EVAPOTRANSPIRATION OF AN HEDGE-PRUNED OLIVE ORCHARD IN A SEMIARID AREA OF NE SPAIN

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Abstract

The evapotranspiration of hedge-pruned olive orchards (*Olea eruropaea* L. cv. Arbequina) was measured under the semiarid conditions of the middle Ebro River Valley in a commercial olive orchard (57 ha) during 2004 and 2005. No measured ET_c values for this type of olive orchards have previously been reported. An eddy covariance system (krypton hygrometer KH20 and 3-D sonic anemometer CSAT3, Campbell Scientific) was used. The eddy covariance measurements showed a lack of the energy balance closure (average imbalance of 26 %). Then sensible and latent heat (LE) flux values were corrected using the approach proposed by Twine et al. (2000) in order to get daily measured olive evapotranspiration (ET_c) and crop coefficient (K_c) values. The highest measured monthly ET_c averages were about 3.1 to 3.3 mm day^{-1}, while the total seasonal ET_c during the irrigation period (March to October) was about 585 mm (in 2004) and 597 mm (in 2005). Monthly K_c values varied from about 1.0 (Winter) to 0.4-0.5 (Spring and Summer). These K_c values were similar to K_c values reported for round-shape canopy olive orchards, adjusted for ground cover, particularly during late Spring and Summer months when differences among measured an published K_c values were about less than 0.1.

Keywords

Crop Coefficient; Eddy Covariance; *Olea europaea* L.; Water Use; High Density Orchard

1. Introduction

Olive (*Olea europaea* L.) orchards are common in semiarid Mediterranean regions. In Europe, there were about 5.5 million ha in 2005 of which 2.5 million ha were located in Spain (Eurostat, 2008). 93 % of the Spanish olive orchards are for olive oil production and about 16 % of all Spanish olive orchards are irrigated (Anuario de Estadística Agroalimentaria, 2007). Traditional rainfed olive orchards in Spain have about 100 vigorous trees ha^{-1} and ground covers rarely exceed 25 %, while modern orchards are generally drip-irrigated, with low vigor varieties at about 200-300 trees ha^{-1} and 40-50 % ground cover (Villalobos et al., 2000). Olive trees are commonly grown in areas where water is scarce. Therefore, the optimization of the water use in irrigated olive orchards is paramount (Palomo et al., 2002; Orgaz et al., 2006). The seasonal olive evapotranspiration (ET_c) have been reported to range from 560 up to 1020 mm depending upon environmental conditions, crop characteristics (variety, geometry, etc.) and orchard management (Fernández and Moreno, 1999; Villalobos et al., 2000; Testi et al., 2006).

Commonly, ET_c is estimated as: $ET_c = ET_o \times K_c$ (Allen et al., 1998), where ET_o is the reference evapotranspiration, and K_c is the crop coefficient. For fruit tree and olive orchards it is also recommended to include an additional reduction coefficient (K_r) to take into account the ground cover fraction (f_c); thus, $ET_c = ET_o \times K_c \times K_r$

(Fereres and Castel, 1981). Several works have measured or estimated ET_c as well as K_c using several approaches: water balance (Fernández and Moreno, 1999; Palomo et al., 2002), evaporation pans (Michelakis et al., 1996), semiempirical ET equations, eddy covariance (Villalobos et al., 2000), sap flow (Fernández et al., 2001; Palomo et al., 1998). Allen et al. (1998) reported olive crop coefficients ranging from 0.55-0.65 at the beginning of the season to 0.65-0.70 the rest of the season for ground covers of 40-60 %, similar K_c values than those reported by Goldhamer et al. (1994) for California (USA). For similar ground covers, Pastor and Orgaz (1994) reported crop coefficients for Córdoba (Southern Spain) decreasing from 0.65 in Spring and Fall to 0.45 in Summer. These Spring and Fall values were similar to those reported by Michelakis et al. (1994) for Crete (Greece) but Summer values for Southern Spain were about 0.1 lower as Crete weather conditions are milder. Fernández and Moreno (1999) recommended increasing these values by 0.05 as Pastor and Orgaz (1994) did not take soil evaporation into account. Villalobos et al. (2000), also for Córdoba, estimated K_c values for 30-40 % ground cover olive orchards ranging from 0.9-1.0 in Winter to 0.4 in August. Fernández et al. (2006) reported K_c values of 0.76-0.77 in May and October, 0.70-0.72 in June and September, and 0.63 in July and August for Sevilla (also in Southern Spain). Differences in K_c in these works were partially due to ground cover. In some cases, reported K_c were in fact K_c x K_r. In addition, Fernández et al. (2006) pointed that variations in K_c values from different locations might be due in part to the method used to compute ET_o. Pereira et al. (2006) reported that olive transpiration can be estimated, at a daily step, as the product of ET_o estimated by the FAO Penman-Monteith (Allen et al., 1998) and the ratio of olive plant leaf area to the reference grass leaf area (which is assumed to be 2.88 m^2 of leaf $plant^{-1}$). These authors reported that this simplified method also worked well for other wood species as apples and grapevines.

Reported K_c values depend on the geometric characteristics (canopy shape, distance between trees, etc.) of the olive orchards. These coefficients are therefore limited in some extent to the type of orchards where they were developed. Obtaining crop coefficients more universal would need to know the contribution of transpiration alone to total ET_c, for instance by sap flow measurements. However, this technique has a limited capability for measuring transpiration for a whole orchard due to the high variability of the sap flow measurements because of the considerable heterogeneity of the conductive area in mature olive trees (Fernández and Moreno, 1999). Therefore, research efforts have been devoted during the last decade to model olive K_c as the sum of several components. Allen et al. (1998) presented the dual approach to get daily K_c estimates as the sum of basal crop coefficients (K_b) due to transpiration and evaporation coefficients (K_e) due to soil evaporation. Villalobos et al. (2000) followed a similar approach but the K_e was also divided in two components, a first one due to evaporation in wetted areas, and a second one due to evaporation in non-wetted areas. Villalobos et al. (2000) developed a model to compute daily olive ET in response to the main soil, climate and canopy conditions that influence it. This model was improved and validated by Testi et al. (2006). Daily simulations with this model allowed to Testi et al. (2006) to estimate average K_c values ranging from 1.2-1.6 during Winter months to 0.5-0.7 during Summer months, while annual ET could range from 830-940 mm for a 100 trees ha^{-1} density up to 930-1025 mm for a 300 trees ha^{-1} density depending upon locations. The simulated variability depended upon the specific tree density and geometry and the meteorological conditions of the simulation sites among other factors. The daily model by Testi et al. (2006) was used by Orgaz et al. (2006) for a wide range of orchard scenarios (varying tree density, tree canopy volume and the fraction wetted by the emitters) to develop functional relationships to calculate K_c at a monthly time step as the sum of four components: tree transpiration, direct evaporation of the water intercepted by the canopy, evaporation from the soil and evaporation from the areas wetted by the emitters. Simulations of Orgaz et al. (2006) gave values of annual olive ET from 480 mm (100 trees ha^{-1} densities) to 1090 mm (400 trees ha^{-1} densities) for Southern Spain.

