the evaporative demand during stage one. An equation to calculate the K_{s1} component for a month was fitted to the averaged E_s values obtained from the scenario runs of the daily time-step olive ET model (Testi et al., this issue):

$$K_{s1} = \left[0.195 - 0.11 F_{gc} - 0.021 ET_0 + \frac{4.0 f_r (1 - f_r)}{ET_0} \right]$$

valid for $f_r \leq 0.5$,

where ET_0 is $mm\ day^{-1}$ and f_r is the fraction of rainy days in the month. In this equation, values of f_r exceeding 0.5 should be taken equal to 0.5. Eq. 9 can give unrealistic low values of K_{s1} when applied to some extreme orchard scenarios (i.e. very high F_{gc} and very low f_r), so its use must be constrained to:

$$K_{s1} \geq \frac{0.3}{ET_0} \quad (10)$$

K_{s1} must be applied to the fraction of the soil that is not wetted by irrigations ($1-F_w$, see Eq. 2).

The artificially wetted soil evaporation component, K_{s2}

Evaporation from the soil wetted by the emitters (E_{ws}) is important in many situations under microirrigation. Even though the wetted soil surface is usually a small fraction of the total area, water evaporates at a high rate because the soil is nearly always in stage one under high frequency irrigation. Additionally, microadvection—the transfer of energy from the dry soil surface areas of the orchard to the wet spots—will increase E_{ws} during hot, dry periods.

The environmental and management variables that influence E_{ws} are mainly the radiation incident on the wet spots (which defines the evaporation rate in stage one), the ET_0 (which influences the duration of stage one) and the irrigation frequency. A mechanistic model for the calculation of daily E_{sw} in olive was developed by Bonachela et al. (2001), and is included as a sub-model in the daily time-step model of olive ET (Testi et al., this issue) that was used to generate the dataset of monthly averaged evaporation components for the cases of Table 1. The monthly E_{ws} from this dataset was used to fit the following empirical equation for the calculation of the monthly K_{s2} :

$$K_{s2} = \frac{1.4 e^{-1.6 \cdot Q_d} + \left(4.0 \frac{\sqrt{i-1}}{ET_0}\right)}{i}, \quad (11)$$

where Q_d is calculated with Eqs. 4 and 5, ET_0 is in $mm\ day^{-1}$ and i is the interval between irrigations (days).

Eq. 11 is based on the integration over time of the model of Bonachela et al. (2001), with empirical adjustments and simplifications. At high irrigation frequencies and low ET_0 , Eq. 11 can exceed the K_c value of a soil in stage one (which is unreasonable), so it must be constrained as follows:

$$K_{s2} \leq 1.4 e^{-1.6 \cdot Q_d} \quad (12)$$

K_{s2} must be applied only to the fraction of soil wetted by the drippers (F_w , see Eq. 2)

Input requirements

The monthly K_c calculation method presented here is designed to be applicable with the minimum number of input data easily available. The following list includes all the data required to obtain the monthly K_c by solving Eq. 2 to 12.

Orchard characteristics:

1. V_u ($m^3\ m^{-2}$), average canopy volume per unit ground area
2. D_p (trees ha^{-1}), tree density
3. F_{gc} ratio, fraction of ground cover (canopy horizontal projection)

Irrigation management:

1. F_w ratio, fraction of the soil that is wetted by the emitters
2. i (days), average irrigation interval

Climate

1. ET_0 (mm day^{-1}), reference evapotranspiration (average in the month)
2. f_r , fraction of rainy days in the month

Results

The olive monthly K_c calculation method (Eqs. 2–12) is based on empirical equations designed to respond to the environmental and management variables influencing the components of ET. The assumptions of these equations can intrinsically lead to imprecision in the monthly K_c calculation, because the variables considered (transpiration, soil surface humidity, canopy wetting, etc.), act on olive ET at time scales different from the month. The goodness-of-fit of the K_c calculation method to the dataset of daily ET used to calibrate the method equations should thus be observed carefully.

