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Consumptive water use and crop coefficients of irrigated sunflower

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Abstract In semi-arid environments, the use of irrigation is necessary for sunflower production to reach its maximum potential. The aim of this study was to quantify the consumptive water use and crop coefficients of irrigated sunflower (*Helianthus annuus* L.) without soil water limitations during two growing seasons. The experimental work was conducted in the lysimeter facilities located in Albacete (Central Spain). A weighing lysimeter with an overall resolution of 250 g was used to measure the daily sunflower evapotranspiration throughout the growing season under sprinkler irrigation. The lysimeter container was 2.3 m × 2.7 m × 1.7 m deep, with an approximate total weight of 14.5 Mg. Daily ET_c values were calculated as the difference between lysimeter mass losses and lysimeter mass gains divided by the lysimeter area. In the lysimeter, sprinkler irrigation was applied to replace cumulative ET_c, thus maintaining non-limiting soil water conditions. Seasonal lysimeter ET_c was 619 mm in 2009 and 576 mm in 2011. The higher ET_c value in 2009 was due to earlier planting and a longer growing season with the maximum cover coinciding with the maximum ET_o period. For the two study years, maximum average K_c values reached values of approximately 1.10 and 1.20, respectively, during mid-season stage and coincided with maximum ground cover values of 75 and 88 %, respectively. The dual crop coefficient approach was used to separate crop transpiration (K_{cb}) from soil evaporation (K_e). As the crop canopy expanded, K_{cb} values increased while the K_e values decreased. The seasonal evaporation component was estimated to be about 25 % of ET_c. Linear relationships were found between the lysimeter K_{cb} and the canopy ground cover (f_c) for the each season, and a single relationship that related K_{cb} to growing degree-days was established allowing extrapolation of our results to other environments.

Introduction

Sunflower (*Helianthus annuus* L.) is one of the most important oil crops worldwide (Škorić 1992), and among oil crops, it is the fifth most cultivated annual crop. The sunflower global planted area was 26 million ha in 2011, with a production of 40.2 million Mg. In the European Union (EU), more than 4 million ha were cultivated in 2011 with a production of 8.3 million Mg, approximately 21 % of the world production. In Spain, the sunflower cultivated area has increased in the recent years from 516,000 ha in 2005 to nearly 860,000 ha in 2011 (FAOSTAT 2011). Sunflower is cultivated in several Spanish regions to produce oil, to feed livestock and to produce biodiesel. Recently, the latter use is increasing. Drought-tolerant energy crops are seen as promising cropping alternatives in semi-arid areas, given their capacity of adaptation to dry climatic conditions.

Only about 10 % of the total area of sunflower cultivated in Spain is irrigated, although irrigation often results in yield increases of over 100 % (MAGRAMA 2010). In other semi-arid areas, such as Turkey, Lebanon, Kansas (USA) and Texas (USA), irrigation of sunflower has

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increased seed yields ranging from 33 to 92 % (Unger 1982; Stone et al. 1996; Göksoy et al. 2004; Karam et al. 2007). Tolk and Howell (2012) reported that irrigation increased seed yields, but the amount of increase varied with soil texture.

Irrigated agriculture is the biggest water consumer in the world and often competes with industrial and urban sectors for water supply. In semi-arid environments with limited, irregular rainfall, the use of irrigation is necessary for crop production to reach its maximum potential. In areas with a shortage or overexploitation of water resources, such as the area of this study (Central Spain), plans for developing new water resources such as those proposed by the Irrigation Users Association of Eastern Mancha (IUAMO) (Martin de Santa Olalla et al. 2003) are more restricted each year. Under these conditions, reducing seasonal irrigation use could mitigate aquifer overexploitation. Because sunflower has a shorter growing season than other important crops in the area such as maize, onion or alfalfa, it could reduce the irrigation needs in this region. Moreover, sunflower has a deep root system that has been shown to extract more available soil water to greater depths compared with other crops (e.g., sorghum and soybean) (Bremmer et al. 1986; Fereres et al. 1993; Stone et al. 2002). Hence, sunflower is more tolerant of short periods of water stress (Tolk and Howell 2012). In a previous work, Soriano et al. (2004) reported that the evapotranspiration (ET_c) of sunflower in southern Spain ranged between 417 and 572 mm depending on planting date, with early plantings having greater ET than later plantings. Karam et al. (2007) reported that the ET_c of sunflower under several irrigation treatments ranged between 300 and 700 mm in Turkey. Sezen et al. (2011) reported the effects of 5 irrigation regimes on seed yields of sprinkler and drip irrigated sunflower in 2 growing seasons in the Mediterranean region of Turkey. The seasonal sunflower ET ranged between 680 and 709 mm with sprinkler irrigation. In a recent study, Tolk and Howell (2012) reported a seasonal ET ranged between 581 and 698 for fully irrigated sunflowers in northern Texas.

Crop water requirements are commonly calculated with the standard FAO approach (Allen et al. 1998) that uses reference evapotranspiration (ET_o) and a crop coefficient (K_c). Crop coefficient values, obtained by measuring crop evapotranspiration (ET_c), often with lysimeters, and then relating it to ET_o (Doorenbos and Pruitt 1975), are available for many crops. While the major field crops have been the subject of many lysimeter studies, the K_c values of crops of less importance are often estimated based on fewer studies and often where ET_c is determined with alternative methods that have less precision. It is desirable to determine the K_c values for sunflower with the precision that a weighing lysimeter provides.

