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Citrus orchard evapotranspiration: Comparison between eddy covariance measurements and the FAO-56 approach estimates

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Abstract
The aim of this study was to use the FAO-56 single and dual crop coefficient approaches to estimate actual evapotranspiration (ETa) over an irrigated citrus orchard under drip and flood irrigations in Marrakech, Morocco. The results showed that, by using crop coefficients suggested in the FAO-56 paper, the performance of both approaches was poor for two irrigation treatments. The Root Mean Squared Error (RMSE) between measured and simulated ETa values over the citrus orchard under drip irrigation was about 1.43 and 1.27 mm/day for the single and dual approaches, respectively, while the corresponding statistics for the orchard irrigated by the flooding technique was 1.87 and 2.48 mm/day.

After determination of the appropriate values of the crop coefficient (Kc) based on eddy covariance measurements of ETa, the performance of both approaches greatly improved. The obtained Kc values were lower than the FAO-56 values by about 20%. The low Kc values obtained reflect the practice of drip irrigation for one field and the low value of cover fraction for the other field. Additionally, the efficiency of the irrigation practices was investigated by comparing the measured Kc for two fields. The results showed that a considerable amount of water was lost by direct soil evaporation from the citrus orchard irrigated by flooding technique.

Keywords: Crop coefficient, drip and flood irrigation, citrus orchard, semi-arid region

Introduction
Citrus are one of the main components of agricultural systems in many semi-arid regions around the Mediterranean, and cover more than 1,000,000 ha (FAO 2003). With its Mediterranean climate, Morocco has good potential for citrus production. However, in this region, water is scarce and/or expensive. Therefore, it is necessary to accurately determine water requirements of citrus orchards, in order to determine suitable irrigation schedules and to improve water use efficiency in irrigated agriculture. Good irrigation management requires an accurate quantification of crop evapotranspiration. The most common approach to calculate evapotranspiration (ET) is the FAO-56 method (Allen et al. 1998). This approach is often preferred due to its simplicity and its applicability on an operational basis. Recently, many studies have shown that this approach provides acceptable ET estimates when compared to ground measurements (e.g. Hunsaker et al. 2003, 2005; Vu et al. 2005; Er-Raki et al. 2007, 2008). In the FAO-56 method, crop evapotranspiration (ET) is estimated using a reference evapotranspiration (ET0), which represents the atmospheric demand, and the crop coefficient (Kc), which depends on ground cover, soil type, irrigation method and crop characteristics. There are two methods to estimate ET: the single and the dual crop coefficients. The single crop coefficient is used for irrigation planning and design, irrigation management, basic irrigation scheduling and real-time irrigation timing for less frequent water applications. The dual crop coefficient, which consists of two coefficients: a basal crop coefficient Kcb and a soil evaporation coefficient Kse, is mainly used in research, real-time irrigation scheduling for highly frequent water applications, supplemental irrigation,
and detailed soil and hydrologic water balance studies (Allen et al. 1998). The crop coefficient changes with growth stages, and can be determined by dividing measured ET with ET\textsubscript{0}. Allen et al. (1998) have suggested that the crop coefficient values need to be derived empirically for each crop based on lysimetric data and local climatic conditions. Crop coefficient values for a number of crops in different climatic conditions were proposed by Doorenbos and Pruitt (1977), and later updated by Allen et al. (1998). These values are commonly used in places where local data are not available. However, specific adjustment of crop coefficients in various climatic regions is necessary, since they integrate several factors related to pedological, biophysical, physiological, and aerodynamic processes (Katerji et al. 1991; Testi et al. 2004; Rana et al. 2005; Katerji & Rana 2006). Although the ET for some citrus orchards has been documented in Morocco (Yacoubi 1982; El Hari 1992), the crop coefficient values for citrus orchards growing in the semi-arid region of southern Morocco are not currently available.

In the present study, we focused on the use of the FAO-56 single and dual crop coefficient approaches to estimate seasonal ET\textsubscript{a} and K\textsubscript{c} of citrus orchards in this region. The specific objectives were to investigate whether the use of the crop coefficient values provided in the FAO-56 paper is appropriate for accurately estimating ET\textsubscript{a} over an irrigated orchard in the semi-arid region of southern Morocco, and to assess the impact of irrigation method on the performance of the approaches.

