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Evapotranspiration and crop coefficients of rice (*Oryza sativa* L.) under sprinkler irrigation in a semiarid climate determined by the surface renewal method

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Abstract

The evapotranspiration (ET_c) of sprinkler irrigated rice was determined for the semiarid conditions of NE Spain during 2001, 2002 and 2003. The surface renewal method, after calibration against the eddy covariance method, was used to obtain values of sensible heat flux (H) from high-frequency temperature readings. Latent heat flux values were obtained by solving the energy balance equation. Finally, lysimeter measurements were used to validate the evapotranspiration values obtained with the surface renewal method. Seasonal rice evapotranspiration was about 750-800 mm. Average daily ET_c for mid-season (from 90 to 130 days after sowing) was 5.1, 4.5 and 6.1 mm day^{-1} for 2001, 2002 and 2003 respectively. The experimental weekly crop coefficients fluctuated in the range of 0.83 to 1.20 for 2001, 0.81 to 1.03 for 2002 and 0.84 to 1.15 for 2003. The total growing season was about 150 to 160 days. In average, the crop coefficients for the initial (K_{cini}), mid-season (K_{cmid}) and late-

season stages (K_{cend}) were 0.92, 1.06, and 1.03, respectively, the length of these stages being about 55, 45 and 25 days, respectively.

Introduction

Rice (*Oryza sativa* L.) is an important crop covering an area of approximately 158 million ha in the world. In Europe, there are 668,370 ha of rice of which 119,300 ha are located in Spain (FAO, 2009), mostly in the Ebro River (north-east Spain) and the Guadalquivir River (southern Spain) basins (MARM, 2009).

Worldwide rice paddies are traditionally irrigated using a continuously flooded irrigation system (anaerobic rice). Rice may be also grown in non-flooded soils like wheat and maize (aerobic rice) (Xue et al., 2008; Alberto et al., 2009). Traditionally the rice crop in Aragón (middle Ebro River basin) is cultivated on saline-sodium soils which favour the blockage of the pores and minimize deep percolation. Growing crops other than rice is practically impossible on these soils due to the anaerobic conditions. There has recently been some expansion of rice production to other more permeable soils where rice becomes one of the rotations used by farmers. At the same time, irrigation districts in this region have been modernized to pressurized irrigation systems. This has stimulated interest in determining the response of rice to sprinkler irrigation on more typical, permeable soils.

Increasing demand for water by the different users, e.g. agriculture, urban, industrial, has caused irrigators to demand more accurate information on the crop water requirements (ET_c) to enable more precise determination of irrigation requirements. This is more critical in semiarid areas where the availability of water may not always cover all water needs and the farmers require precise information on ET_c so that they can decide which crops they can afford to grow. ET_c depends upon environmental conditions, characteristics of the crop and cultural practices including irrigation management which is very important for rice crops. ET_c for flooded rice is not very different from that of crops like cotton, sorghum or sugar cane (Allen et al., 1998). ET_c is often calculated by multiplying a crop coefficient (K_c) by the reference evapotranspiration: $ET_c = K_c \times ET_o$ where the reference surface is well irrigated grass, 12-cm tall, completely shading the ground, and disease and weed free (Allen et al., 1998). The K_c depends upon local climate, crop canopy height, percent ground cover, stage of the crop growth and crop and irrigation management.

Previous work has quantified the ET_c for flooded rice resulting in different values as a function of the climatic conditions and the management practices of the study area. Thus seasonal flooded rice ET_c has been reported as 400 to 500 mm (wet season) and 600 to 700 mm (dry season) for the Philippines (Tabbal et al., 2002), 590 mm in the semiarid conditions of India (Tyagi et al., 2000), 540 to 730 mm in the Punjab (India) (Chahal et al., 2007), and 850 mm in southern Spain (Aguilar and Borja, 2005). Mean daily ET_c rates have been reported to be approximately 4.0 to 5.0 mm day^{-1} (wet season) and 6.0 to 7.0 mm day^{-1} (dry season) in tropical areas (De Datta, 1981), and approximately 3.6 to 4.0 mm day^{-1} for aerobic rice fields in the Philippines (Alberto et al., 2011). Fewer publications are available related to sprinkler irrigated rice. Spanu et al. (2009) reported seasonal values of 700 to 800 mm (sowing to maturity) for Mediterranean conditions in Italy and mean daily rates of 6.0 mm day^{-1} during the mid-season stage.