Allen et al. (1998) established the standard methodology for predicting the effects of soil evaporation on K_c values. The procedure consists of separating K_c into two different coefficients, basal crop coefficient (K_{cb}), related to crop transpiration, and a soil evaporation coefficient (K_e). Thereby, the ET_c is calculated as: $ET_c = (K_{cb} + K_e) \times ET_o$.

The K_c curve represents the evolution of K_c overtime throughout the season (Wright 1985). K_c and K_{cb} curves can be expressed either in terms of time since planting, growing degree-days (GDD) since planting, or of percent of ground cover by vegetation (f_c) (Jensen 1974; Grattan et al. 1998; López-Urrea et al. 2009; Bryla et al. 2010). An advantage of using a crop-based term such as f_c is that the K_c and K_{cb} functions should be transferable to other growing conditions. This is not necessarily true when the K_c and K_{cb} functions are expressed as a function of chronological time (Al-Jamal et al. 1999).

This sunflower water use study was conducted in a weighing lysimeter installation located in Castilla-La Mancha, Spain, to (a) quantify the water use of sunflower under no soil water limitations during two growing seasons; (b) determine the single crop coefficient (K_c) and dual crop coefficient ($K_{cb} + K_e$) functions for sunflower; and obtain the relationship between the basal crop coefficient K_{cb} and the percent of ground cover by vegetation (f_c).

Local as well as regional diffusion of the results from this research will be largely conducted by the Irrigation Scheduling Service of Albacete (ISS) (Montoro et al. 2011).

Materials and methods

This study was conducted during 2009 and 2011 in the "Las Tiesas" farm, located near Albacete (Central Spain) (longitude 2°5′10″ West, latitude 39°14′30″ North, at an altitude of 695 m above sea level). The climate is semi-arid, temperate Mediterranean with 320 mm of average annual rainfall mostly concentrated in the spring and fall. Average mean, maximum and minimum temperatures are 13.7, 24.0 and 4.5 °C, respectively. For a more detailed description of the climate of the area, see López-Urrea et al. (2006).

The soil is classified as Petrocalcic Calcixerepts (Soil Survey Staff 2006). Average soil depth of the experimental plot was only 35 cm, and plant rooting is limited by a more or less fragmented petrocalcic horizon. Texture is silty clay loam, with 13 % sand, 49 % silt and 38 % clay, with a basic pH. The soil is low in organic matter and nitrogen, and has a high content of active limestone and potassium.

To determine sunflower (*H. annuus* L. cv. 'Oleko') ET_c, we used a weighing lysimeter with continuous electronic

Fig. 1 *Top left*, lysimeter field on June 4, 2009 and *top right*, sunflower inside the lysimeter on July 3, 2009. *Bottom left*, lysimeter field on August 3, 2011 and *bottom right*, sunflower inside the lysimeter on August 15, 2011

data recording (López-Urrea et al. 2006). Daily ET_c values were calculated as the difference between lysimeter mass losses (from evapotranspiration) and lysimeter mass gains (from precipitation, irrigation or dew) divided by the lysimeter area (6.21 m^2). In the lysimeters, irrigation was applied to replace ET_c (weight loss) and maintain non-limiting soil water content. Soil inside the lysimeter was similar to the surrounding field soil with a limited (35 cm) rooting depth, and thus, irrigation was managed for only 35 cm of sunflower root depth. The water holding capacity and permanent wilting point in the 35 cm root zone were 117 and 63 mm, respectively, resulting in total available water of 54 mm. Irrigation was applied when the lysimeter weight indicated soil water depletions of 24 mm, thus insuring that no more than 44 % of the total available water was depleted.

The lysimeter is located in the center of a 100 × 100 m plot, where sunflower was sown on April 21, 2009 and on June 15, 2011. These different sowing dates and populations are representative of the studied area (early planting in April and late planting in June). In previous work conducted in Cordoba (Spain), Soriano et al. (2004) concluded that early planting in sunflower has greater water use and water use efficiency than late planting.

In the field and lysimeter, the spacing between rows was 0.76 (three evenly spaced rows on the 2.3 m wide lysimeter) in 2009, in-row plant spacing averaged 0.165 m, giving 8 plants m^{-2}, whereas in 2011, in-row plant spacing was 0.106 m, giving a more dense 12.4 plants m^{-2}. The plant population inside the lysimeter was identical to that in the rest of the field, thus allowing for representative measurements of ET_c. Diligent efforts were made to keep the crop inside the lysimeter at the same size, growth stage and plant population as the crop outside and to minimize edge effects to insure that the lysimeter area was representative of the field surface. Figure 1 shows four photographs of the crop in the lysimeter field at different growth stages during the two experimental seasons.

Fertilizer was applied before sowing at a rate of 56 kg ha^{-1} of N, 28 kg ha^{-1} of P_2O_5 and 28 kg ha^{-1} of K_2O. The sunflower seed was harvested on 7 September and on 27 September in 2009 and 2011, respectively. The experimental field had a permanent sprinkler irrigation system with sprinklers on a grid of 15 × 12.5 m that provided a precipitation rate of 8.6 mm h^{-1}.

The lysimeter container is 2.7 m long, 2.3 m wide and 1.7 m deep, with an approximate total weight of 14.5 Mg. The lysimeter soil-containing tank sits on a system of beams and counterbalances that offsets the dead weight of the soil and the tank and reduces the load on the weigh beam by 1,000:1. A steel load cell (model SB2, Epelsa Ind., S.L., Spain) is connected to the weigh beam. The system allows measurement of ET in the lysimeter with a resolution of 0.04 mm equivalent water depth. Additional information about the technical features of the lysimeter is given in López-Urrea et al. (2006). The lysimeter weight data were checked daily to identify individual errors in the readings not explainable by natural processes of water input and loss. Data collected during precipitation events, weight and calibration verifications, and when works were carried out in the soil of the lysimeter tank were not used in the final ET calculations.