Those models have been developed and tested for traditional and intensive olive orchards, with round-shape tree crowns. However, they have not been tested for hedge-pruned, high density olive orchards which have different tree canopy shape and root system. Tree canopy in hedge-pruned olive orchards forms a continuous “wall” within the rows (Gómez del Campo and Fernández, 2007), while hedgerow profiles can be rectangular, truncated rectangular, and triangular (Connor, 2006). The volume of the root system and the soil moisture distribution are conditioned by plant density. Commonly, hedge-pruned olive orchards have a higher tree density (up to 2000 trees ha^{-1} in some cases), a much lower tree canopy volume, and a much higher ratio of sunlit leaf surface to tree crown volume (Gómez del Campo and Fernández, 2007). In addition, the illumination patterns on canopy walls are affected by row height, wall slope, and alley and row widths. Many combinations of these factors can provide equal areas of adequately illuminated foliage per unit orchard area, being the row width as the major design criterion to optimize the illumination pattern of the walls (Connor, 2006). The hedge-pruned olive orchards are a good alternative due to an early start of production, and mechanization and economy of harvest, using continuous fully mechanized harvester riding over the trees. Hedge-pruned olive orchards are not much extended yet, about 35000 ha in the world of which 20000 ha are in Spain, but the cropped surface is growing at a rate of more than 8000 ha per year (Gómez del Campo and Fernández, 2007).

No experimental work has been done so far to get values of crop evapotranspiration and crop coefficient appropriate for hedge-pruned olive orchards. The only previous works on this topic were those by Grattan et al. (2006) and Berenguer et al. (2006), carried out in California. However, they used a fixed value of K_c = 0.75 for the whole season, modified by multiplying by a factor (K_r), varying from 0.72 to 1.0, depending upon canopy size of trees under different irrigation water treatments. Under these conditions, the estimated ET_c for the period May to October was about 570 mm.

The aim of this work was to measure evapotranspiration of hedge-pruned olive orchards under the semiarid conditions of the middle Ebro River Valley, as well as to get monthly crop coefficients for the whole crop season.

2. Material and methods

The experiment was carried out at Sástago (Zaragoza, NE Spain) from February 2004 to January 2006. Thereinafter the year “2004” refers to the period February 2004 to January 2005 and the year “2005” refers to the period February 2005 to January 2006. The geographical coordinates of the experiment location were 41°18’ N latitude, 0°22’ W longitude, and 150 m elevation above sea level. The long-term average annual meteorological conditions in the area are: precipitation, 315 mm; mean temperature, 14.9 °C; minimum air relative humidity, 41 %; global solar radiation, 185 W m^{-2}; wind speed at 2 m above ground, 3.1 m s^{-1}; and reference evapotranspiration, 1392 mm.

The experiment was performed at a commercial olive orchard (*Olea europaea* cv. ‘Arbequina’) orchard of about 57 ha (Figure 1). Average soil slope in the orchard was 2.0 %. Soil texture is silty loam (0 to 30 cm depth) and silty clay loam (30 to 60 cm). The average values of volumetric field capacity and permanent wilting point from 0 to 90 cm were 36.3% and 21.0%, respectively. The trees were planted in 1997 at a spacing of 6.0 m x 3.0 m, thus tree density was 556 trees ha^{-1}. The tree height was about 3.5 m above ground. As the tree crowns formed a continuous hedge wall within the rows of about 2.0 m width (average measured value), ground cover fraction (f_c) as observed from nadir (overhead) was estimated as the base of the parallelepiped-shaped crown times the tree density (expressed in trees m^{-2}); then, in this work, f_c = 0.334. The base of the tree crown was measured to be at about 1.0 m above ground. Then, the tree crown volume was estimated following Gómez del Campo and Fernández (2007) as the product of the tree crown height (2.5 m), row width (2.0 m) and the distance between trees within the row (3.0 m), i.e., 15 m^3 tree^{-1} or 8340 m^3 ha^{-1}, a much lower figure than that of traditional rainfed or round-shape crown drip irrigated orchards, 60-130 m^3 tree^{-1} or 9200-10200 m^3 ha^{-1} (Testi et al., 2006; Gómez del Campo and Fernández, 2007). Leaf area density was estimated as 1.8 m^2 m^{-3} from the tree crown volume following Orgaz et al. (2006). The olive orchard was surrounded by other smaller olive and fruit orchards, range and bushes.

All management practices (irrigation, pruning, herbicide application) were performed according to the farmer’s criteria. Herbicides were periodically applied between the lines of olives to avoid presence of weeds in the orchard. Pruning was performed in winter. Mechanical topping of the olive trees was made at a height of 3.5 m with a hedging machine with circular saws mounted in a rotor. Hydraulic scissors were used to eliminate the lower branches and small hedging operations.

Drip irrigation was applied from March to October each year, using preinstalled emitters at 1 m spacing and a discharge of 3.8 L h^{-1}. Thus, each olive tree was irrigated with three emitters. Ground area wetted by the emitters was about 17 %. Daily irrigation depths were measured with an automatic flow meter. Table 1 lists the irrigation depths and number of irrigations per month for both years. Irrigation seasons lasted from 28 March to 28 October 2004, and from 11 March to 22 October 2005.

Measurements were performed with an eddy covariance system installed on a micrometeorological tower (6.0 m height). It consisted of a krypton hygrometer (Campbell Scientific, model KH20) and a 3-D sonic anemometer (Campbell Scientific, model CSAT3). Both sensors were installed at 5.0 m above soil surface (with a distance of 0.11 m among them), pointing to the northwest direction (the predominant wind direction in the area), and operated at 10 Hz to record 30-minute averages, standard deviations and the respective covariances of water vapor densities, the three-component wind velocities, and the sonic temperature. Likewise, a net radiometer (Radiation and Energy Balance Systems, model Q-7) and two soil temperature probes (Campbell Scientific, model TCAV) operating at 0.05 Hz were used to record 30-minute averages of net radiation (R_n) and soil temperature. The net radiometer was installed in the same tower and at the same height above the soil as the KH20 and the CSAT3; Villalobos et al. (2000) did not find significant differences between net radiation values measured over the trees and over the space between adjacent rows in an olive orchard planted at a spacing of 6.0 m x 6.0 m in Southern Spain. The soil temperature probes were buried at 0.02-0.06 m depths, one between adjacent rows and the other between trees within the same row. A CR23X (Campbell Scientific) datalogger was used to monitor all these sensors and store the recorded data. Reliable eddy covariance measurements require, among other factors, to have enough fetch (upwind distance from plot edge to measurement spot). In the studied area, the predominant wind is northwest, and therefore the chosen measurement spot should have at least enough fetch for northwest winds. According to Monteith and Unsworth (1990), the fetch should be about 100 times the measurement height above crop canopy. This requirement would have been met in several spots within the studied olive orchard. However, soil stoniness in the plot decreased from north to south, and access tubes installation for soil water monitoring with capacitance probes is easier in soils without stoniness. For these two reasons, fetch and soil stoniness, the measurement spot was located in the southern part of the orchard (Figure 1).

A second datalogger (CR10X, Campbell Scientific) was used to monitor an air temperature and relative humidity probe (Vaisala, model HMP45AC), four soil heat flux plates (Hukseflux, model HFP01) and a rain gage (Campbell Scientific, ARG100). These sensors also operated at 0.05 Hz and were used to record 30-minute averages of air temperature and relative humidity, soil heat flux, and precipitation, respectively. The HMP45AC probe was installed at 4.1 m above soil surface. The HFP01 plates were buried at 0.08 m depth, at the same spots as the TCAV probes. The recorded soil heat flux values were corrected as described by Allen et al. (1996) using the soil temperature records to get soil heat flux at the soil surface. At each 30-minute period, the four soil heat flux values thus obtained were averaged to get a single value of soil heat flux (G). The rain gage was installed at the middle of the spacing between two consecutive tree rows at a height of about 2 m above ground.