**Materials and methods**

**Site description**

The study was conducted during 2004 and 2005 in two orange tree sites located in the Tensift Al Haouz, Marrakech province, southern Morocco. This area has a semi-arid Mediterranean climate, characterized by low and irregular rainfall with an annual average of about 240 mm against an ET\textsubscript{0} of 1600 mm/year. The first field named “Saada 1” was planted with 13-year old mandarin trees, at a spacing of 5 × 3 m, i.e. to about 70% cover fraction. The average height of the trees was about 3.15 m. The crop was maintained under well watered conditions, by drip irrigation, supplied every day. Fertilization and pest and weed control were performed. The second field, named “Saada 2”, was planted with 15-year-old mandarin trees. The trees were planted in a regular square pattern (7 × 7 m) and the cover fraction was about 30%. The average height of the trees was about 3.3 m. The site was periodically surface-irrigated through basin level flood irrigation. Each tree is bordered by a small earthen levy that retains the irrigation water. The irrigation frequency was every one to three weeks, depending on climatic conditions and rainfall, in order to avoid water stress. The amount of water applied during each irrigation event was approximately 40 mm. The soils have high sand and low clay contents (12% clay, 38% silt, and 50% sand). Further details about the sites are given in Ezzahar et al. (in this issue) and Boulet et al. (2006), which provide additional information about Saada 1 and Saada 2, respectively.

**Data description**

Meteorological measurements were made using an automated weather station as follows: incoming solar radiation was measured with a Kipp and Zonen, CM5, air temperature and humidity were measured with Vaisala HMP45C probes, wind speed was measured with A100R anemometers (R.M. Young Company, USA), net radiation was measured with a Kipp and Zonen CNR1 net radiometer placed over the canopy. Six heat flux plates continuously monitored changes in soil heat storage, and rainfall was measured with a FSS500 tipping bucket automatic rain gauge (Campbell Inc., USA). All meteorological measurements were measured at 6 m height, and were recorded in a data logger (CR10, Campbell Scientific, Logan, UT), sampled at 1 Hz and averaged over 30 min. Daily average values of climatic data were calculated in order to compute the daily ET\textsubscript{0} (mm/day), according to the FAO-56 Penman–Monteith parameterization scheme (Allen et al. 1998, 2006).

Two eddy covariance systems were installed over two fields of orange trees to provide continuous measurements of vertical fluxes of heat, water vapour at 6.9 m. The eddy covariance system used consisted of commercially available instrumentation: a 3D sonic anemometer (CSAT3, Campbell Scientific Ltd.) which measured the fluctuations in wind velocity components and temperature, and an open-path infrared gas analyzer (Li7500, Campbell Scientific Ltd.) that measured concentration of water vapour and carbon dioxide. Raw data were sampled at a rate of 20 Hz and were recorded using CR23X data loggers (Campbell Scientific Ltd.). The half-hourly values of fluxes were later calculated off-line after performing coordinate rotation, correcting the sonic temperature for the lateral velocity and the humidity effects, making frequency integration, and including the mean vertical velocity according to Webb et al. (1980), Schotanus et al. (1983) and Wilczak et al. (2001). The calculation of actual evapotranspiration ET\textsubscript{a} (mm) at a daily time scale was obtained by summing the half-hourly values. ET\textsubscript{a} measurements were taken from a central location of the field, determined by the frequency
of the wind direction analysis, to obtain the longest unobstructed wind fetch (Ezzahar et al., in this issue). The size of both fields was large enough so that the required fetch conditions required for eddy covariance are fulfilled. Missing data in some days is due to problems with the power supply.

The performance of flux measurements was assessed by the energy balance closure. By neglecting the term of canopy heat storage and the radiative energy used in photosynthesis (Baldocchi et al. 2000; Testi et al. 2004), the energy balance equation is given by:

\[ R_n - G = H_{EC} + L_{Ve_{EC}} \]

where \( R_n \) is the net radiation; \( G \) is the soil heat flux; \( H_{EC} \) and \( L_{Ve_{EC}} \) are, respectively, the sensible heat flux and the latent heat flux measured by the eddy covariance system. Figure 1 shows how well the available energy \( (R_n - G) \) was balanced by \( (H_{EC} + L_{Ve_{EC}}) \) on a daily time scale over the two study sites. The slope of the regression forced through the origin was 1.08 for Saada 1 and 1.03 for Saada 2, indicating that an underestimation of the flux \( (H_{EC} + L_{Ve_{EC}}) \) was less than 10% of the available energy \( (R_n - G) \). These results indicate a good closure of the energy balance, which is in agreement with other studies (Baldocchi et al. 2000; Twine et al. 2000; Testi et al. 2004; Boulet et al. 2006; Ezzahar et al. 2007).