Several publications have reported crop coefficients (K_c) for rice. Allen et al. (1998) suggested the following values for permanently flooded rice: 1.05, 1.20 and 0.9 to 0.6, during the initial, mid-season, and late-season stages, respectively. Doorenbos and Pruitt (1977) suggested a 15 to 20 % lower K_c for the initial crop stage for upland rice conditions. Tyagi et al. (2000) reported mean K_c values of 1.15, 1.23, 1.14 and 1.02 for the initial, crop development, reproductive and maturity stages, respectively, for the semiarid conditions of Karnal (India) and total season length of about 150 days. Seung Hwan et al. (2006) reported K_c values between 0.78 and 1.58 during the mid-season stage for transplanted paddy rice in nine regions of Korea with total growing season lengths of 100 to 110 days after transplanting. An average K_c value equal to 0.95 during the growing season for rain-fed paddy rice fields was reported for the tropical climate of Thailand (Attarod et al., 2006). Lower K_c values have been reported for aerobic rice, 0.95, 1.0, and 0.97 for the vegetative, reproductive and the ripening stages, respectively (Alberto et al., 2011). Little information is available for the K_c of rice under sprinkler irrigation. Spanu et al. (2009) reported values between 0.90 and 1.07 for a total growing season of about 140 days (sowing to maturity) and Mediterranean conditions in Sardinia (Italy).

The aim of the current work was to quantify the evapotranspiration of sprinkler irrigated rice during the growing season under the semiarid conditions of middle Ebro River Valley using the surface renewal method (SR). In addition, the evolution of the corresponding crop coefficients during the growing season was quantified as was the variability between years.

Material and methods

2.1. Site and crop

The research was carried out at an experimental farm located in Montañana (Zaragoza, NE Spain) during the 2001, 2002, and 2003 growing seasons. The geographical coordinates are: latitude, 41º 43’ N; longitude, 0º 49’ W; elevation, 225 m. Long-term mean annual values for precipitation, air temperature and wind speed (2 m above ground) are 330 mm, 15 °C and 2.4 m s^{-1}, respectively. Wind direction is variable but the most frequent wind direction is northwest (Martínez-Cob et al., 2008). Measurements were performed over two plots: plot A during 2001 and 2002, and plot B during 2003 (Figure 1). Both plots were separated by about 1.3 km and located in the center of an irrigated area of 8,000 ha where the main crops are corn (*Zea mays* L.), alfalfa (*Medicago sativa* L.), and wheat (*Triticum spp.*) (Cavero et al., 2009). The minimum distance of the experimental plots to the border of the irrigated area was 2.5 km. The soil was sandy loam (plot A) and clay loam (plot B), classified as Typic Xerofluvent (Cavero et al., 2009). Both plots were cultivated with rice (*Oryza sativa* cv. Guadiamar) sown on May 18 (2001), May 21 (2002) and April 28 (2003) with 230 kg of seed per hectare. Harvest occurred on October 29 (2001), October 30 (2002) and September 29 (2003).

Irrigation was applied using a solid-set sprinkler irrigation system, with 15 m x 15 m spacing in plot A, and 18 m x 15 m spacing in plot B (Fig. 1). Weekly irrigation water requirements were estimated following the guidelines of Allen et al. (1998) using the daily meteorological data recorded in a grass plot adjacent to the rice plot A (Fig. 1). The study area is located in the central sector of the Ebro Tertiary Basin, characterized by Oligo-Miocene sediments deposited in evaporite and carbonate shallow lakes in a continental environment, disconnected from the sea (Gutiérrez Elorza and Gutiérrez Santolalla, 1998). The bedrock mainly consists of sub-horizontal evaporites of the Oligo-Miocene Zaragoza Gypsum Formation with laminated and nodular gypsum alternating with marls and lutites. As a consequence, both soils and surface water (the main source of irrigation water in the area) of the middle Ebro River Basin may have the potential to contribute to salinity problems. Thus it is necessary to "over irrigate" by the addition of a leaching fraction to avoid soil salinity build-up in both commercial and experimental plots within the region. A leaching fraction of approximately 15 %, particularly during the early stages of crop growth, was applied in this study. Irrigation was applied every 2-3 days on average although this frequency changed during the growing season depending on current meteorological conditions. Due to the texture, structure and infiltration characteristics of the experimental plot, the average irrigation depth was approximately 14 to 16 mm per irrigation to minimize the risk of water ponding. The rice crop was well-watered and without water stress during the growing season.

2.2. Micrometeorological measurements

A micrometeorological station was installed at each plot (Fig. 1) to estimate the latent heat flux (LE) as the residual of the surface energy balance:

$$LE = R_n - G - H \tag{1}$$

where: R_n is the net radiation, G is the soil heat flux, and H is the sensible heat flux, all in W m^{-2}.