Meteorological variables during the experiment were measured with an automated weather station located over a reference grass surface less than 100 m from the sunflower lysimeter. All sensors were located between 1.5 and 2 m above the grass surface, and weather data were registered in 15 min, hourly and daily time steps. Variables measured, sensor type, model, manufacturer and the sampling frequency (SF) were as follows: *air temperature* (PRT 100 Ohm, model MP100, Campbell Scientific Instrument, Logan, UT, USA, SF: 1 s); *relative humidity* (Rotronic Hygromer C-80, model MP100, Campbell Scientific Instrument, Logan, UT, USA, SF: 1 s); *wind speed* (Switching Anemometer, model A100R, Vector Instruments Ltd., UK, SF: 1 s); *wind direction* (Potentiometer Windvane, model W200P, Vector Instruments Ltd., UK, SF: 1 s); *shortwave radiation* (Pyranometer, model CM14, Kipp & Zonen Delft, Holland, SF: 10 s); *longwave radiation* (Pyrgeometer, model CG2, Kipp & Zonen Delft, Holland, SF: 10 s); *rainfall* (Rain gauge, model ARG100, Campbell Scientific Instrument, Logan, UT, USA, SF: 1 s). All data were stored in two dataloggers (model CR10X, Campbell Scientific Instrument, Logan, UT, USA). ET_o values were calculated with the daily time step FAO56 Penman–Monteith (FAO56 P-M) equation (Allen et al. 1998) using the recorded meteorological variables. Previous grass lysimeter studies at the same location showed good performance for this equation (López-Urrea et al. 2006). The daily ET_o and ET_c values were used to calculate K_c for the sunflower in the lysimeter.

The basal crop coefficient was estimated with the standard FAO56 dual crop coefficient approach (Allen et al. 1998). The basal crop coefficient (K_{cb}) was calculated from the lysimeter K_c values minus the estimated evaporation component K_e values calculated with the FAO56 methodology. The values of the main parameters used to compute K_e were as follows: total evaporable water (TEW), 25 mm; readily evaporable water (REW), 10 mm; fraction of soil surface wetted (f_w) by sprinkler irrigation (1.0) and by precipitation (1.0). Additionally, $K_{c\ max}$, evaporation reduction coefficient (K_r) and exposed and wetted soil fraction (f_{ew}) were calculated using the equations proposed by Allen et al. (1998).

The percent of ground surface covered by vegetation (f_c) was determined based on the classic methodology for calculating green plant cover developed by Cihlar et al. (1987) using a supervised classification technique of digital photographic images with the maximum probability algorithm, in order to assign the current classes of green vegetation in the image. Digital photographs over the lysimeter area were taken weekly at solar noon vertically from an approximate height of 4.0 m above ground. Supervised classification of these digital images was later carried out with the help of the ENVI® version 4.8 computer program (Exelis Visual Information Solutions 2012). To apply this methodology, it is necessary to interpret each pixel of the visible panchromatic digital image and to decide which areas of the image make up the best training areas of green vegetation (with and without shade), and which are the areas of dry vegetation and those of bare soil (Calera et al. 2001; Montoro 2008).

Cumulative growing degree-days (GDD) for sunflower were calculated as described in North Dakota Agricultural Weather Network (2012):

$$\mathrm{GDD} = \sum_{i=1}^{n} \left[\frac{T_{\mathrm{D_{max}}} + T_{\mathrm{D_{min}}}}{2} \right] - T_{\mathrm{base}} \quad (1)$$

where $T_{\mathrm{D_{max}}}$ is the daily maximum temperature (°C), $T_{\mathrm{D_{min}}}$ is the daily minimum temperature (°C) and T_{base} is the base temperature for sunflower (6.7 °C). For sunflower, there is a T_{min} constraint: if the daily T_{max} and/or $T_{\mathrm{min}} < 6.7$ °C, T_{min} set equal to 6.7 °C.

García-Vila and Fereres (2012) used a T_{base} of 4 °C for sunflower, whereas Connor and Sadras (1992) reported that the maximum germination percentage is maintained between 6 and 23 °C.

Difference between two regressions was tested with the help of the IBM SPSS Statistics version 19 computer software (IBM SPSS Statistics 2012).

Results

Meteorological conditions

Table 1 summarizes the meteorological conditions for each month of the two growing seasons. The two growing seasons at "Las Tiesas" farm (Albacete) were typical of the long-term average weather of Central Spain, although the rainfall during 2009 and 2011 growing seasons, 29 and 22 mm, respectively, was about 50 % lower than the historical mean. Most rainfall during the growing season in the region occurs during the spring and in September. Average wind speed at 2 m elevation during the two growing seasons was 2.6 m s^{-1}.