A brief description of FAO-56 method

In this section, only a brief summary of the FAO-56 approach is provided. The reader can refer to Allen et al. (1998) for more details. In the single crop coefficient approach, the effects of crop transpiration and soil evaporation are combined into a single \( K_c \) coefficient while in the dual crop coefficient approach, the effects of crop transpiration (\( K_{cb} \)) and soil evaporation (\( K_e \)) are determined separately. The overall equations using the single and dual crop coefficient to calculate crop maximal evapotranspiration (\( ET_c \)) are, respectively:

\[ ET_c = K_c \times ET_0 \]

\[ ET_c = (K_{cb} + K_e) \times ET_0 \]

When the available soil water of the root zone drops below a critical level, crop water stress can occur and reduce \( ET_c \). In the FAO-56 dual procedures, the effects of water stress on \( ET_c \) can be estimated by multiplying \( K_{cb} \) by the water stress coefficient (\( K_s \)). When the single crop coefficient is used, the effect of water stress is incorporated into \( K_c \). So actual evapotranspiration, denoted as \( ET_a \) is calculated as (Allen et al. 1998):

\[ ET_a = K_s \times K_c \times ET_0 \]

\[ ET_a = (K_s \times K_{cb} + K_e) \times ET_0 \]

Following Equations 3 and 4, three parameters are necessary to determine \( ET_a \) by using the dual approach: \( K_{cb}, K_e \) and \( K_s \). Where the single approach is used, only two parameters are needed to determine \( ET_a \): \( K_c \) and \( K_s \). Soil and crop parameters used for the computation of these coefficients are presented in Table I.

Applicability of FAO-56 in estimation of citrus \( ET_a \) was evaluated. We firstly simulated the time course of \( ET_a \) using the FAO-56 based single and dual crop coefficient approaches with standard values of \( K_c \) and after with the adjusted \( K_c \). The simulation was performed during 2004 for a citrus orchard receiving drip irrigation, and during 2005 for an orchard irrigated by flooding technique.
Results and discussions

Evolution of reference evapotranspiration (ET₀)

The evolution of reference evapotranspiration (ET₀), which is the main input of the FAO-56 model and the most important component in the determination of crop water requirement, was determined. Figure 2 presents the seasonal variations of ET₀ calculated according to the FAO–Penman–Monteith equation (Allen et al. 1998). The temporal pattern of ET₀ values is typically that of a semi-arid continental climate type. It is characterized by a high climatic demand, with an average accumulated annual ET₀ of 1480 mm. The lowest values of ET₀ occurred during the winter and autumn (1.23 mm/day) and the highest values occurred in the summer (7.8 mm/day). Comparing the annual average rainfall (240 mm) with the product Kc*ET₀ = 1036 mm (Kc is the crop coefficient of citrus trees given in the FAO-56 paper), indicates the necessity to irrigate citrus orchards to avoid water stress and hence obtain a profitable yield.

Simulation of actual evapotranspiration (ETₐ) by FAO-56 single and dual crop coefficient approaches

We simulated the time course of ETₐ using the FAO-56 based single and dual crop coefficient approaches over citrus tree using the parameters given in FAO-56 tables (Table I). Figure 3 shows the estimated actual ETₐ by the FAO-56 single crop coefficient approach versus the one measured by the eddy covariance system over citrus tree irrigated by drip irrigation (upper panel) and by flooding irrigation (lower panel). It is obvious that the performance of the single crop coefficient approach is poor over both sites. The Root Mean Square Error (RMSE), defined as the square root of the averaged quadratic difference between observations and simulations, between measured and simulated ETₐ values under drip and flooding irrigations were about 1.43 and 1.87 mm/day, respectively. A linear regression analysis forced through the origin is presented in the figures. The slopes were 1.44 and 1.51 for Saada 1 and Saada 2, respectively. The model tends to overestimate actual ETₐ over both fields (Saada 1 and Saada 2) by about 44% and 51%, respectively. This behavior might be explained by the fact that the values of Kc are not appropriate. Standard Kc values given in FAO-56 were established for specific conditions which vary substantially from region to region, with climate and cropping conditions, and with crop variety. Therefore, the determination of appropriate Kc values is required in order to improve estimates of crop water requirements.