A net radiometer (Radiation and Energy Balance Systems, model Q-7) was placed at 1.5 m above the soil surface. Two soil heat flux plates (Hukseflux, model HFP01) at 0.08 m, and one averaging soil temperature probe (Campbell Scientific, model TCAV) at 0.03 and 0.06 m from the soil surface recorded soil heat flux (Allen et al., 1996). Both net radiation and soil heat flux values were recorded every 10-s and averaged every 30-min using a datalogger (Campbell Scientific, model CR10X).

Sensible heat flux (H) was estimated every 30-min using the surface renewal (SR) method. This method is based on the presence of ramp-like structures in the high-frequency readings of air temperature (Paw U et al., 1995, 2005). These readings were recorded every 0.75-s using chromel-constantan thermocouples of 72 μm diameter (Campbell Scientific, model TCBR-3) placed at different heights that were moved to correspond to crop growth (Table 1). The time lag of 0.75-s was proposed for wheat in the same region by Zapata and Martínez-Cob (2002) and chosen because of the similar crop architecture of rice and wheat. This time lag value is within the ranges used for crops with canopy structure and height similar to rice (Mengistu and Savage, 2010; Paw U et al., 2005). These high-frequency readings of temperature were monitored by the abovementioned CR10X datalogger, and analyzed as described elsewhere (Paw U et al., 2005; Moratiel and Martínez-Cob, 2011) to determine 30-min values of the corresponding parameters [A, amplitude (ºC), and τ, inverse frequency (s)] that characterize the ramp-like structures of the high-frequency air temperature. Thus, half-hour values of the surface renewal H (H_{SR}, W m^{-2}) were estimated at each measurement height as follows (Paw U et al., 2005):

$$H_{SR} = \alpha H_{NC} = \alpha\left(\rho c_p \frac{A}{\tau} z\right) \qquad (2)$$

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where: α is a weighting (or calibration) factor, ρ is the density of air (kg m^{-3}), z is the measurement height, c_p is the specific heat capacity of air at constant pressure (J kg^{-1} °C^{-1}), and H_{NC} is the non-calibrated surface renewal H.

Among other factors, the value of α depends on crop roughness, the measurement height, sensor size and atmospheric stability conditions. Uneven heating within the canopy leads to different α values (Paw U et al., 1995, 2005; Snyder et al., 1996; Spano et al., 1997). Normally appropriate values of α are obtained by comparing H_{NC} values (i.e. those estimated using Eq. 2 with α=1.0) against H values obtained with a sonic anemometer using the eddy covariance approach (Snyder et al., 1996; Spano et al., 1997). Thus, an eddy covariance system for sensible heat consisting of a 3-D sonic anemometer (Campbell Scientific, model CSAT3) and a second datalogger (Campbell Scientific, model CR23X) was installed during part of the growing seasons of 2002 (July 23 to September 24) and 2003 (May 1 to May 27 and September 12 to September 21). Measurement height was that listed in Table 1 as Z2. The eddy covariance system was monitored at 10 Hz and the corresponding sonic temperature and wind speed values were used to determine 30-min averages of the eddy covariance sensible heat flux (H_{EC}, W m^{-2}):

$$H_{EC} = \rho C_p \overline{w' T_s'} \tag{3}$$

where: $\overline{w' T_s'}$ is the covariance between the fluctuations of vertical wind speed (w', ms^{-1}) and those of the sonic temperature (T_s', ºC).

The predominant wind direction in the area is northwest. The fraction F of fluxes sensed at the different measurement heights (Table 1), and generated from a specific distance of upwind fetch, was estimated as described by Allen et al. (1996) taking into account the dimensions of the experimental plots (Fig. 1):

$$F = \exp\left\{ \frac{(z-d)\left[1-\ln\left(\frac{z-d}{z_{0m}}\right)\right]-z_{0m}}{k^2\, x_f \left(1-\frac{z_{0m}}{z-d}\right)} \right\} \tag{4}$$

where: z is the measurement height (m), d is the zero-plane displacement (m), z_{0m} is the momentum roughness length (m), x_f is the upwind fetch (m) in the predominant wind direction (about 85 m for plot A and 75 m for plot B), and k is the von Kármán constant (0.41). Following Allen et al. (1996), d and z_{0m} were computed as $d = 2/3\ h_c$, and $z_{0m} = 0.123\ h_c$, where h_c is the crop height (m).