Sensible (H_{EC}) and latent (LE_{EC}) heat fluxes (in W m^{-2}) were obtained each 30-minute period from the eddy covariance instrumentation recordings as follows:

$$H_{EC} = \rho\, c_p\, \overline{w' T'_{son}} \tag{1}$$

$$LE_{EC} = (\lambda / C_{KH})\, \overline{w' q'} \tag{2}$$

where: ρ, air density (kg m^{-3}); c_p, specific heat of air, J kg^{-1} °C^{-1}; λ, latent heat of vaporization, J g^{-1}; C_{KH}, factory calibration factor of the krypton hygrometer, ln(mV) m^3 g^{-1}; $\overline{w' T'_{son}}$, covariance between the fluctuations of vertical wind speed (w', m s^{-1}) and those of sonic temperature (T'_{son}, °C); $\overline{w' q'}$, covariance between w' and the fluctuations of water vapor density (q'), recorded as the natural logarithm of the sensor voltage output according to the KH20 krypton hygrometer specifications (Campbell Scientific, 1996). ρ, c_p, and λ were computed from recorded air temperature and relative humidity as described by Ham (2005). The factory calibration factors C_{KH} were -0.165 ln(mV) m^3 g^{-1} (in 2004) and -0.230 ln(mV) m^3 g^{-1} (in 2005) as the krypton hygrometer installed in 2004 was removed and a new one installed instead.

The half-hour values of LE_{EC} were later averaged to get daily values that were converted to olive evapotranspiration (ET_c, in mm day^{-1}) by dividing by the latent heat of vaporization (λ) and taking into account the appropriate time unit conversion (1 day = 86400 s). Experimental daily and monthly values of the olive orchard crop coefficient, K_c, were derived as the ratio of daily (or monthly average) measured ET_c and the daily (or monthly average) estimated reference evapotranspiration (ET_o), computed by the FAO Penman-Monteith method (Allen et al., 1998) from the daily meteorological variables (wind speed, solar radiation, and air temperature and relative humidity) recorded in a nearby standard weather station located over grass.

$$K_c = ET_c / ET_o \tag{3}$$

Soil water content was measured using Enviroscan permanent multisensor capacitance probes (manufactured by SENTEK, Stepney, Australia) installed in 12 sites around an olive tree (Figure 2) with sensors installed at 0.1, 0.2, 0.3, 0.5 and 0.8 m depths. Readings were taken at hourly steps along the season.

3. Results and discussion

The meteorological conditions during the two years of measurements were different (Table 2). Thus, total precipitation during 2004 (365 mm) was slightly higher than during 2005 (345 mm). However, the distribution of precipitation along the season was completely different between both years. In 2004, about 62 % of the total precipitation was recorded from February to May, while about 55 % of total precipitation in 2005 was recorded from August to November. Only the recorded precipitation in May was quite similar in both years (Table 2). Differences in air temperature were smaller: annual averages were 14.4 °C in 2004 and 14.6 °C in 2005; in general, average temperature was about 1.1 to 1.7 °C higher in 2004 from August to October and 3.5 °C in December, while it was about 1.3 to 2.4 °C higher in 2005 from January to July. In correspondence with the monthly distribution of precipitation, monthly minimum air relative humidity in 2004 was higher from February to May, while it was higher (but in a lesser extent) during Fall in 2005. Finally, the average wind speed values show the windy conditions of the area for the whole season in both years but October; the highest differences between both years were observed in January and February (Table 2). Predominant wind directions during the measurement period were northwest (NW) and west northwest (WNW) which amounted about 52 % in both years, although the east southeast (ESE) and southeast (SE) directions were also frequent during some periods and amounted about 21 % in both years (Figure 3).

Figure 4 shows the comparison between the measured R_n-G and the measured H_{EC}+LE_{EC} values for 30-min and daily periods. Although the coefficient of determination was quite high, it was obvious that the turbulent flux (H_{EC}+LE_{EC}) of the energy balance equation was lower than the available energy (R_n-G) term. In average, the ratio of the turbulent flux term to the available energy term was about 0.74 both for 30-min and daily periods. A lack of an appropriate energy balance closure is commonly observed when performing eddy covariance measurements over quite different cropped surfaces (Twine et al., 2000; Wilson et al., 2002). Assuming the metabolic energy and the storage heat in plant tissues as negligible, the energy balance closure is defined as the ratio (R_n-G) / (H_{EC}+LE_{EC}) (Twine et al., 2000; Foken, 2008). This ratio should approach a value of 1.0 although a value between 0.7 and 1.0 is generally considered as reasonable (Twine et al., 2000).

Several reasons could explain the lack of closure of the surface energy budget (Twine et al., 2000; Wilson et al., 2002); among others, the lack of coincidence of the source areas among various flux components measured very near a surface, no one-dimensional transport arising from insufficient fetch, missing of low frequency fluctuations, advective flux due to mean vertical velocities different than 0, and measurement errors related to sensor separation, frequency response, alignment problems, interference from tower or instrument-mounting structures. Twine et al. (2000) and Wilson et al. (2002) made a comprehensive review of surface fluxes measured with eddy covariance system under different locations, vegetation types, heterogeneity and other characteristics and concluded that there is a general lack of energy balance closure of about 20 % as an average. The imbalance was even present under ‘ideal’ conditions (flat, homogeneous surfaces and short vegetation) and after performing several corrections to the measured sensible and latent heat fluxes as described for instance in Foken (2008).

In this work, it was assumed that fetch was adequate most of the time due to the predominant wind direction (Figure 3) and the location of the measurement spot within the plot (Figure 1). Fetch may have not been so adequate during periods with ESE or SE predominant wind direction. In addition, the measurements were performed under semiarid conditions (where advection may be significant) and over sloping terrain, and thus some of the problems mentioned in the previous paragraph may have been occurred. The average imbalance was about 26 % (Figure 4), close to the average value reported by Twine et al. (2000) and Wilson et al. (2002). In flood-irrigated olive orchards grown in Morocco, imbalances of about 74 % (Williams et al., 2004) and 8-10 % (Er-Raki et al., 2008) have been reported. Williams et al. (2004) argued that this lack of energy balance closure was due to energy storage within the olive tree biomass. Twine et al. (2000) proposed forcing closure as a possible solution. They assumed that the different problems affect in a similar proportion to the sensible and latent heat flux measured values, i.e. they assumed that the Bowen ratio (β, the ratio of sensible to latent heat flux), is correctly measured by the eddy covariance system, so that ‘corrected’ eddy covariance values of latent heat (LE_{EC_C}) fluxes can be derived as:

$$LE_{EC\_c} = (R_n - G) / (1 + \beta) \qquad (4)$$

This is the approach followed in this work. Because β may be close to -1 during near sunrise and near sunset periods, and thus LE_{EC_c} may not be computed during those periods, it was decided to average the 30-minute values of H_{EC}, LE_{EC},

R_n and G to get the corresponding daily averages, and then to apply Eq. (4) to get daily LE_{EC_c} values for the studied olive orchard. These daily averages were only computed if all 48 half-hour periods of a given day were available. The LE_{EC_c} daily values were later used to get measured ET_c and K_c (Eq. 3) values. A total of 425 daily values of olive evapotranspiration were finally obtained.

Figure 5 shows the daily and monthly measured values of ET_c and those of estimated ET_o for the measurement period. Daily values showed significant variability along the season. In general terms, both ET_c and ET_o showed a similar pattern, along the season, increasing from Winter to mid-Summer and then decreasing thereafter. The highest daily measured ET_c value was about 5.0 mm day^{-1}. The highest monthly averages of measured ET_c (about 3.1 to 3.3 mm day^{-1}) and estimated ET_o (7.4 to 7.8 mm day^{-1}) values were observed in June in 2004, and in July in 2004. These figures were about twice than those reported for intensive olive orchards with about a half plant density (Fernández and Moreno, 1999; Fernández et al., 2006).