Similarly, Figure 4 shows the estimated ETₐ by the FAO-56 dual crop coefficient approach versus the one measured by the eddy covariance system over citrus trees irrigated by drip irrigation (upper panel)
and by flooding irrigation (lower panel). As for the single approach, the performance of the dual approach was very poor, especially over the orchard irrigated by the flood technique. The RMSE between measured and simulated ETa values under drip and flooding irrigations were 1.27 and 2.48 mm/day, respectively. It is clear that the model tends to overestimate ETa values over both fields. The over-estimation is larger (about 77%) for the field irrigated by the flooding technique. This behavior might be explained by two factors: (1) the values of Kcb suggested by Allen et al. (1998) are not valid for the two fields; (2) the FAO-56 dual crop coefficient approach predicts high soil evaporation during the wetting event, especially for the flood irrigation.

According to these results, a clear overestimate of actual ETa by both approaches (single and dual) over the two fields is evident. Thus, a local estimation of Kc and Kcb is needed to estimate accurately the crop water requirement of orange orchards.

**Derived crop coefficient**

Since we are interested in the determination of crop water requirement and hence irrigation management, crop coefficient values are crucial for planning and management of water resources. Figure 5 shows the computed crop coefficient Kc values following the FAO-56 single and dual crop coefficient approaches for orange trees irrigated by drip irrigation (upper) and by flood irrigation (lower panel) as well as the basal crop coefficient (Kcb). The variation of Kc and Kcb at mid-season stage corresponds to the adjustment of both parameters with relative humidity and wind speed, as suggested by Allen et al. (1998) (equation 62 in FAO-56). The values of Kc and Kcb were determined based on eddy covariance measurements of ETa and ET0 estimated by the FAO–Penman–Monteith method. The Kc values for the orchard irrigated by drip and flooding irrigations at three crop growth stages (initial, mid-season and maturity) were about 0.45, 0.6, 0.5 and

**Figure 3.** Actual ETa estimated by the single approach versus the one measured by the eddy covariance system over the citrus orchard irrigated by drip irrigation (upper) and by flooding irrigation (lower) by using the Kc values given in FAO-56.

**Figure 4.** Actual ETa estimated by the dual approach versus the one measured by the eddy covariance system over the citrus orchard irrigated by drip irrigation (upper) and by flooding irrigation (lower) by using the Kcb values given in FAO-56.
0.58, 0.55, 0.6, respectively (Table I). These values were lower than those suggested by the FAO-56 paper (Table I). The low \( K_c \) values obtained reflect the effect of practising localized drip irrigation that reduces soil evaporation. These results are considered reasonable since they support the reported conclusions of many studies regarding the significant reduction in crop water requirement when localized irrigation is practiced (Allen et al. 1998; Amayreh & Al-Abed, 2004; Er-Raki et al. 2006). For the orchard irrigated by the flooding technique, the reduction in the \( K_c \) values can be explained by the low value of cover fraction (about 30%), which can reduce transpiration (\( K_{cb} \)) when the soil surface is dry.

As shown in Figure 5, the difference between the total crop coefficient computed by the dual approach and the basal crop coefficient during wetting events (irrigation or rainfall) corresponds to the soil evaporation coefficient. As expected, the dual crop coefficient approach calculates the actual increase in crop coefficient \( K_c \) for each day as a function of plant development \( K_{cb} \) and the wetness of the soil surface (soil evaporation). It can be seen that after the wetting events (rainfall or irrigation), soil evaporation was higher for flooding irrigation than the drip technique.

After the determination of the appropriate crop coefficient \( K_c \), the FAO-56 single crop coefficient approach gives acceptable estimates of ET\(_a\) for citrus orchards under different types of irrigation (flooding and drip) in the semi-arid region of Tensift Al Haouz. The RMSE was reduced from 1.43 to 1.15 mm/day for the orchard irrigated by drip irrigation, and from 1.87 to 0.82 mm/day for the orchard irrigated by flood irrigation, corresponding to relative reductions of 20% and 57%, respectively. The performance of the single crop coefficient approach is lower for the orchard irrigated by the drip technique. This may be due to an overestimate of soil evaporation, which is included implicitly in the single crop coefficient.

Similarly, after the determination of the local basal crop coefficient \( K_{cb} \), the FAO-56 dual crop coefficient approach gives acceptable results of ET\(_a\) under both types of irrigation. The RMSE between measured and simulated ET\(_a\) values under drip and flooding irrigations were about 0.97 and 1.26 mm/day, respectively. The model still overestimates ET\(_a\) values by about 34% over the field irrigated by the flooding technique. This is due to the fact that the FAO-56 dual crop coefficient approach predicts high soil evaporation due to the lower cover fraction (about 30%) for the orchard irrigated by flooding.