A value of α was obtained for each measurement height by comparing the half-hour values of H_{NC} and H_{EC} for each of the periods for which H_{EC} was available. A simple linear regression was developed between measurement height z (independent variable) and α (dependent variable). This linear regression was used to estimate the appropriate α values for estimating H_{SR} using Eq. (2) for all the measurement heights during the growing season (sowing to harvest) for 2001, 2002 and 2003. Finally, the computed H_{SR} values for these different measurement heights were averaged to get one single sensible heat flux value for each half-hour. These H_{SR} values were used with Eq. (1) to get 30-min values of latent heat flux by the surface renewal method (LE_{SR}). These values were also averaged to get daily latent heat flux values that were transformed to evapotranspiration (ET_{SR}, mm day^{-1}) by dividing by the latent heat of vaporization, estimated as described by Ham (2005).

2.3. Lysimeter measurements

A weighing lysimeter, 1.7 m in depth with 6.3 m^2 effective surface area, was located in the center of plot A (Fig. 1). A load cell connected to a Campbell Scientific datalogger (CR500) recorded lysimeter mass losses every 30-min, which allowed computation of 30-min and daily evapotranspiration rates (ET_{lys}, mm day^{-1}) during 2001 and 2002 as described by Martínez-Cob (2001). The resolution of the lysimeter was 0.05 mm water depth. Identical management practices (sprinkler irrigation, fertilization and herbicide application) were performed simultaneously in both the lysimeter and the surrounding plot.

The weighing lysimeter produced precise evapotranspiration measurements. However, missing values of daily ET_{lys} were relatively frequent as days with irrigation, precipitation and other management practices must be discarded. Therefore it was decided to use the daily ET_{SR} values to get rice crop coefficient values as the number of missing ET_{SR} values was much lower than daily ET_{lys} values. The lysimeter measurements were used for an independent validation of the ET_{SR} estimates as the eddy covariance system only allowed calibration of the H_{SR} values. Thus the weekly averages and daily cumulative values of ET_{SR} and ET_{lys} were compared by linear regression and error analyses performed. The weekly time frame was used because sprinkler irrigation scheduling of a large number of crops is frequently made on a weekly basis. The error statistics computed were the root mean squared error (RMSE), the relative error (RE) and the index of agreement (IA) (Willmott, 1982).

Experimental daily values of the rice crop coefficient (K_{cexp}) were obtained from the ratio of the daily ET_{SR} to the daily estimated ET_o using Eq. (5). The reference ET was computed using the FAO Penman-Monteith method (Allen et al., 1998) from the daily meteorological variables (air temperature, relative

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humidity, solar radiation and wind speed) recorded over grass grown under reference conditions following Allen et al. (1998) in a plot next to the rice plot A (Fig. 1).

$$K_{C\,exp} = \frac{ET_{SR}}{ET_o} \qquad (5)$$

2.4. Additional measurements

The ground cover during the season was determined as GC = 1- (PAR_{ss}/PAR_{in}), where GC is the fraction of ground cover, PAR_{ss} is the average photosynthetically active radiation (PAR) recorded at 10 points near the soil surface along a line of 2.0 m length and parallel to the crop rows, and PAR_{in} is the PAR recorded above crop canopy (average of four readings, two before and two after the PAR_{ss} readings). Readings were taken several times during the season around solar noon using a SunScan Canopy Analysis System (Delta-T Devices, Cambridge, UK) (Potter et al., 1996). The crop height during the season was also obtained as the mean height of 4 locations of 5 plants each.

Results and discussion

There were slight differences in the meteorological conditions between years (Fig. 2). The recorded precipitation during the crop season was 105, 212 and 167 mm for 2001, 2002 and 2003, respectively. The year 2002 was more humid and cooler than 2001 and 2003. The cumulative precipitation from 1 July to 31 August during 2002 was 50 mm while it was about 9 mm for 2001 and 2003. Air temperatures were relatively similar for all years, although values recorded during 2002 were slightly lower especially during late summer and autumn. The mean vapour pressure deficit (VPD) was generally lower in 2002 and generally higher in 2003, particularly during late summer and autumn. The average wind speed was higher for 2002 during spring while it was relatively similar between the three years for the rest of the season (Fig. 2). The monthly and total irrigation water applied during the three experimental seasons was similar for 2001 (758 mm) and 2003 (790 mm), and slightly lower for 2002 (660 mm) (Table 2) due to the different meteorological conditions.

The rice crop reached a maximum height approximately 100 to 120 days after sowing (DAS) (Fig. 3). This maximum height was somewhat higher (0.6 to 0.7 m) in 2001 and 2003 compared to 2002 (about 0.45 m) due to the cooler meteorological conditions of 2002. Subsequently, the maximum ground cover fraction (approximately 90 %) was reached about 100 DAS, and the ground cover fraction during 2002 was slightly lower than during 2001 and 2003 (Fig. 3).