On Fig. 1, the monthly averaged ET/ET_0 coming from the 20-year simulations with the daily time-step model of Testi et al. (this issue) are compared with the average monthly K_c calculated with Eq. 2 to 12, for all the 124 orchard scenarios of Table 1 (1,488 points). The fit is quite good, with a limited amount of scatter ($R^2=0.98$). The regression line gives a slope of 0.97 and an intercept of 0.02 (not significant); the RMSE (Root Mean Square Error) is 0.042. When the K_c is used to calculate the average orchard ET for the month (mm day^{-1}) the agreement with the output of the detailed daily ET model is also very good, as shown in Fig. 2. The regression equation for the ET has an R^2 of 0.97, and a slope and intercept of the regression line of 0.97 and 0.05 mm day^{-1} (not significant), respectively; the RMSE is 0.147 mm day^{-1} .

The accuracy in the calibration of the four specific monthly K_c components equations is shown in Fig. 3. The plant transpiration component K_p (Fig. 3a, Eq. 3) shows a good fit with the E_p/ET_0 calibration data: the slope of the regression line is 0.99, and the intercept is (0.01 (not significant)). There is a limited amount of scatter ($R^2=0.95$), and the RMSE is 0.031. The plant direct evaporation component K_{pd} (Fig. 3b, Eq. 8) fits almost perfectly the calibration dataset of averaged E_{pd}/ET_0 , despite Eq. 8 is very simple. The regression line has a slope of 0.99 and a null intercept; the scatter is minimal ($R^2=1.00$) and the RMSE as low as 0.005.

The goodness-of-fit of the soil components of the K_c calculation method,— K_{s1} and K_{s2} —to the calibration dataset is shown in Fig. 3c and d, respectively. The

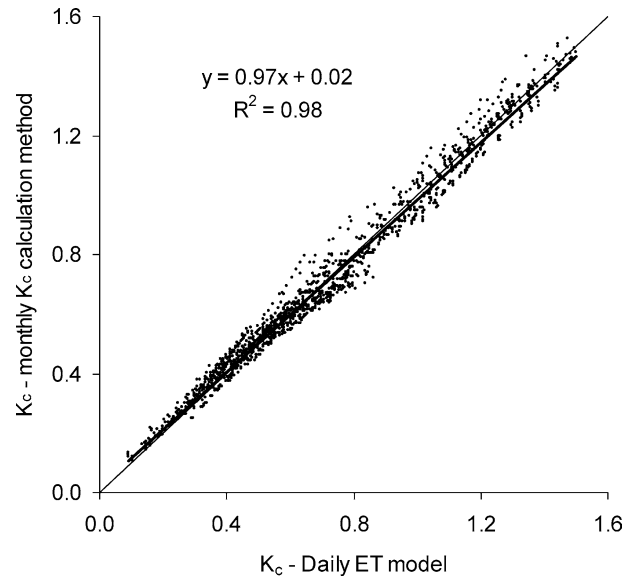


Fig. 1 Comparison of the crop coefficient K_c calculated with the monthly K_c calculation method (Eqs. 2 to 12) against ET/ET_0 from the calibration dataset obtained with a daily olive ET model (Testi et al., this issue) for a wide range of olive orchards in Cordoba, Spain. Each of the 1,488 points represents the 20-year average of the K_c for a given month and for every orchard type of those described in Table 1; $N=1,488$. The regression coefficients and R^2 are also shown. RMSE (Root Mean Square Error)=0.042

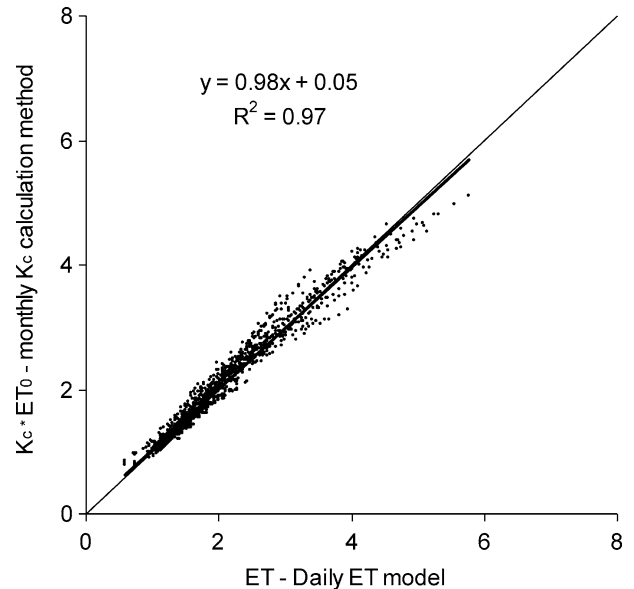


Fig. 2 Comparison of the monthly averaged daily evapotranspiration (ET , mm day^{-1}) calculated with the monthly K_c calculation method against the calibration dataset obtained from the daily time-step model. Same details as in Fig. 1. RMSE=0.147 mm day^{-1} .