Crop development, evapotranspiration values and applied irrigation water

The maximum canopy cover in this study was reached about 40 days after planting, same number of days described by García-Vila and Fereres (2012) of between 40

Table 1 Summary of monthly meteorological variables during the sunflower growing seasons

Season: Month	T_{mean} (°C)	Wind speed (m s^{-1})	Net radiation (MJ m^{-2} day^{-1})	Rainfall (mm)	RH_{min} (%)
2009					
April	10.6	3.5	8.8	27.1	35.3
May	16.8	2.5	11.6	21.7	30.0
June	21.7	2.5	13.7	6.5	24.4
July	24.5	2.6	14.4	0.0	19.0
August	23.7	2.4	11.8	0.2	25.6
September	18.1	2.3	7.7	26.0	40.7
2011					
June	20.6	2.5	14.5	12.6	30.1
July	23.0	2.8	17.1	0.0	26.0
August	23.8	2.7	13.9	4.9	26.4
September	19.8	2.2	10.0	17.6	32.2

[a] Monthly totals

Table 2 Description of sunflower growth stages during 2009 and 2011 growing seasons (Schneiter and Miller 1981)

Stage	Description	Season 2009 Date	 2011 Date
Sowing		21 April	15 June
V-2	Two true leaves at least 4 cm in length.	19 May	27 June
R-1	The terminal bud forms a miniature floral head rather than a cluster of leaves.	17 June	20 July
R-6	Flowering is complete, and the ray flowers are wilting.	17 July	24 August
R-9	The bracts become yellow and brown. This stage is regarded as physiological maturity.	7 September	25 September
Harvest		7 September	27 September

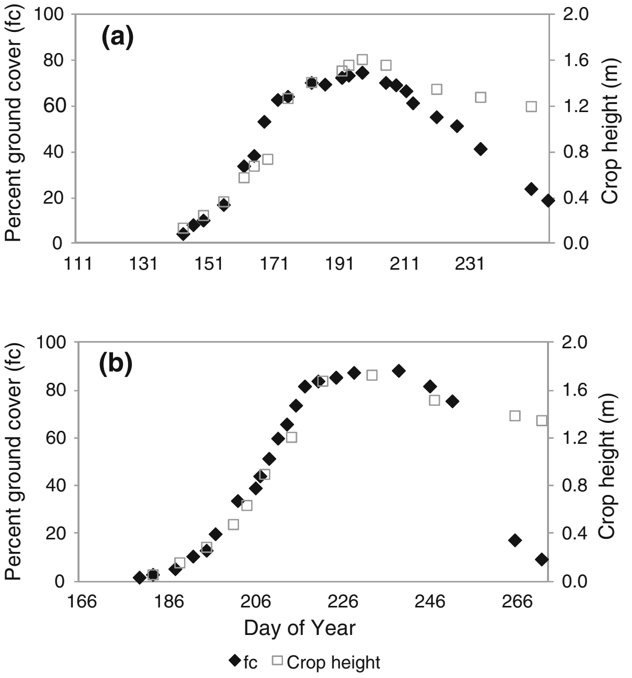

Fig. 2 Sunflower ground cover and plant height during 2009 (**a**) and 2011 (**b**) growing seasons, at "Las Tiesas" farm (Central Spain)

and 50 days after planting, under near-optimal temperatures. Table 2 shows crop growth stages during the two seasons. Figure 2 shows sunflower growth in terms of crop height and percent of ground cover during the experimental periods. In 2009, sunflower crop height reached 1.6 m and the maximum ground cover (75 %) in mid-July. In 2011, maximum ground cover (88 %) and crop height (1.7 m) were reached in mid-August, one month later than in 2009 due to the later planting, but both years during the reproductive stage. Early planting in 2009 produced a slower crop development than in 2011. The maximum f_c in 2011 was higher than in 2009 due to the higher plant population.

Grain yields were 3,300 and 3,000 kg ha^{-1}, in 2009 and 2011, respectively. These yields were higher than the average yields under irrigated conditions in the Albacete province of La Mancha (around 2,500 kg ha^{-1}). The yield and the water applied to the whole area outside the lysimeter were very similar to the lysimeter values. The water use efficiency for seed yield (seed yield/ET_c) was 0.53 kg m^{-3} in 2009 and 0.52 kg m^{-3} in 2011.

Reference evapotranspiration (ET_o) from sowing to harvest was 821 mm in 2009 and 646 mm in 2011 (Table 3; Fig. 3). This difference was caused primarily by the 2009 sunflower growing season being 35 days longer than that of 2011. In 2009, maximum ET_o occurred in the

Table 3 Irrigation, rainfall, reference evapotranspiration (ET_o), sunflower water use (ET_c) and crop coefficients (K_c) during 2009 and 2011 growing seasons

Season:	Dates	Irrigation depth (mm)	Rainfall (mm)	ET_o (mm)		ET_c (mm)		K_c
Crop growth stages				Daily	Period	Daily	Period	
2009								
Initial	21 April to 4 June	57	22.0	4.8	216	1.8	80	0.38
Crop development	5 June to 23 June	79	7.0	5.4	103	4.7	89	0.86
Mid-season	24 June to 24 July	193	0.0	7.2	223	8.2	253	1.13
Late season	25 July to 7 September	227	0.2	6.2	279	4.4	197	0.71
Full crop season		556	29.2		821		619	
2011								
Initial	15 June to 8 July	104	0.0	6.9	166	3.6	87	0.50
Crop development	9 July to 7 August	192	0.0	6.7	201	6.6	198	0.99
Mid-season	8 August to 2 September	226	10.0	6.2	162	7.7	199	1.23
Late season	3 September to 27 September	67	12.0	4.7	117	3.7	92	0.79
Full crop season		589	22.0		646		576	