Table 3 indicates the fraction F of fluxes sensed at the different measurement heights that were generated from the upwind fetch available in the experimental plots. As expected, that fraction decreased with measurement height. Nevertheless the fraction F was relatively high, above 75 to 80 %, for most of the measurement periods and the three seasons. Thus it can be assumed that the micrometeorological station was recording fluxes generated to a large part from within the rice plot.

Fig. 4 shows the comparison of estimated H_{NC} versus measured H_{EC} half-hour values for the period 12 to 21 September 2003 and for the measurement height of Z1 = 1.0 m above the ground. There was a strong (R^2 = 0.847) linear relationship between the two sets of H values. The corresponding linear regression was forced through the origin so the slope was taken as an estimation of the α value corresponding to this particular measurement height and period. In general terms, a similar behaviour was observed for the remaining measurement heights and periods (July 23 to September 24, 2001, and May 1 to May 27, 2003). Table 4 lists all of the α values obtained for the different measurement heights and periods for which H_{NC} and H_{EC} were compared. The variable affecting the variability of α in this experiment was the measurement height as the time lag and sensor size were the same throughout the experiment. The value of α decreased with the measurement height (Fig. 5). This behaviour has also been reported in previous studies over short dense (Snyder et al., 1996; Spano et al 1997) and tall sparse canopies (Spano et al., 2000). Spano et al. (1997) reported a value of α=0.81 over a 0.7 m tall wheat with z=1.3 m (ratio z/h_c=1.86). Similar values for α, between 0.82 and 0.74, were obtained in this experiment for ratios of z/h_c between 1.5 and 2.0 for $z \geq 1$ m. Other authors like Snyder et al. (1996) reported α=1.00 for alta fescue grass with a z/h_c ratio of 1.29. The different time lags used in previous experiments explain the difference in resulting values of α.

Paw U et al. (1995, 2005) argued that the α values for given conditions of measurement height, sensor size and time lag are stable and do not change due to meteorological conditions unless there are considerable changes in vegetation canopy structure. Therefore the linear regression depicted in Fig. 5 was used to estimate the appropriate α values for the remaining periods during which H_{NC} values were available but H_{EC} values were not. The corresponding half-hour H_{SR} values were obtained using Eq. (2) during the different days of the three growing seasons.

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Fig. 4 shows a dense cluster of points around the origin. Thus most of the half-hour H_{SR} values obtained in this experiment, about 80 % of 19,127 values, were in the range of -50 to 50 W m^{-2}. H is often small in well irrigated systems as most part of the net radiation is converted into latent heat flux (LE) (Fig. 6). The monthly averages of the fraction of 30-min H to 30-min R_n during the different seasons were low (the maximum average H/R_n was 15.0 %), as expected for a well-watered crop transpiring at a maximum rate. H was even lower than G at the beginning of the growing season because of the low crop height. H increased compared to G as the season advanced and the ground cover fraction increased (Figs. 3 and 6). The behaviour of the energy balance observed for 2001 (Fig. 6) was quite similar for the other two seasons in 2002 and 2003. Thus, in general higher values of H were obtained once the ground was effectively covered by the crop.

Table 5 indicates the comparison between the weekly averages and the cumulative daily estimated (ET_{SR}) and measured (ET_{lys}) rice evapotranspiration during 2001 and 2002. The corresponding coefficients of determination were quite high for field experiments, above 0.78. The indices of agreement also showed a strong similarity between measured and estimated values. The RMSE statistics and corresponding relative errors were relatively low. However, the ET_{SR} estimates were slightly biased as most of the RMSE was systematic. On average, the ET_{SR} values were between 4 (weekly) to 6 % (cumulative) lower than the measured values as indicated by the ratios of means (Table 5). The relatively frequent irrigation events applied in this experiment due to the need for salt leaching, particularly at the initial crop stages, may have caused some increase of the measured ET_{lys} values due to the relatively wet soil surface. But, that relatively wet soil surface should also have affected the partition of R_n into the different energy balance components and thus should have affected the H_{SR} (and H_{EC}) and the ET_{SR} values. Nevertheless, this bias is much less than the reported bias for the eddy covariance systems elsewhere (Twine et al., 2000; Wilson et al., 2002; Franssen et al., 2010). Thus the resulting daily and weekly ET_{SR} values can be considered to be reliable and accurate estimates of rice evapotranspiration (ET_c).