These results suggest that the single crop coefficient approach can be used to derive a good estimate of water consumption of citrus orchards irrigated by the flooding technique with less frequent water applications, while the dual approach can be used for real-time irrigation scheduling with highly frequent water applications, as in the case of the drip-irrigated citrus orchards. These results are in agreement with the recommendations suggested in the FAO-56 paper by Allen et al. (1998).

### Irrigation efficiency assessment

The efficiency of the irrigation practices over two orange orchards was investigated. For that, we compared the measured \( K_c \) for both sites during the period when rainfall is absent (from DOY 116 to DOY 160 during 2005) (Figure 6). The irrigation

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**Figure 5.** Computed crop coefficient by the FAO-56 single and dual crop coefficient approaches for a citrus orchard irrigated by drip irrigation (upper) and by flooding irrigation (lower). Crop coefficients suggested by FAO-56 (\( K_c\)-FAO-56) are plotted in the same figures. DOY = day of year.

**Figure 6.** Comparison between the measured crop coefficients over the two sites, one irrigated by drip irrigation and the other by flooding irrigation.
events over each field are presented in the same figure. As can be seen in this figure, the $K_c$ of the orchard irrigated by flooding increased after irrigation and reaches 0.80. This value is higher than that corresponding to the orchard irrigated by the drip technique (0.55). This overestimate, of about 45%, could be explained by soil evaporation, which is higher for the flooding irrigation, especially when the cover fraction ($f_c$) is lower, i.e. for the Saada 2 site ($f_c \approx 30\%$). To save this considerable amount of water lost by soil evaporation, which is not used by the plant, the choice of an adequate irrigation method, like drip irrigation, is advisable. A good evaluation of the amount of water lost by direct soil evaporation needs a partitioning of total evapotranspiration into its soil evaporation and plant transpiration components. This can be achieved through sap flow or isotope measurements (Williams et al. 2004, Rana et al. 2005). Therefore, separate measurements of transpiration and soil evaporation are desirable.

**Conclusions**

The general objective of this study was to use the FAO-56 single and dual crop coefficient approaches to estimate actual evapotranspiration ($ET_a$) over an irrigated citrus orchard under drip and flood irrigations in Marrakech, Morocco. The results showed that, by using crop coefficients suggested by the FAO-56 paper, both approaches overestimate $ET_a$ for both irrigation methods.

After obtaining the appropriate values of crop coefficient ($K_c$) and basal crop coefficient ($K_{cb}$) based on eddy covariance measurements of $ET_a$, the performance of both approaches was greatly improved over the two fields studied in this paper. The FAO-56 model simulation was improved by about 20 and 57% for the single approach and 24 and 49% for the dual one, over Saada 1 and Saada 2, respectively. Despite this improvement, both approaches (single and dual) still slightly overestimate $ET_a$ values for Saada 1 and Saada 2. This may be due to an overestimate of soil evaporation.

The obtained values of $K_c$ were below the FAO-56 values for both irrigation methods (flooding and drip). On the citrus orchard under drip irrigation, the average crop coefficient ($K_c$) over the entire growing season was 0.52, which is about 20% lower than the $K_c$ recommended by the FAO-56 method. This reduction in $K_c$ reflects the practice of drip irrigation, which reduced soil evaporation. In the citrus orchard under flood irrigation, the reduction in $K_c$ can be explained by the low value of cover fraction (about 30%) which may reduce plant transpiration. These updated values of crop coefficients will improve future estimation of crop water requirements, and thus help to establish proper irrigation schedules and thus water use efficiency, in irrigated agriculture.

The output of the single source model is mostly dependent on one coefficient only, which means that it is difficult to adjust it when there is a balanced contribution of both the soil and the vegetation to total evapotranspiration. In the dual source approach however, one can adjust separately the contribution of the soil and the vegetation. For incomplete cover and/or drip irrigation, the dual crop coefficient seems, therefore, to be more suited since it is more flexible. Unfortunately devices to estimate plant transpiration were not available during the course of this study. Future investigations will be directed toward the assessment of the performance of the FAO-56 dual approach in terms of the partitioning of evaporation and transpiration.

**Acknowledgments**

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**References**