general soil evaporation component K_{s1} (Eq. 9) seems to over-estimate the E_s/ET_0 from the calibration dataset in some months, while under-estimating in others (Fig. 3c). Nevertheless, the parameters of the regression are good (slope=0.98 and intercept=0.01, not significant), the R^2 is 0.98 and the RMSE is 0.034.

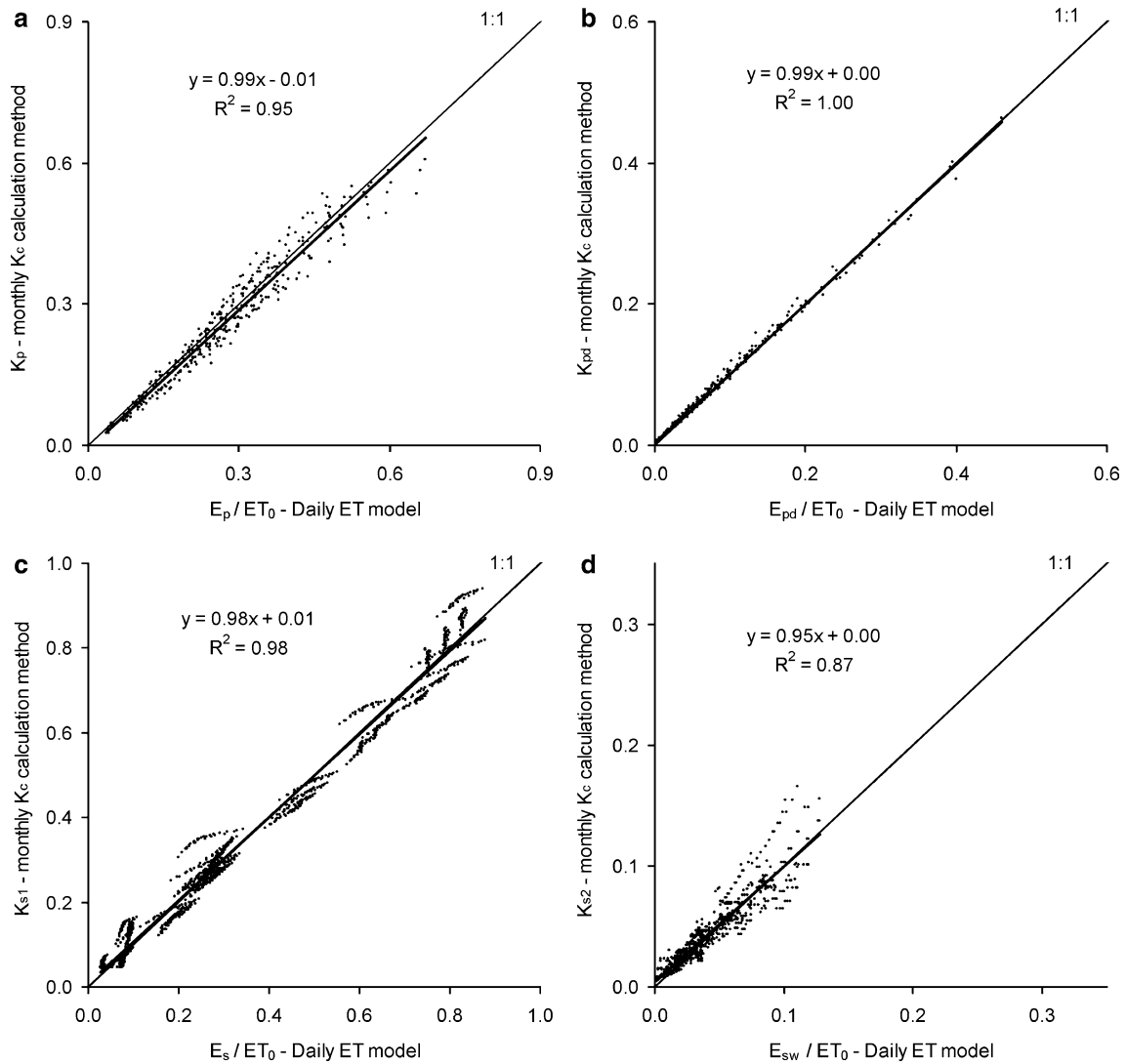


Fig. 3 Comparison of the four components of the K_c (K_p , K_{pd} , K_{s1} and K_{s2} , represented respectively in **a**, **b**, **c** and **d**) against the equivalents E_p/ET_0 , E_{pd}/ET_0 , E_s/ET_0 and E_{sw}/ET_0 averaged from the calibration dataset. Same details as in Fig. 1, except in **d** where

the cases with subterranean irrigation (i.e. $F_w = 0$) are not included: thus $N = 1,116$ for this case. The RMSE is 0.031, 0.005, 0.034 and 0.011 for **a**, **b**, **c** and **d**, respectively.