Figure 5 also shows that the differences among ET_c and ET_o also increased from Winter to mid-Summer and decreased thereafter. The differences between ET_c and ET_o during Spring 2005 were higher than those during Spring 2004. The lower sum of precipitation (thus higher average solar radiation) and irrigation dose (Table 3), and minimum relative humidity, and the higher air temperature during this period in 2005 (Table 2) led to higher estimates of ET_o but lower ET_c by the olive orchard with respect to 2004. The opposite was observed in late Summer and Fall 2005. The higher sum of precipitation and irrigation dose in this period during 2005 lead to a higher ET_c with respect to 2004. Considering the irrigation period (March to October), seasonal ET_c was slightly higher in 2005 (597 mm) than in 2004 (585 mm).

Therefore, the differences in ET_c and K_c between both years were mainly due to the different meteorology observed.

It must be pointed out that ET_c is the sum of transpiration by the crop and soil evaporation. This latter component can be a significant part of a heterogeneous crop such an olive orchard, particularly during rainy periods. Villalobos et al. (2000) and Testi et al. (2006) reported that soil evaporation could be as much as 25-40 % of total ET_c of an olive orchard. Therefore, the lower ET_c values shown in Figure 5 for Spring 2005 were mainly due to a reduction of soil evaporation because the small amounts of recorded precipitation, and the higher ET_c values observed in late Summer and Fall 2005 were due to the increased precipitation during this period regarding to the same period in 2004. Thus, Figure 6 shows the evolution of soil water content at different soil depths along the irrigation seasons recorded next to the emitter (tube 3, Figure 2). In general terms, a daily fluctuation of soil moisture was observed particularly during irrigation days at soil depths of 0.1, 0.2, 0.3 and 0.5 m proving that irrigation water reached these soil layers till the middle of July in both experimental years. Figure 6 shows also that from the middle of July till the end of August irrigation did not affect the capacitance sensor located at 0.5 m depth. Regulated deficit irrigation was applied in this period, that coincides with the pit hardening phase, since agronomically is very convenient (Alegre et al., 1999). It can also be observed that soil moisture content at 0.8 m depth was kept above the field capacity threshold along all the irrigation season. Results showed that transpiration by the olive orchard was not limited by water availability except in the pit hardening phase. Likewise, according to Fereres et al. (2005), olives under a good irrigation supply maintain a leaf water potential at solar noon around -1.5 MPa. The average value of midday leaf water potential measured in 26 May 2005 in exposed mature leaves in the studied orchard was -1.57 MPa (coefficient of variation, 7.0 %). Then, this suggests that there were no indications of water stress in the studied orchard in Spring and early Summer.

Berenguer et al. (2006) and Grattan et al. (2006) estimated cumulative ET_c (May to October) of about 570 mm for high-density (1700 trees ha^{-1}) 3-4 years old olive orchards (ground cover fraction of about 0.5) in California at an area with about 50 % more rainfall but similar temperature and ET_o values to those observed in this work. This figure of 570 mm was about 14 % higher than the average cumulative ET_c from May to October measured in this work (about 500 mm). Nevertheless, Berenguer et al. (2006) and Grattan et al. (2006) concluded that irrigation dose of about 70-75 % and of 30-40 % of estimated ET_c maximized yield and oil quality, respectively. In this work, the May-to-October irrigation dose was 281 mm in 2004 and 293 mm in 2005. These values represent 60 and 55 % of the measured ET_c in 2004 and 2005 (May to October), respectively, values that are included in the range of irrigation water suggested as adequate in the Berenguer et al. (2006) and Grattan et al. (2006) experiments. The olive yields of the Arbequina orchard of the present study were 4900 and 6300 kg ha^{-1} in 2004 and 2005, respectively. These values are considered optimum for intensive olive orchard under the semiarid conditions of the middle Ebro River Valley. The oil quality obtained from this orchard was excellent, classified as extra virgin olive oil.

Likewise, using a simulation model to estimate olive evapotranspiration and crop coefficients under different scenarios, Orgaz et al. (2006) estimated seasonal ET_c of 1087 mm in Córdoba (south of Spain) for a plant density of 400 trees ha^{-1} (the maximum simulated density) with a ground cover fraction of 0.65 and a wetted soil fraction (by drip irrigation) of 0.1. These plant density and wetted soil fraction were relatively close to those observed in this work. But ground cover fraction was about double. It is common to estimate ET_c of fruit tree and olive orchards by multiplying the crop coefficient by a reduction coefficient (K_r) estimated as a function of ground cover fraction (f_c), for instance using the equation by Fereres and Castel (1981): $K_r = (2\ f_c) / 100$ (with the limit of $K_r = 1.0$ for $f_c > 50$ %, f_c expressed in percent). In this work, f_c was 33.4 %, and thus K_r could be estimated as 0.67. Thus, if this K_r coefficient is multiplied by the seasonal ET_c of 1087 mm estimated by Orgaz et al. (2006), a value of 728 mm is obtained, which is quite close to the seasonal ET_c (722 mm) observed in this work as an average value for both years. In addition, Orgaz et al. (2006) simulated a monthly ET_c in July (the peak month) of 150 mm for the same orchard. Again, multiplying this value by the estimated $K_r = 0.67$, a value of 100 mm is obtained, quite close also to the average monthly ET_c in July (97 mm) measured in this work. Villalobos et al. (2000) also simulated evapotranspiration for olive orchards in Córdoba under different scenarios and reported seasonal ET_c of 758 m for ground cover fraction of 0.3. Palomo et al. (2002) measured olive evapotranspiration in Sevilla (south of Spain) for an olive orchard with a ground cover fraction of 0.34 and found seasonal ET_c of 653 mm, about 10 % lower than that observed in this study. Therefore, in terms of seasonal ET_c, the values obtained in this work for a hedge-pruned olive orchard were reasonably similar to those found for round-shape crowns olive orchards under drip irrigation and similar ground cover fractions.

Table 4 lists the monthly K_c values obtained in this work for the measurement period. The K_c values were different between both years but in Summer (June to August). These differences among years responded to the different meteorological conditions of both years as discussed previously for the monthly ET_c values. Table 4 also lists the average monthly K_c values for both years. Figure 7 shows the average monthly K_c curve obtained in this work. This curve showed a U-shape, with K_c values close to 1.0 observed in Winter, decreasing to values close to 0.40 during Summer and increasing again to values close to 1.0 during early Winter. This U-shape is in accordance with simulated K_c curves at different scenarios by Testi et al. (2006) in Córdoba (Spain) and Fresno (California, USA), and with measured K_c curves reported by Villalobos et al. (2000). Other authors have reported K_c curves with a more flat shape although values for Winter months were also higher than during Summer (Figure 7) (Pastor and Orgaz, 1994; Fernández et al., 2006; Orgaz and Fereres, 2001). However, Allen et al. (1998) recommended a K_c curve that had slightly lower values early in the season (Figure 7).