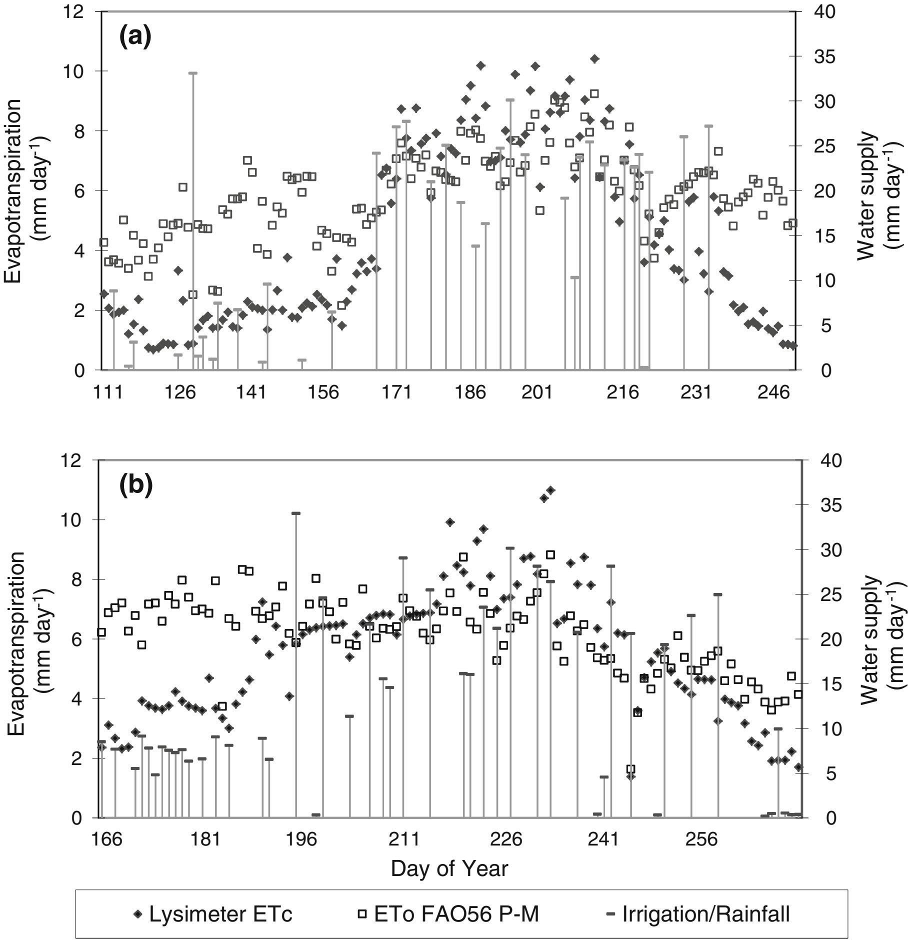

Fig. 3 Daily reference evapotranspiration (ET_o) and daily water use (ET_c) values measured in the sunflower lysimeter during 2009 (**a**) and 2011 (**b**) growing seasons. Irrigation and rainfall are depicted with *vertical bars*

mid-season sunflower growth stage, whereas in 2011, maximum ET_o occurred during the crop development stage.

Figure 3 presents the daily sunflower water use (ET_c) data and the water input from irrigation and rainfall for the 2 years of study. ET_c rose rapidly during the development stage due

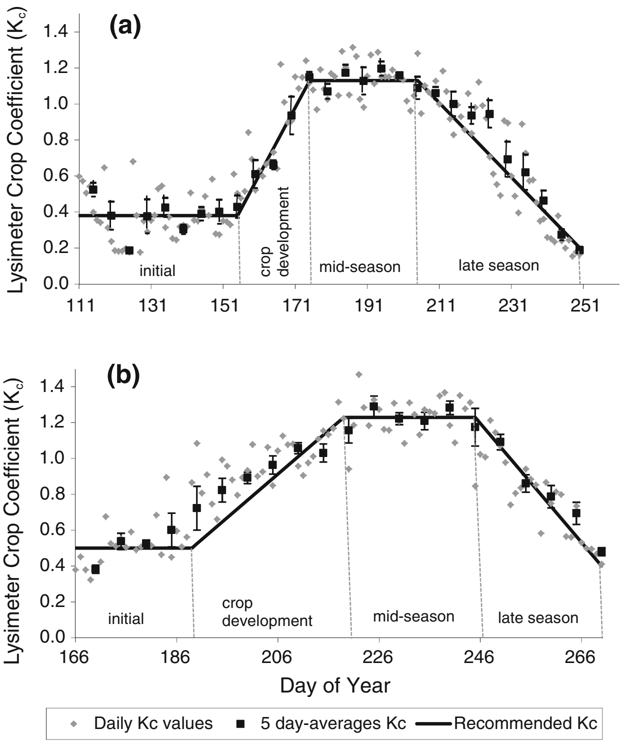

Fig. 4 Daily single crop coefficient (K_c) data for sunflower calculated from the ratio of lysimeter ET_c and P-M ET_o. *Diamonds* show daily K_c values, and *squares* indicate 5-day averages calculated during 2009 (**a**) and 2011 (**b**) growing seasons. *Bars* indicate the standard error in the 5-day averages. Also shown are FAO four stage K_c relationships

to the fast canopy growth facilitated by the favorable spring and summer temperatures, and increasing evaporative demand. Peak ET_c was reached around mid-season coinciding with the maximum ground cover values and declined during the maturation period as green ground cover and ET_o declined. Seasonal lysimeter ET_c was 619 and 576 mm in 2009 and 2011, respectively. The 7 % higher ET_c value in 2009 was due to the 35 day longer growing season and the maximum cover coinciding with the maximum ET_o period (early planting) and overshadowed the effect of the higher plant population and ground cover in 2011.