The agreement of the artificially wetted soil component K_{s2} (Eq. 11) to the generated calibration dataset of E_{sw}/ET_0 (Fig 3d) show a higher amount of scatter ($R^2 = 0.87$) with respect to the other components. The regression shows a slight under-estimation (slope = 0.95) but a null intercept. The RMSE is 0.011. The cases with $F_w = 0$, representative of subsurface irrigation, have not been included in the regression, as K_{s2} is always zero in those cases.

Discussion

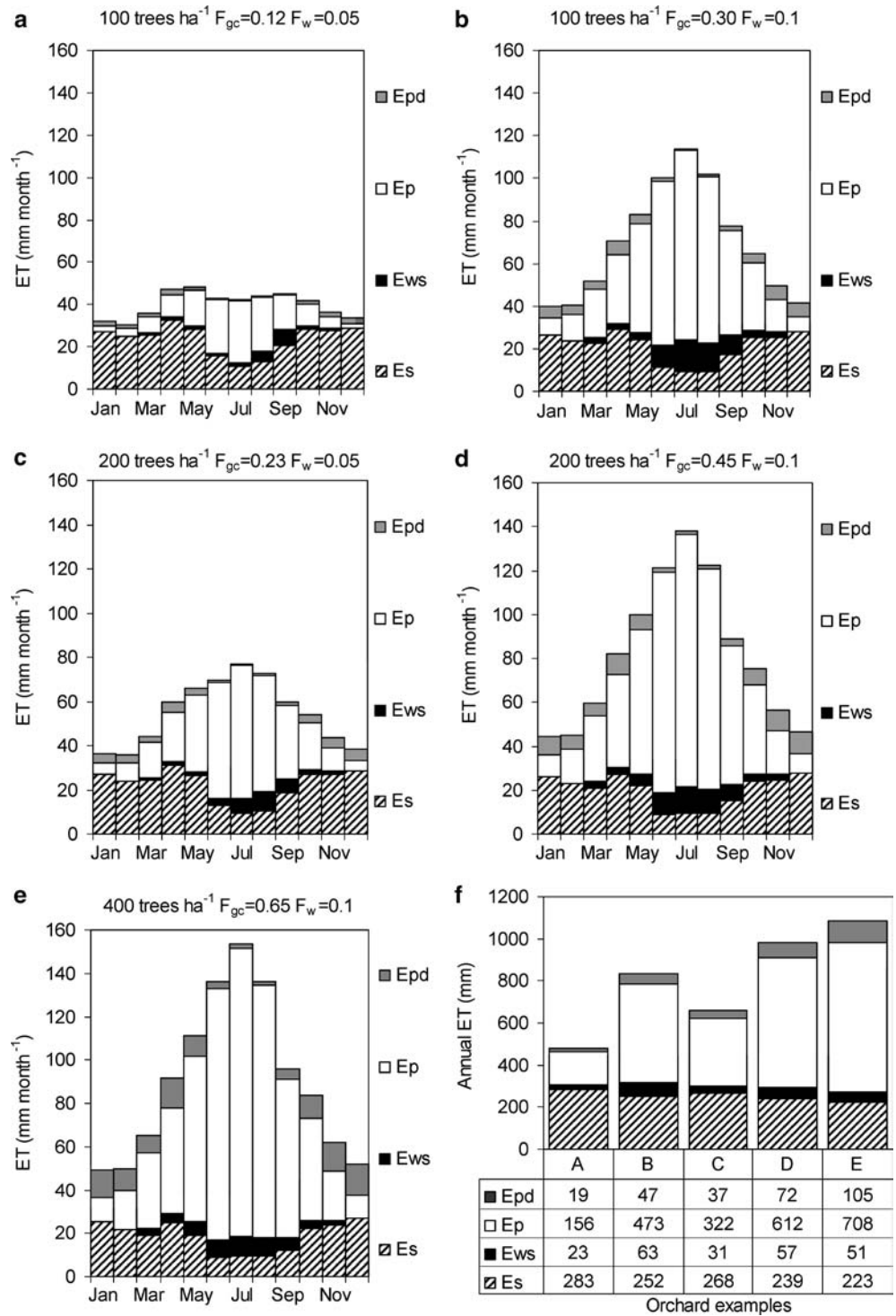
The method proposed here for calculating K_c of olive orchards is slightly more elaborate than the approach used in Allen et al. (1998), the standard for calculating crop water requirements for practical use. The addi-