Figure 7 also compares the experimental monthly K_c values obtained in this work with published K_c values. For this comparison, the selected published K_c values were obtained using the FAO Penman-Monteith equation to estimate ET_o except for the Pastor and Orgaz (1994) case for which the Hargreaves method was used to estimate ET_o. For monthly estimates of this variable, the Hargreaves and FAO Penman-Monteith methods provide similar ET_o estimates in semiarid and windy areas as the one used in this study (Martínez-Cob and Tejero-Juste, 2004). Figure 7A shows the original published K_c values for which K_r =1.0 except in the case of Testi et al. (2006) for which published K_c values correspond to a ground cover of 26 % (K_r = 0.52). Figure 7B shows those published K_c values adjusted for a K_r = 0.67, that obtained in the studied olive orchard. In general, K_c values obtained in this work were similar than those published in the above mentioned papers (after adjusting for K_r) during the middle months of the year as differences were in general less than 0.1 (Figure 7B). The main difference was against K_c values from Pastor and Orgaz (1994), likely due to the fact that these authors did not take soil evaporation into account as argued by Fernandez and Moreno (1999). K_c values from Allen et al. (1998), after adjusting for K_r, were the highest during the summer months. This would lead to overestimation of ET_c during these months. Er-Raki et al. (2008) also reported that K_c values by Allen et al. (1998) led to overestimation of evapotranspiration of flood-irrigated olive orchards in central Morocco (a plant density of 225 trees ha^{-1} and soil surface partly covered by grass).

In the middle Ebro River Basin, where the experimental site (Sástago) is located, most of the rain is recorded in Spring and Autumn (Table 2). Rainfall during Winter is less frequent but foggy days are common. Then a combination of lower evaporative demand (lower ET_o), higher soil moisture in the top soil layer and higher canopy intercepted water could explain that the evaporation of water from top soil and intercepted water can be maintained at a higher rate relative to ET_o. Thus, although olive transpiration rates are lower during colder months, these higher relative evaporation rates of soil moisture and intercepted water could explain those high K_c values observed during Winter and the U-shape of the K_c curve (Testi et al., 2006). Another factor that could explain the relative evaporation rates of canopy intercepted water is the significant canopy water storage capacity of olive orchards due to the maintenance of foliage during Winter. In addition, as ET_o is low in colder months, a small energy supply, for instance from canopy or soil cooling, may allow increasing the K_c by 0.4 to 0.5 (Testi et al., 2006). It is interesting to note that the K_c values during Winter reported by Villalobos et al. (2000) and Testi et al. (2006) were much higher than those reported in this work likely due to the higher rainfall (both relative and absolute) recorded during Winter in south of Spain. Finally, it should be pointed that ratios (such the K_c) are statistics that are unstable and unbounded when the denominator is close to zero (Wilmott, 1981). Therefore, when ET_o is low, as in

Winter, that is another factor that can explain the high K_c values observed in colder months.

The experimental K_c values listed in Table 4 integrate the different components of K_c, those due to transpiration, soil evaporation and intercepted water evaporation. The daily K_c values obtained in this work showed high variability, both within a given month and between years. This was expected due to the contribution of several factors, such as the soil evaporation, which is highly dependent on precipitation, a variable that has also a high variability. Because the different components of K_c have not been measured in this work, the usefulness of the recorded daily K_c values is limited to the experimental years. Monthly K_c values, as those listed in Table 4, are more useful because they smooth out variability observed due to the specific meteorological conditions of the experimental years. Further research should be performed to quantify the components of K_c separately for this type of olive orchards. Models developed for round-shape canopy orchards such as those of Testi et al. (2006) and Orgaz et al. (2006) could help in this future research. These models would be more suitable to be used for precise irrigation where daily K_c values are required. These models would need to be validated for hedge-pruned olive orchards.

4. Conclusions

The eddy covariance measurements reported in this paper showed a lack of the energy balance closure. The average imbalance was about 26 %. Thus, following to Twine et al. (2000), corrected eddy covariance H and LE values were obtained by forcing the energy balance closure assuming that the Bowen ratio was correctly determined by the eddy covariance system.

The highest daily measured olive orchard evapotranspiration (ET_c) value was about 5.0 mm day^{-1}, while the highest monthly average of measured ET_c was about 3.1 to 3.3 mm day^{-1}. The seasonal evolution of ET_c relative to that of ET_o was different in both studied years mainly because the contribution of soil evaporation due to the different seasonal distribution pattern of rainfall and, in a lesser extent, air relative humidity. The highest differences between ET_c and ET_o were observed during the drier months. Considering the irrigation period (March to October), seasonal ET_c was about 585 mm (in 2004) and 597 mm (in 2005).

In accordance with the seasonal evolution of ET_c and ET_o, experimental crop coefficients (K_c) were different in both years. These K_c values showed a U-shape curve, with the highest values being observed during Winter months (close to 1.0) and the lower values during Spring and Summer, about 0.4 to 0.5. In general, the K_c values obtained in this work were similar to those reported in previous works (after adjusting for ground cover), particularly during late Spring and Summer when differences were less than 0.1 in general.

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Tables

Table 1. Monthly irrigation depths (ID) and number of irrigations (NI) during: a) March to October 2004; b) March to October 2005.

Variable	Year	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
ID, mm	2004	28.0	31.8	23.6	59.5	55.7	58.1	54.8	29.2
	2005	33.2	40.6	46.9	59.4	68.5	56.8	38.9	22.7
NI	2004	2	18	16	26	30	30	27	20
	2005	7	24	31	30	31	30	27	11

Table 2. Average monthly meteorological conditions during the measurement period recorded at a nearby grass station. a) 2004 (February 2004 to January 2005); b) 2005 (February 2005 to January 2006).

Month	Pr (mm)		T_{air} (°C)		RH_{min} (%)		U_2 (m s^{-1})	
	2004	2005	2004	2005	2004	2005	2004	2005
January	2.4[a]	27.4[b]	3.6[a]	5.0[b]	66[a]	68[b]	4.5[a]	2.4[b]
February	53.4	18.2	5.1	4.9	67	40	2.4	5.0
March	59.4	5.0	8.6	10.2	46	31	3.1	3.2
April	67.8	15.2	11.7	13.9	45	32	3.5	3.9
May	45.0	48.2	16.2	18.6	35	29	2.7	3.0
June	2.0	23.2	24.0	23.9	24	23	3.1	2.8
July	29.0	7.8	24.0	25.3	25	21	3.1	3.3
August	25.0	36.4	24.6	23.5	25	26	2.5	3.7
September	12.4	65.6	21.7	20.0	30	32	3.4	2.6
October	29.6	54.0	17.1	16.0	36	50	2.1	2.0
November	8.4	35.4	8.3	9.1	56	58	4.1	3.2
December	30.2	9.0	7.2	3.7	65	60	3.8	2.8

Pr, precipitation; T_{air}, mean air tempeature; RH_{min}, minimum relative humidity; U_2, mean wind speed at 2.0 m above ground.

[a] during 2005; [b] during 2006.

Table 3. Monthly sum of precipitation and irrigation dose (mm) during the measurement period. a) 2004 (February 2004 to January 2005); b) 2005 (February 2005 to January 2006).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2004	2.4[a]	53.4	87.4	99.6	68.6	61.5	84.7	83.1	67.2	58.8	8.4	30.2
2005	27.4[b]	18.2	38.2	55.8	95.1	82.6	76.3	93.2	104.5	76.7	35.4	9.0

[a] during 2005; [b] during 2006.

Table 4. Monthly values of experimental crop coefficients during the measurement period a) 2004 (February 2004 to January 2005); b) 2005 (February 2005 to January 2006).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2004		0.69	0.68	0.69	0.67	0.43	0.42	0.38	0.35	0.66	0.70	
2005	0.90[a]		0.29	0.31	0.45	0.48	0.42	0.45	0.72	0.88	1.23	0.94
Average	0.90	0.69	0.49	0.50	0.56	0.46	0.42	0.42	0.54	0.77	0.97	0.94

[a] during 2006.

Figure captions

Figure 1. Olive orchard and location of the eddy covariance station. UTM, Universal Transverse Mercator.