Irrigation management in the lysimeter field followed the standard practice in the area for attaining maximum yields. Sprinkler applications were applied every 3–10 days in 2009 and every 2–5 days in 2011, depending on the ET rate. The lysimeter field received 27 irrigations throughout the 2009 season and 35 irrigation applications in 2011 that varied in depth between 8, in the early initial stage, and 28 mm, both experimental years (Fig. 3; Table 3). The total amount of applied irrigation water was 556 mm in 2009 and 589 mm in 2011 resulting in a total irrigation plus precipitation application of 585 mm in 2009 and 611 mm in 2011. No drainage from the lysimeter tank was recorded during the study period.

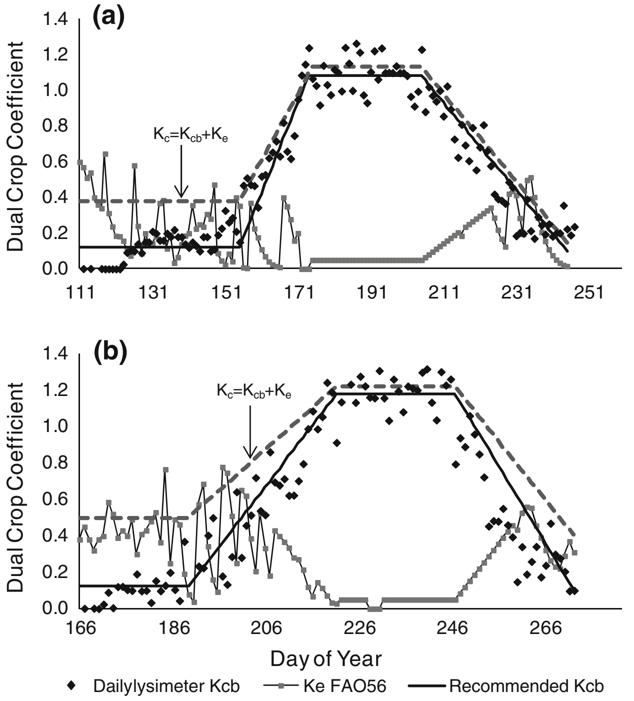

Fig. 5 Dual crop coefficient, K_{cb}, for irrigated sunflower during 2009 (**a**) and 2011 (**b**) growing seasons. K_e was calculated with the standard FAO56 approach, and K_{cb} was calculated from lysimeter K_c values minus calculated K_e values. Also shown are FAO four stage K_{cb} relationships

Single and dual crop coefficient curves

Figure 4 presents the K_c data during the 2 years of study, calculated as the ratio of the lysimeter measured ET_c and ET_o calculated by FAO56 P-M from the weather station. The average K_c data for each stage are shown in Table 3. The K_c values were lower in 2009 than in 2011 due to the sparser canopy in 2009. Maximum ground cover was 75 and 88 % in 2009 and 2011, respectively. The maximum average K_c values of 1.10 in 2009 and 1.20 in 2011 were reached during the mid-season stage.

In the two study years, four distinct stages were identified in the seasonal changes in K_c. In the first stage (Initial), the K_c values were more or less constant and relatively low. In the second stage (crop development), the daily K_c values increased and maximum values were reached as the plants reached maximum cover, which coincided with the initial reproductive growth stage (R1). In the third stage (mid-season), the K_c values were high and more or less constant, and in the fourth stage (late season), there was a continuous decline in daily sunflower K_c.

The soil evaporation component of ET_c can be high after a rainfall or sprinkler irrigation, particularly in the beginning of the growing season when the ground surface covered by vegetation is small. To assess the importance of the soil evaporation component, the dual crop coefficient approach

Table 4 Evaporation (E), transpiration (T) and dual crop coefficient for irrigated sunflower during 2009 and 2011 growing seasons

Season	Dates	E (mm)		T (mm)		K_e	K_{cb}
Crop growth stages		Daily	Period	Daily	Period		
2009							
Initial	21 April to 4 June	1.2	52	0.6	26	0.26	0.12
Crop development	5 June to 23 June	0.7	13	3.7	70	0.13	0.63
Mid-season	24 June to 24 July	0.4	11	7.8	241	0.05	1.08
Late season	25 July to 7 September	1.2	54	3.9	175	0.20	0.60
Full crop season			130		512		
2011							
Initial	15 June to 8 July	2.8	67	0.8	20	0.38	0.12
Crop development	9 July to 7 August	2.2	67	4.3	130	0.33	0.65
Mid-season	8 August to 2 September	0.3	7	7.4	191	0.05	1.18
Late season	3 September to 27 September	1.6	39	3.0	74	0.33	0.62
Full crop season			180		415		

was used to separate crop transpiration, estimated by the basal crop coefficient, K_{cb}, from soil evaporation (evaporation coefficient, K_e). Results shown in Fig. 5 and in Table 4 show that the highest K_e values occurred during initial stage when the ground cover was small and following rainfall or irrigation when the soil surface was wet. During the late season period, the K_e values increased due to the declining values of f_c in that period (crop senescence). As the crop canopy expanded, K_{cb} values increased while the K_e values decreased. The seasonal evaporation component with the relatively frequent sprinkler irrigation applications amounted to 130 mm in 2009 and 180 mm in 2011, or about 25 % of ET_c. The estimation of crop transpiration was obtained by multiplying the ET_o times the K_{cb}, yielding transpiration values of 512 mm in 2009 and 415 mm in 2011.