tional complexity is justified, in our view, to address the specific aspects of olive as an evergreen tree crop that often covers a small fraction of the ground and is commonly irrigated by drip.

K_c components

From the fit with the calibration dataset, it appears that the main uncertainties in the monthly K_c calculation method are associated with the soil evaporation components K_{s1} (Eq. 9; Fig. 3c) and K_{s2} (Eq. 11; Fig. 3d). Equation 9 overestimates or underestimates E_s/ET_0 of the calibration dataset, depending on the time of the year. Inaccuracies in K_{s1} may be more relevant when the other components of Eq. 2 (especially K_p) are very small, as in the case of very young orchards. Equation 9 could

Fig. 4 Application of Eq. 2 for the calculation of the average (1983–2002 period) annual ET of five different orchards (a through e) in Cordoba, southern Spain. Orchard characteristics are given in each plot: F_{gc} , ground cover fraction; F_w , fraction of the soil wetted by the emitters. The monthly average ET (mm day^{-1}) is partitioned into its four components E_s , E_{ws} , E_p , E_{pd} (general soil evaporation, evaporation from the wetted spots, transpiration and direct evaporation of intercepted rainfall, respectively) presented bottom-up in the monthly bars. The f plot represents the total annual ET for the five cases, and gives the values for the four ET components and the five cases



be probably improved by including soil-specific parameters or a site-specific parameterisation, although its precision may be considered acceptable for irrigation purposes.

The performance of Eq. 11 in fitting the calibration dataset of E_{ws}/ET_0 (Fig. 3d) suggests that the higher the K_{s2} , the greater is the error, but these errors are not associated with specific groups of orchard cases. A

source of imprecision in Eq. 11 is that the radiation reaching the wet spots is estimated as a spatially averaged value. It is likely that better results in the fitting of K_{s2} would be obtained with the introduction of some parameter/s describing the position of the wet spots in relation to the canopy. However, such an approach may be too complex, although it deserves further testing.

The K_p formula (Eq. 3) is more satisfactory in fitting the averaged monthly E_p/ET_0 of the calibration dataset. Eq. 3 is based on a semi-mechanistic component for the calculation of intercepted radiation by the canopy (Eqs. 4, 5), and on an empirical coefficient (F_2) that addresses the recently found seasonal variations in olive bulk canopy conductance (Moriana et al. 2003; Testi et al. 2006). Although the accuracy of Eq. 3 is good (see Fig. 3a) over a wide range of ground cover fractions (from 0.05 to 0.70 in the simulations performed in this work) there is still uncertainty regarding the values that F_2 may assume in different climates.

Calculating the water requirements of olive groves

In a climate where annual rainfall is a significant fraction of ET_0 , the water use of an olive orchard may vary widely as shown in Fig. 4, where the monthly K_c calculation method is used to obtain ET over the average year for five different orchards in the climate of Cordoba. Figure 4a and b represent a traditional orchard in its developing and mature stage, respectively; the F_w would increase when emitters are added as trees grow, as it occurs in practice. In plots c and d of Fig. 4, the method is applied to a more semi-intensive orchard, (7×7 m tree spacing); plot e is an example of a modern, highly intensive orchard at 7×3.5 m spacing. Plot f in Fig. 4 summarises the annual water requirements of the five simulations: tree transpiration ranged from 156 to 708 mm (32% to 65% of the total ET), while evaporation from soil varied much less, from 223 to 283 mm; evaporation from wet spots only represented from 5 to 7% of annual ET under the assumed wetted areas by the emitters. The intercepted and directly evaporated rainfall represented from 4 to 10% of the annual ET.