The weekly averages of rice evapotranspiration (ET_c) and ET_o showed similar trends during the season for the three years, increasing from spring to mid-summer and decreasing thereafter (Fig. 7). The ET_c and ET_o values were quite similar although ET_c was slightly lower during the first part of the season and slightly higher later on. The similarity between ET_c and ET_o during 2002 was even higher since the rice evapotranspiration was lower due to the cooler weather conditions. The rice crop is quite sensitive to temperature. One of the reasons for the traditional flooding system of this crop is to temper the influence of temperature due to the continuous presence of a water depth, which is not present using sprinkler irrigation. The average daily ET_c for mid-season (from 90 to 130 DAS) was 5.1, 4.5 and 6.1 mm day^{-1} for 2001, 2002 and 2003, respectively. This value was lower during 2002 due to the meteorological conditions as previously explained. The daily ET_c during the 2003 mid-season was higher than 2001 and 2002 due to the earlier sowing date. Thus the crop mid-season in 2003 occurred mostly during July, the peak water demand period, while the crop mid-season in 2001 and 2002 occurred mostly during August. These average daily ET_c values are similar to those reported in the literature although some differences were observed due to the specific climatic conditions, sowing dates and occurrence of the mid-season stage, the highest water demand period. Tyagi et al. (2000) reported an average weekly value of about 6.0 mm day^{-1} for flooded rice in India. Alberto et al. (2011) reported average values of mid-season ET_c of about 5.0 mm day^{-1} in the Philippines for rice with a total season of about 130 days. Spanu et al. (2009) reported evapotranspiration values similar to those found in this work for rice under sprinkler irrigation for the semiarid conditions of Sardinia (Italy).

The seasonal rice evapotranspiration (from 6 to 146 DAS) was 755 mm in 2001 and 811 mm in 2003. The length of the growth stages was 165 days and 155 days for 2001 and 2003, respectively. The seasonal rice evapotranspiration for 2002 was not computed due to missing values for some measurement periods (Fig. 7). Alberto et al (2011) reported seasonal rice evapotranspiration of 500 and 534 mm in Phillipines with growing periods of 126 and 136 days, respectively. The seasonal values reported by Spanu et al. (2009) for rice under sprinkler irrigation were similar to those found in this work for a total growing season of about 140 days from sowing to maturity.

According to Allen et al. (1998), the initial stage runs from planting date to approximately 10 % ground cover, the mid season stage runs from effective full cover (80% of ground cover) to the start to maturity, and the late season stage runs from the start of maturity to harvest or full senescence. In this work these stages lasted from 0 to 55 DAS (initial stage), 55 to 85 DAS (crop development stage), 85 to 130 DAS (mid-season stage) and 130 to 155 DAS (late season stage) on average. These lengths were similar to those reported by Allen et al. (1998) for Mediterranean conditions although a longer period for the initial stage and a slightly shorter period for the mid-season and late-season stages were observed.

Fig. 8 indicates the weekly averages of the experimental K_c obtained for sprinkler irrigated rice in this experiment. The trend and the values of K_c during the season were similar for the three years. Weekly K_c varied in the range of 0.83 to 1.20 for 2001, 0.81 to 1.03 for 2002 and 0.84 to 1.15 for 2003. The K_c values at the beginning of the season were approximately 0.8 to 1.0 but there was a slight increase beyond 50 DAS, reaching values of 1.0 to 1.2 around 90 DAS. The initial and development stages, as defined by Allen et al. (1998) (10 and 80 % GC, respectively), ended around 50 DAS and 85 DAS (Fig. 3). This was in agreement with the abovementioned trend for the experimental K_c. The K_c values remained approximately constant after 90 DAS until about 130 DAS. This period can be defined as the mid-season stage following the guidelines of Allen et al. (1998). Finally, there was a slight decrease of K_c to values of about 1.0 until 145 DAS near the harvest date. Thus the average K_c values for the initial, mid-season and late-season stages were 0.92, 1.06 and 1.03 in this rice experiment under sprinkler irrigation (Table 6, Fig.8).

An increase of K_c in the last two weeks of the 2001 season was observed due to the relatively high precipitation amount recorded during early fall (Fig. 2) that likely increased soil evaporation. Likewise, this increase of K_c at the end of the 2001 season could also be due partly to the fact that small energy supplies, for instance from canopy or soil, when ET_o is low, may enable an increase in K_c (Testi et al., 2006). It is also interesting to note that 2002 was cooler and thus crop height, GC and K_c were somewhat lower than during 2001 and 2003. But the K_c for 2002 during the period of 30 to 45 DAS was higher while temperature and precipitation were also higher than for similar period during 2001 and 2003. Allen et al. (1998) suggested values of 1.05, 1.20 and 0.6 to 0.9, respectively, for the initial, mid- and late-season stages, for rice under continuous flood irrigation. The observed K_c in this experiment were smaller for the initial and mid-season stage and higher for the late-season stage. The lack of permanent ponded water in the sprinkler irrigated rice led to lower crop coefficients than those suggested by Allen et al. (1998). However, the ponded water in the traditional rice cropping system is drained out a few weeks before harvest while sprinkler irrigation in this experiment was applied almost up to the harvest date, partially due to the need for a leaching fraction to avoid soil salinity build-up. This would explain the higher K_c values observed during the late-season as compared to those suggested by Allen et al. (1998).