Relationships between the basal crop coefficient, K_{cb} and ground cover

To facilitate extrapolation of the results to other areas, the K_{cb} values obtained from lysimeter measurements and evaporation estimates were compared to the evolution of the ground cover, which tracks the crop growth and development. As shown in Fig. 6, K_{cb} was a linear function of ground cover with a high coefficient of determination (R^2) for studied years. These data show some difference between the relationship in 2009 and in 2011. In 2011 (late planting), the ground cover increased rapidly during the initial stage, due to warmer temperatures than in 2009 (early planting) at this period, whereas in 2009 when the crop reached around 50 % f_c, the canopy grew faster than in 2011 due to warm temperatures from mid-June to mid-July. The slopes and the interceptions of two regressions lines are statistically different ($P < 0.05$).

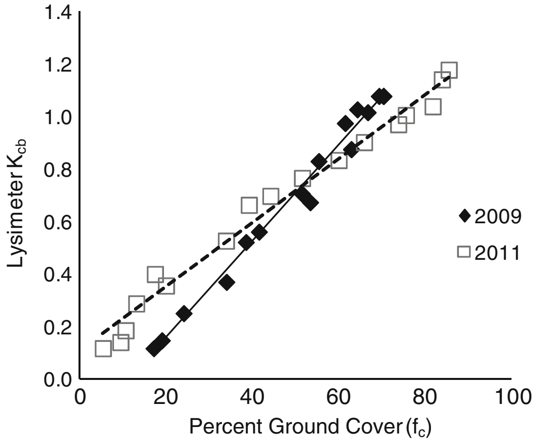

Fig. 6 The relationship between basal crop coefficient obtained from lysimeter measurements and the percent of ground covered by vegetation in the lysimeter. The *solid line* represents a linear regression using data points from 2009 ($y = 0.018x - 0.205$; $R^2 = 0.99$). The *dashed line* represents a linear regression using data points from 2011 ($y = 0.012x + 0.107$; $R^2 = 0.98$)

To account for the climatic differences among years, the ground cover and the K_{cb} were plotted as a function of GDD. Figure 7 presents the results where the data of the two lines of Fig. 6 coalesce into one relationship for f_c (Fig. 7a), and the same occurs for the K_{cb}–GDD relationship (Fig. 7b). Only the period when f_c and K_{cb} were increasing was considered in Fig. 7. For 2009, K_{cb} reached maximum values (1.08) after approximately 825 GDD, whereas in 2011, maximum K_{cb} values (1.18) were reached after 945 GDD.

Additionally, in order to generalize the lysimeter K_{cb} equation for different environmental conditions, a multiple linear regression analysis was conducted for the period when f_c and K_{cb} were increasing. The lysimeter K_{cb} was

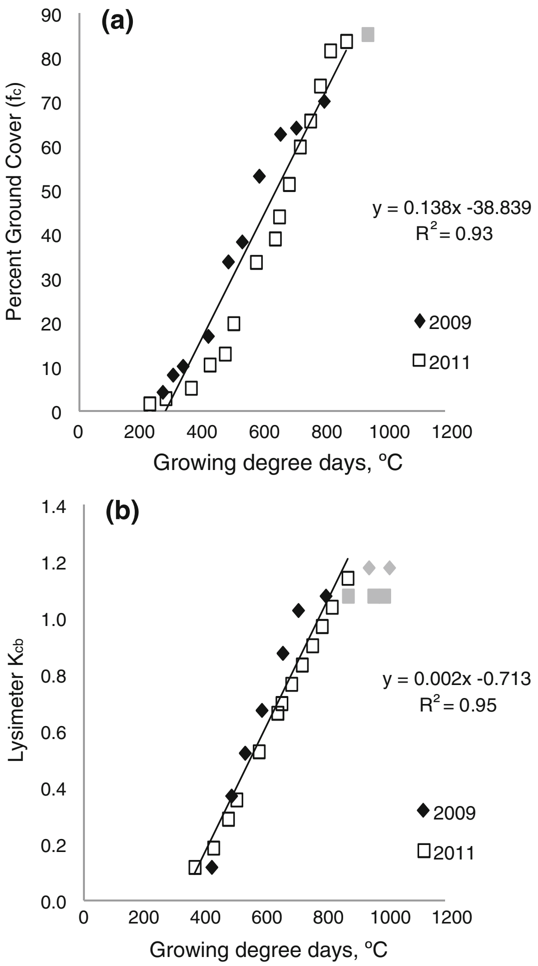

Fig. 7 Relationships for the two experimental years between (**a**) ground cover as a function of degree-days and (**b**) K_{cb} as a function of GDD. The *gray* data were not used to generate the equations

taken as the dependent variable, and GDD and f_c as independent variables. The model obtained was $K_{cb} = -0.3559 + 0.00114 * \text{GDD} + 0.00626 * f_c$. This equation presents a high coefficient of determination ($R^2 = 0.97$).