Operatively, Eq. 2 can be used effectively for both irrigation design and scheduling. The monthly K_c calculation method was obtained from a calibration dataset of 20-year of daily data, thus the annual variability is already removed from the equations of the K_c components. This gives soundness to this method for the task of dimensioning irrigation systems for a given orchard, or for adjusting the intensiveness of new orchards to local water resources, to ensure that systems remain sustainable.

For irrigation scheduling, this method should improve the precision of olive water requirements calculations, that are based on the few single-case K_c values available at present (Allen et al. 1998; Orgaz and Fereres 2000). The method calculates the water requirements of specific olive orchards for the average-year; during atypical years, the method can be corrected by re-applying the method at the end of the

month (when the rainfall events and monthly ET_0 are known); the deviation of the computed olive ET for the past month from the average-year ET calculated a priori, permits the adjustment of orchard water balance dynamically.

A word of caveat about the general applicability of this method. At present, there is no information available on the behaviour of Eq. 2 to 12 in climatic conditions very different from those the Mediterranean climate of Andalusia, Spain, where this method was developed. Therefore, caution should be taken when using the monthly K_c calculation method in conditions departing from those of continental southern Spain, until further testing in new environments, against either olive ET measurements or the output of mechanistic models of olive water use.

References

- Allen RG, Pereira JS, Raes D, Smith M (1998) Crop evapotranspiration : guidelines for computing crop water requirements. Vol 56. Food and Agriculture Organization of the United Nations, Rome, 300 pp
- Bonachela S, Orgaz F, Villalobos FJ, Fereres E (1999) Measurement and simulation of evaporation from soil in olive orchards. *Irrig Sci* 18(4):205–211
- Bonachela S, Orgaz F, Villalobos FJ, Fereres E (2001) Soil evaporation from drip-irrigated olive orchards. *Irrig Sci* 20(2):65–71
- Doorenbos J, Pruitt WO (1977) Guidelines for predicting crop water requirements. Food and Agriculture Organization of the United Nations, Rome, 300 pp
- Fereres E, Goldhamer DA (1990) Deciduous fruit and nut trees. In: Stewart BA, Nielsen DR (eds) *Irrigation of agricultural crops: American Society of Agronomy Monograph n° 30*, Madison, Wisconsin, pp 987–1017
- Goldhamer DA, Dunai J, Ferguson LF (1994) Irrigation requirements of olive trees and responses to sustained deficit irrigation. *Acta Hort* 356:172–175
- Keller J, Karmeli D (1974) Trickle irrigation design parameters. *Trans ASAE* 17(4):678–684
- Moriana A, Orgaz F, Pastor M, Fereres E (2003) Yield responses of a mature olive orchard to water deficits. *J Am Soc Hortic Sci* 128(3):425–431
- Moriana A, Villalobos FJ, Fereres E (2002) Stomatal and photosynthetic responses of olive (*Olea europaea* L.) leaves to water deficits. *Plant Cell Environ* 25(3):395–405
- Orgaz F, Fereres E (1999) Riego. In: Barranco D, Fernandez-Escobar R, Rallo L (eds) *El Cultivo del Olivo*. Mundi-Prensa, Madrid, pp 251–272
- Philip JR (1957) Evaporation, moisture and heat fields in the soil. *J Meteorol* 14(4):354–366
- Ritchie JT (1972) Model for predicting evaporation from a row crop with incomplete cover. *Water Resour Res* 8(5):1204–1213
- Testi L, Villalobos FJ, Orgaz F (2004) Evapotranspiration of a young irrigated olive orchard in southern Spain. *Agric For Meteorol* 121(1–2):1–18
- Testi L, Orgaz F, Villalobos FJ (2006) Variations in bulk canopy conductance of an irrigated olive (*Olea europaea* L.) orchard. *Environ Exp Bot* (in press)
- Villalobos FJ, Orgaz F, Testi L, Fereres E (2000) Measurement and modeling of evapotranspiration of olive (*Olea europaea* L.) orchards. *Eur J Agron* 13(2–3):155–163