In general terms, the K_c values found in this work were slightly higher than those reported for sprinkler irrigated rice (Spanu et al., 2009) and aerobic rice (Alberto et al., 2011) (Fig.8). The likely reason was the additional irrigation applied in this experiment to avoid soil salinity build-up. The crop coefficient during the initial stage for all crops is quite variable depending on the soil wetting frequency (Allen et al., 1998). Thus lower values of K_c, particularly during the initial stage, for rice under sprinkler irrigation could be expected compared to other areas where the relatively high leaching fraction applied in this experiment would not be required. The results obtained in this experiment should be valid in other semiarid areas of the world where similar conditions of soil and water quality require leaching fractions to avoid soil salinity build-up. To our knowledge, no previous K_c values for sprinkler irrigated rice have been reported under these conditions.

Conclusions

The surface renewal method (SR) was used to determine values of ET_c and crop coefficients of sprinkler irrigated rice under the semiarid conditions in the north-east of Spain. The SR method was calibrated using the eddy covariance method. Different calibration values for α were obtained depending on the measurement and crop heights. Nonetheless, agreement between the weekly and cumulative daily values of ET_c obtained with the SR method and the lysimeter-measured values was quite high. The corresponding relative errors were about 13.9 (weekly) and 6.4 % (cumulative daily) and the indices of agreement were well above 0.9.

The weekly averages of rice evapotranspiration (ET_c) and ET_o showed similar trends during the season for the three years, increasing from spring to mid-summer and decreasing thereafter. The average daily ET_c values for mid-season (from 90 to 130 DAS) were 5.1, 4.5 and 6.1 mm day^{-1} for 2001, 2002 and 2003 respectively. The average ET_c values during 2002 were lower due to the cooler meteorological conditions. The seasonal rice evapotranspiration was about 750 to 810 mm from 6 to 146 days after sowing. This variability depended on the specific meteorological conditions of each season.

The experimental weekly K_c obtained for sprinkler irrigated rice varied between 0.83 to 1.20 for 2001, 0.81 to 1.03 for 2002 and 0.84 to 1.15 for 2003. On average, K_c was 0.92 for the initial stage, 1.06 for the mid-season stage, and 1.03 for the late-season stage. The total growing season was approximately

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150 to 160 days. Additional experiments are recommended for locations and climatic conditions where the relatively high leaching fraction applied in this experiment would not be required.

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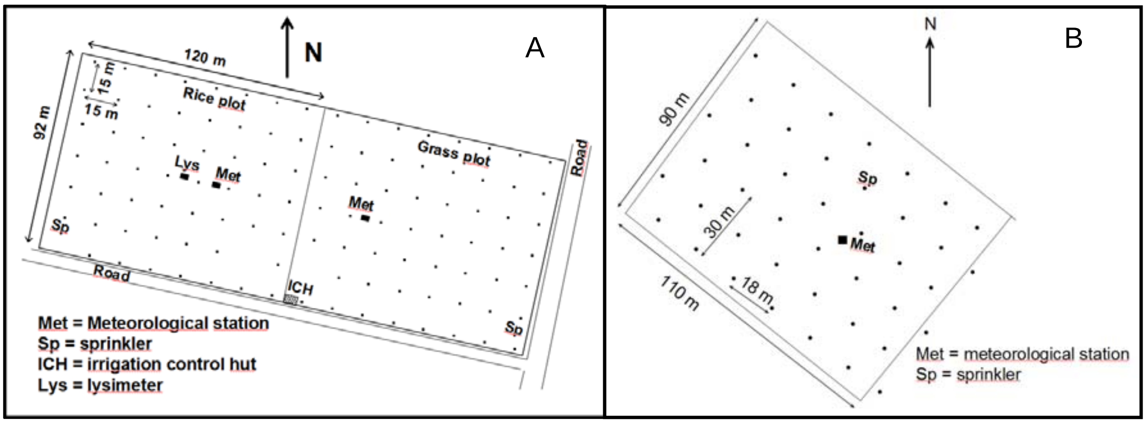