Figure 2. Location of the soil water monitoring access tubes equipped with a capacitance sensors installed at 0.1, 0.2, 0.3, 0.5 and 0.8 m depth. Numbers 1 to 12 are used to identify each access tube.

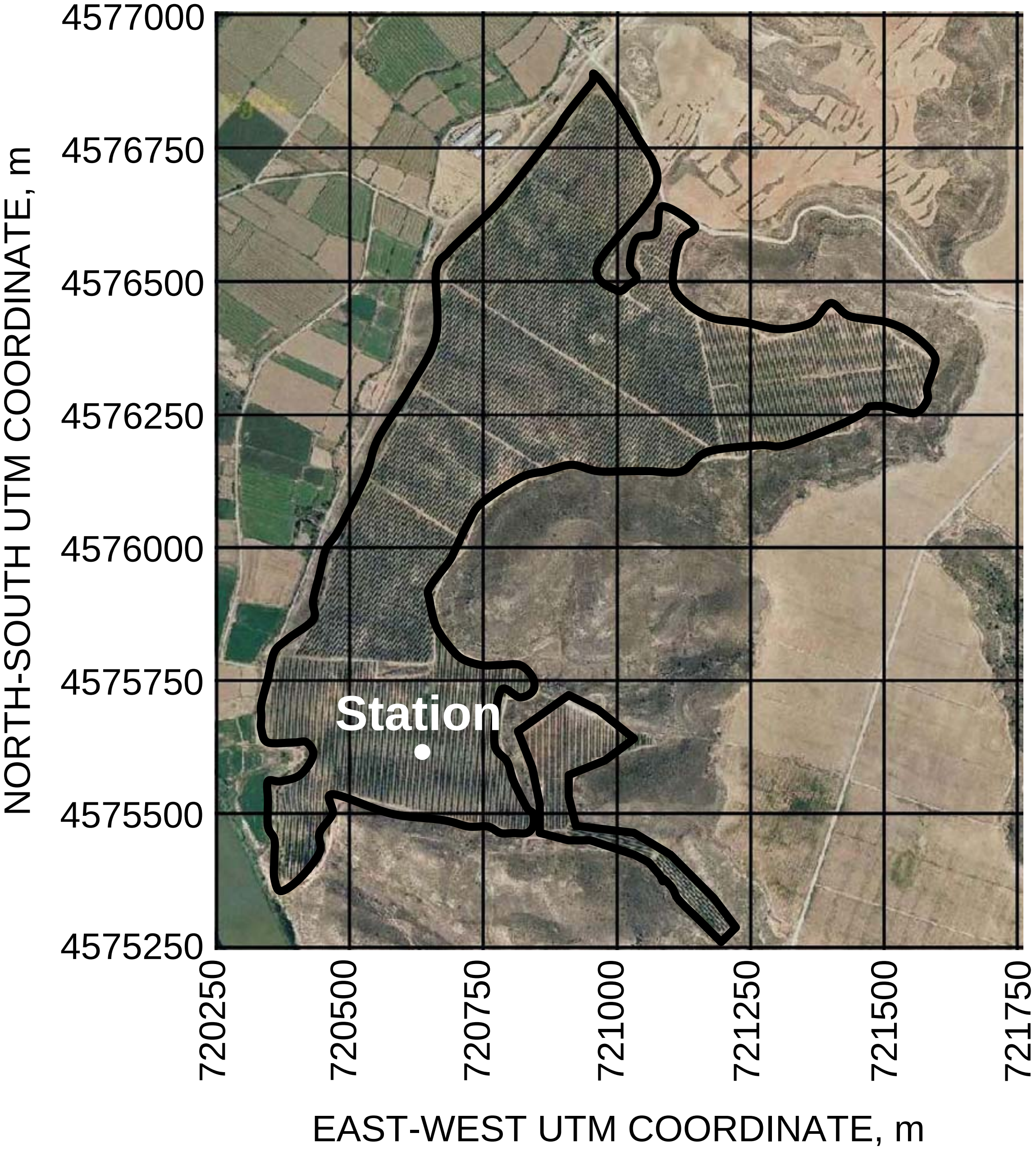
Figure 3. Relative frequencies (%) of different wind directions recorded at the measurement site from February 2004 to January 2006.

Figure 4. Averages of available energy (R_n-G) versus those of turbulent fluxes (LE_{EC}+H_{EC}) for the measurement period. (A) Half-hour; (B) Daily.

Figure 5. Measured olive evapotranspiration (ET_c) and estimated reference evapotranspiration (ET_o, method FAO Penman-Monteith) from February 2004 to January 2006. (A) Daily; and (B) monthly averages (in this case, vertical lines represent one standard deviation).

Figure 6. Hourly readings of soil moisture content at 0.1, 0.2, 0.3, 0.5 and 0.8 m depths from March to October (2004 and 2005) recorded at tube 3 (Figure 2) located next to the emitter.

Figure 7. Average measured monthly crop coefficient at Sástago (Zaragoza, Spain) (Sást) versus monthly crop coefficients reported by Testi et al. (2006) at Córdoba (Tes06), Pastor and Orgaz (1994) (PO94), Orgaz and Fereres (2001) (OF01), Fernández et al. (2006) (F06) and Allen et al. (1998) (FAO56). A) Original published values. B) Published values adjusted for K_r = 0.67.



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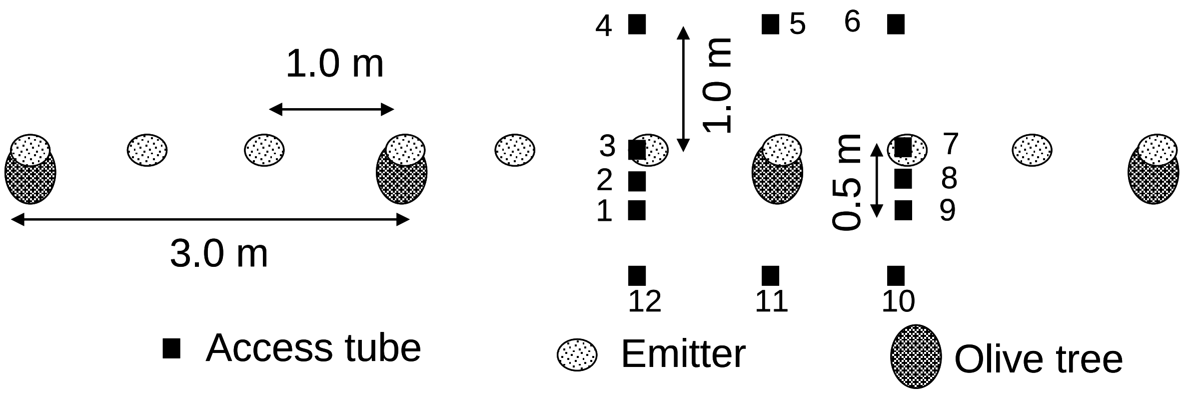