Discussion

Sunflower evapotranspiration

Sunflower water use has been measured or estimated in previous works. There are differences in seasonal ET_c among reports due to different weather conditions, different growing season duration and the diversity of sunflower production systems worldwide. In an experiment carried out in Cordoba (Spain), Soriano et al. (2004) used the soil water balance method to estimate sunflower water use between 527 and 572 mm for early planting, and between 417 and 499 mm for late planting, under rainfed conditions. The lower water use compared to this study was likely due to intermittent water stress. In research conducted in other regions, Stone et al. (1996) reported a seasonal ET for fully irrigated sunflower in the state of Kansas, USA, of 576 mm averaged for nine growing seasons. This value of sunflower water use is equal to our sunflower ET (late planting). The authors used the soil water balance method to estimate sunflower water use. Tyagi et al. (2000) measured the sunflower ET in two growing seasons at Karnal, India, using two electronic weighing lysimeters. Water use for sunflower ranged between 636 and 664 mm. The higher ET compared to this study was possibly due to the higher evaporative demand conditions at Karnal. Their growing season duration was 102 days similar to the 104 day season (late planting) at Albacete. They had a peak value of sunflower ET of 14.1 mm day^{-1}, while this study had maximum daily ET rates between 10 and 10.9 mm day^{-1}. Demir et al. (2006) determined the response of sunflower to 14 different irrigation schedules in sub-humid climatic conditions (Bursa, Turkey). The average sunflower ET was 652 mm for fully irrigation treatments in two study years. Our sunflower ET (early planting) is similar to this study. In research carried out in the central Bekaa Valley of Lebanon, Karam et al. (2007) determined the water requirement for sunflower using a drainage lysimeter as between 765 and 882 mm. Their substantially higher sunflower water use was likely due to use of both a longer maturity variety and higher evaporative demand. In a recent study conducted at Bushland (TX, USA), Tolk and Howell (2012) measured the sunflower water requirements in a semi-arid environment using small lysimeters with several soil textures. They reported water requirements for sunflower ranging from 581 to 698 mm for fully irrigated treatments. In earlier research at the same location, Howell et al. (2012) reported water requirements for sunflower measured in two weighing lysimeters (two growing seasons) ranging from 600 to 644 mm (averaged 630 mm) under sprinkler irrigation. Their growing season duration was 100 days, similar to the 104 days season (late planting) and shorter than the 139 days season (early planting) at Albacete. They had maximum daily ET rates between 12 and 14 mm day^{-1} while this study had a peak value of ET_c of 10.9 mm day^{-1}. The higher maximum ET_c values in Bushland were mainly due to a higher evaporative demand at this location.

Single and dual crop coefficients

In previous works, Allen et al. (1998, 2007) reported sunflower K_c values of K_{cini}: 0.35; K_{cmid}: 1.15; K_{cend}: 0.35 in Mediterranean regions and California, with planting in

April/May. The K_{cmid} basically matched our measurements, whereas that small differences in the K_{cini} and K_{cend} can be due to the higher values of evaporation during these two growth stages in our measurements. These authors reported sunflower K_{cb} values of K_{cbini}: 0.15; K_{cbmid}: 1.10; K_{cbend}: 0.25 under similar environmental conditions. The K_{cbini} and K_{cbmid} are similar to our estimations, but in our work, the K_{cbend} declined more rapidly during the senescence stage. Tyagi et al. (2000) estimated values of K_c for sunflower at the four growth stages (initial, crop development, reproductive and maturity) instead of the three growth stages model curve proposed in FAO-56. The K_c values were 0.52, 1.1, 1.32 and 0.42 based on calculated ET_o with a Penman–Monteith equation reported by Jensen et al. (1990). Our measured mean K_c data (Table 3) are lower than these K_c values. Also, the estimated K_c values of sunflower reported by these authors are higher than the values suggested by FAO-56. These higher K_c values could be due to underestimation of reference ET calculations. In a recent study, Howell et al. (2012) reported mean sunflower K_c of 0.55 during initial stage; 0.85 during crop development; 1.29 at flowering stage; and 0.80 at senescence stage. These measured mean K_c data are similar to our averaged K_c in the different growth stages, shown in Table 3. Furthermore, these authors reported sunflower K_{cb} values of K_{cbini}: 0.15; K_{cbmid}: 1.22; K_{cbend}: 0.15 under semi-arid weather conditions. Our sunflower K_{cb} values are similar to Howell et al. (2012).

Relationships between K_{cb} and ground cover

In a previous work at our location, Montoro (2008) reported a linear relationship between basal crop coefficient and the percent of ground cover for five summer crops (poppy, corn, sugar beet, potato and onion) as follows: $K_{cb} = 0.010 * f_c + 0.208$; $R^2 = 0.99$. The slope and the intercept are different than those obtained in our study. Allen and Pereira (2009) reported a methodology for estimating basal crop coefficients as a function of fraction of ground cover and crop height. Earlier, other authors have shown a good relationship between crop coefficients and ground cover for tree and vegetable crops (Fereres et al. 1981; Grattan et al. 1998; Hanson and May 2006; López-Urrea et al. 2009, Bryla et al. 2010). However, the relationship between the sunflower K_{cb} and the percent of ground cover has not been studied before. In our study, the lysimeter K_{cb} was a linear function of ground cover, although there seems to be some difference between this relationship in 2009 and that fitting 2011 data. In a previous work conducted at our location, López-Urrea et al. (2012) reported the same difference for the relationships between grapevine K_{cb} and canopy cover during three experimental years. In both studies, to account for the climatic difference among years, the percent of ground cover and the K_{cb} was plotted as a function of GDD, resulting in one relationship for ground cover and hence removing the small difference between growing seasons.

Conclusions

A weighing lysimeter was used to determine consumptive water use and crop coefficients of irrigated sunflower in the semi-arid Mediterranean weather conditions in Central Spain. The results show the need to adjust the K_c growth stage durations proposed by FAO-56 (Allen et al. 1998) to local weather conditions and growing practices. These results show that measuring ground cover is a reliable and likely more transferrable approach to estimate K_{cb} values in sunflower. The use of GDD may improve the estimate by removing year-to-year variations in crop development. The robustness of the relationship of Fig. 7b, which was obtained in 2 years differing in climatic conditions and in maximum ground cover, suggests that it can be used to estimate the seasonal evolution of sunflower consumptive use as a function of GDD in different environments. Therefore, these results will facilitate precisely scheduled water applications and improvement of water productivity in sunflower, which is of vital importance in areas of limited water resources.

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