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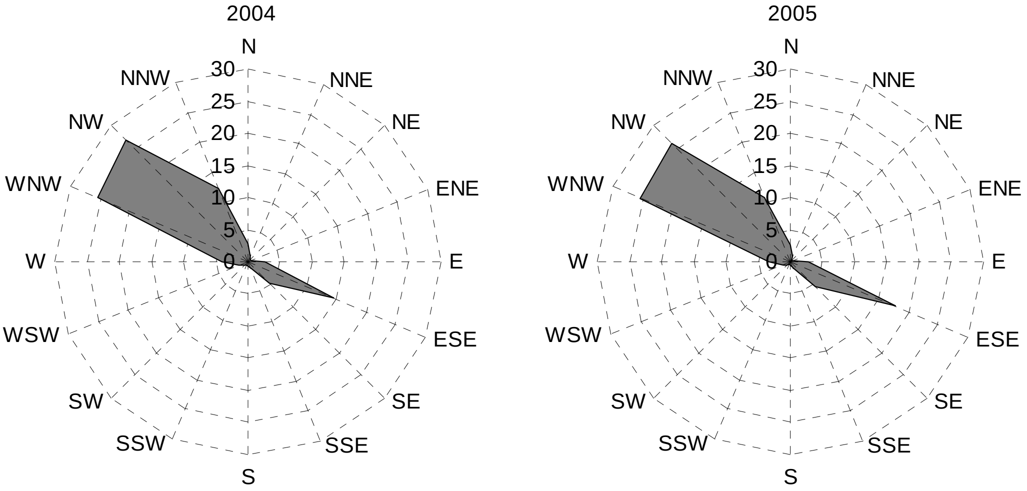

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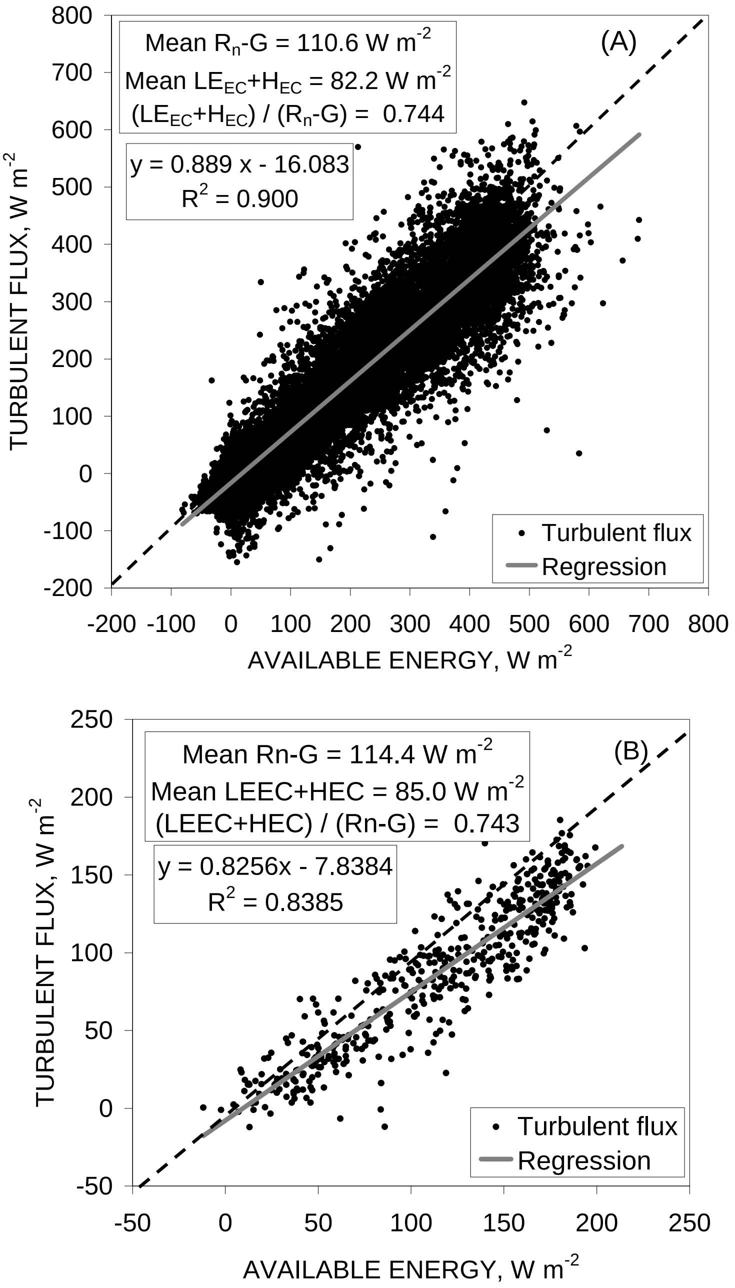

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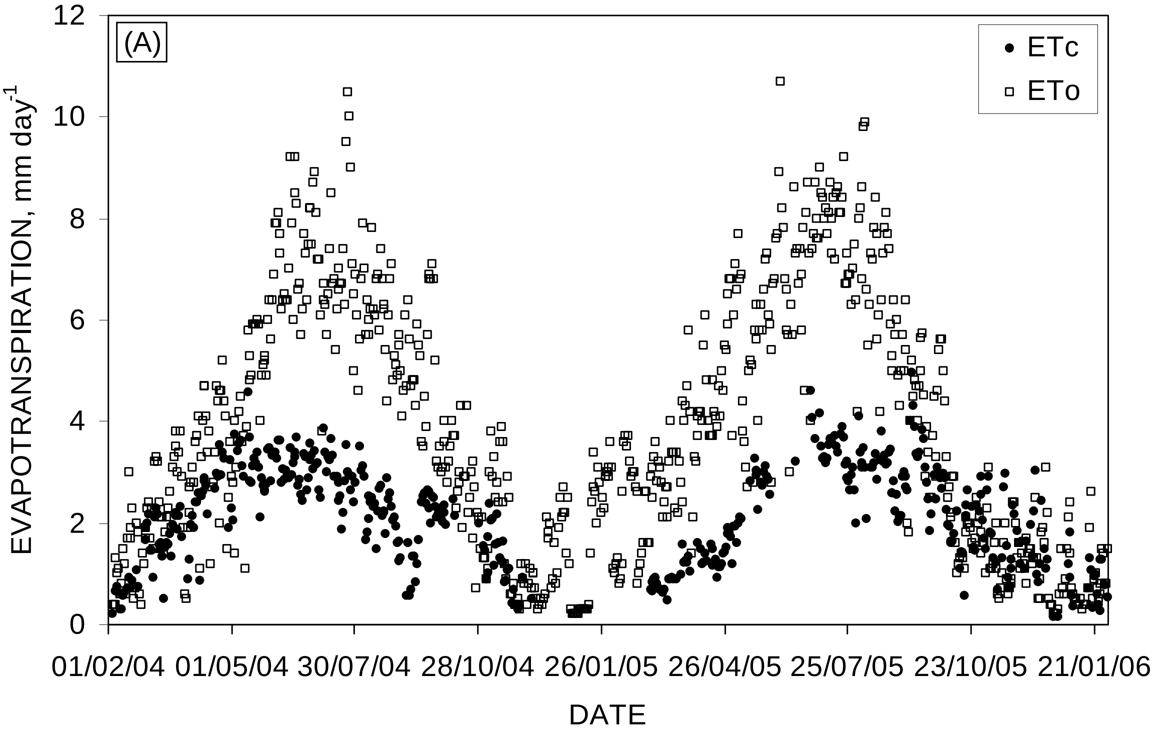

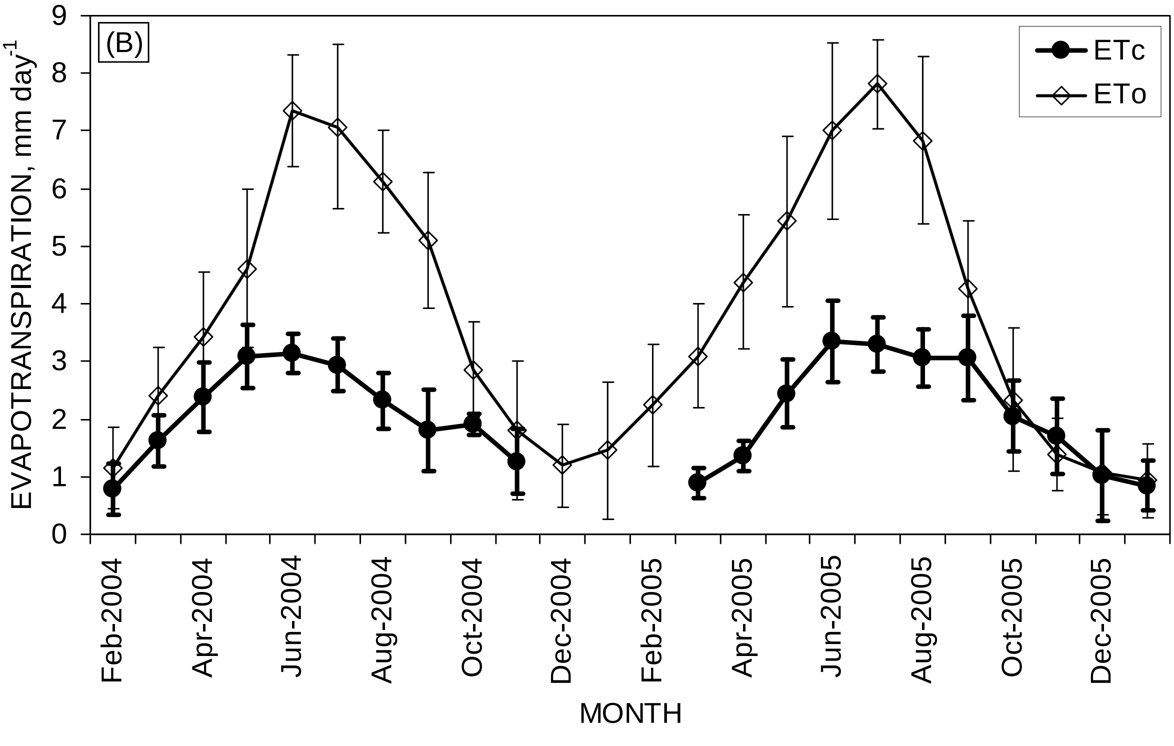

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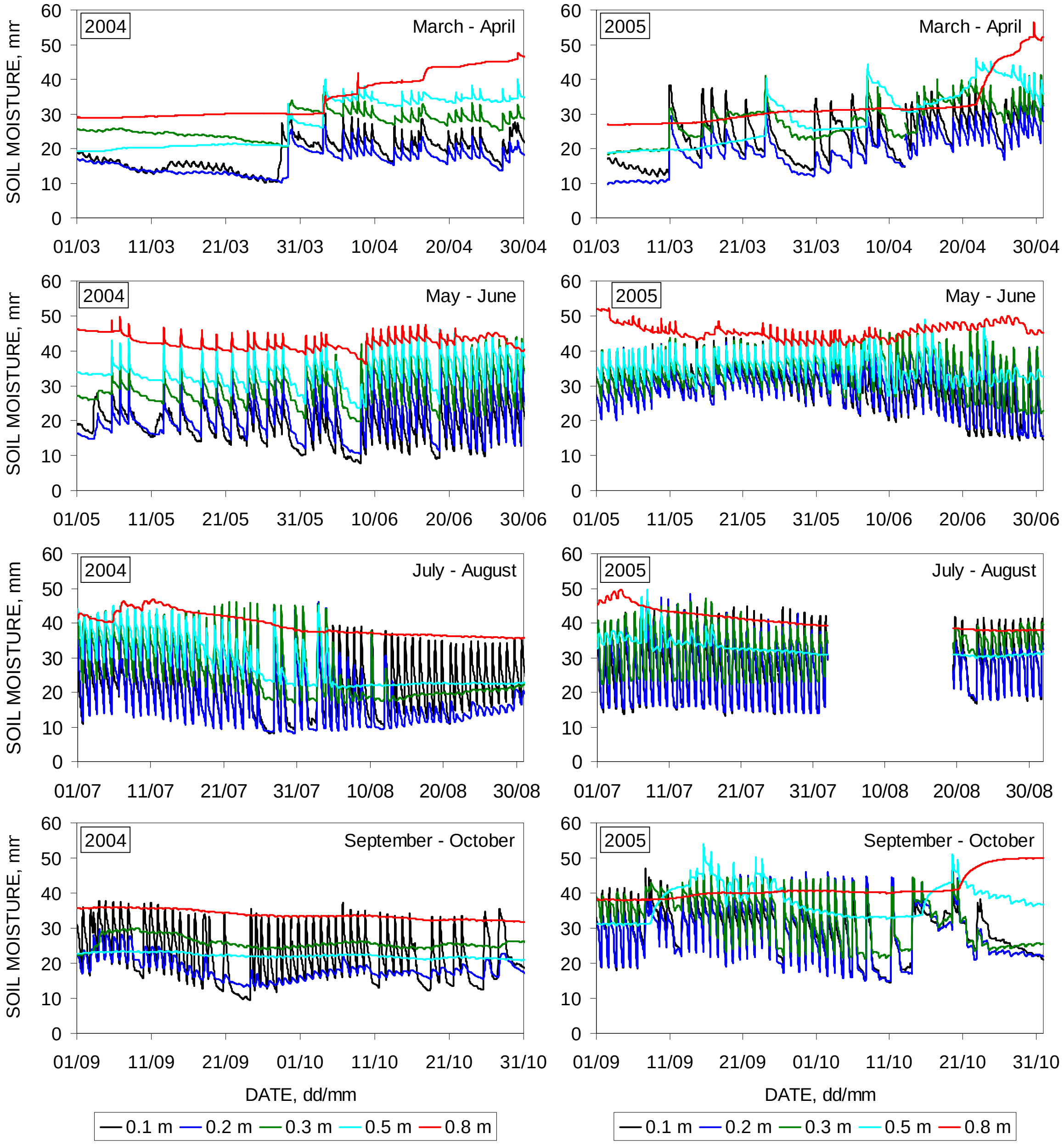

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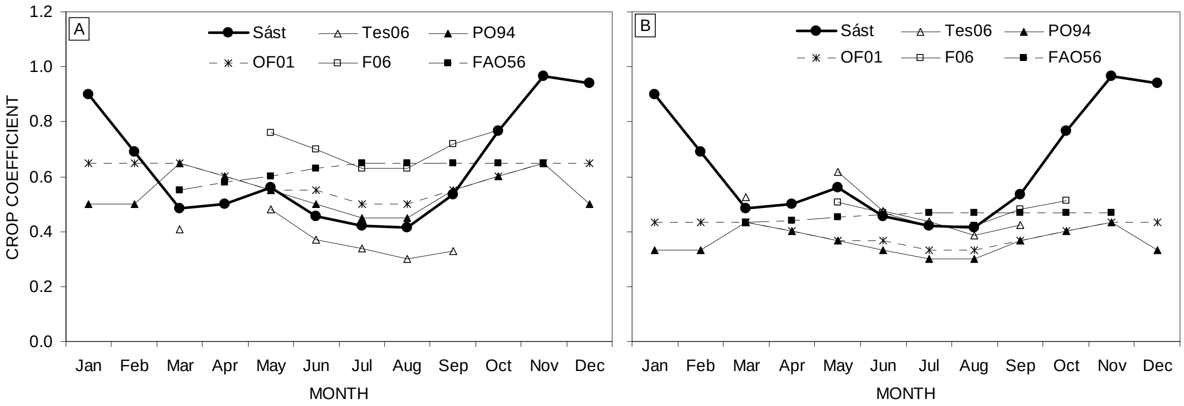

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