Fig. 1. Experimental plots. A, during 2001 and 2002. B, during 2003

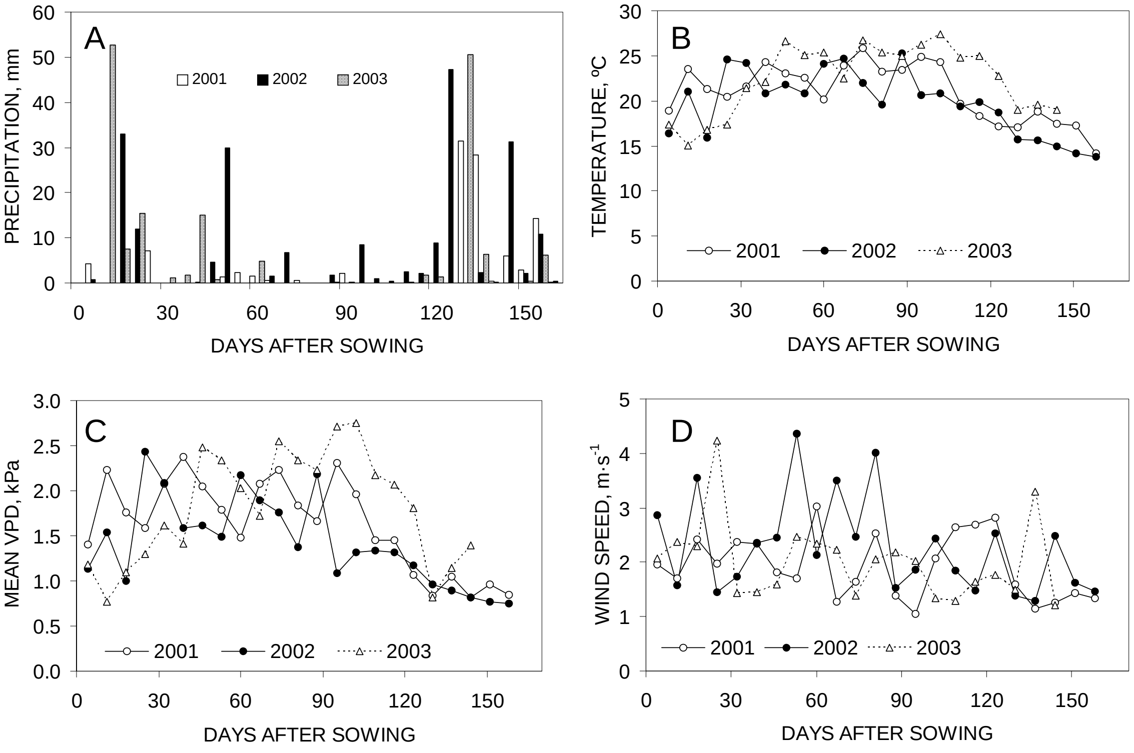

Fig 2. Weekly meteorological conditions during 2001 to 2003 recorded at a standard weather station over grass. A precipitation, B mean air temperature; C, mean vapor pressure deficit (VPD); and D, mean wind speed at 2.0 m above ground. Sowing dates were May 18 in 2001, May 21 in 2002 and April 28 in 2003.

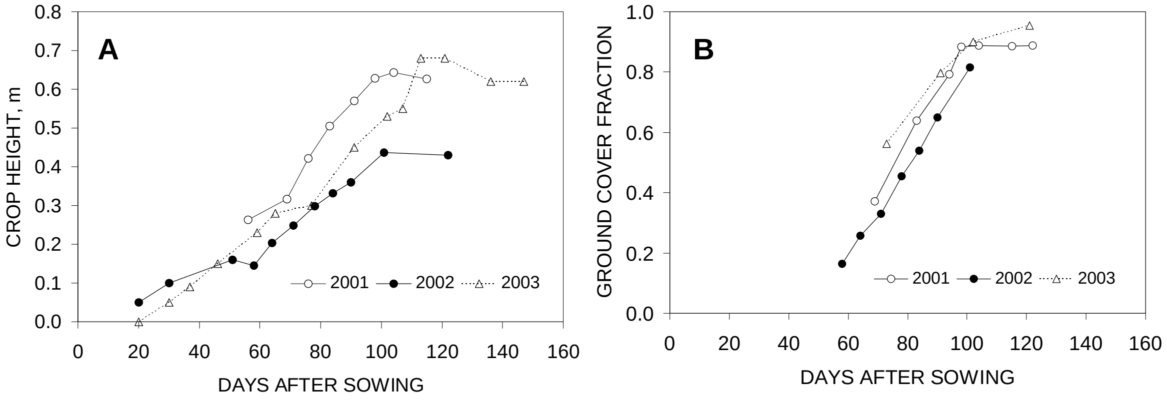

Fig 3. Evolution of crop height (A) and ground cover fraction (B) along the three experimental seasons. Sowing dates were May 18 in 2001, May 21 in 2002 and April 28 in 2003.

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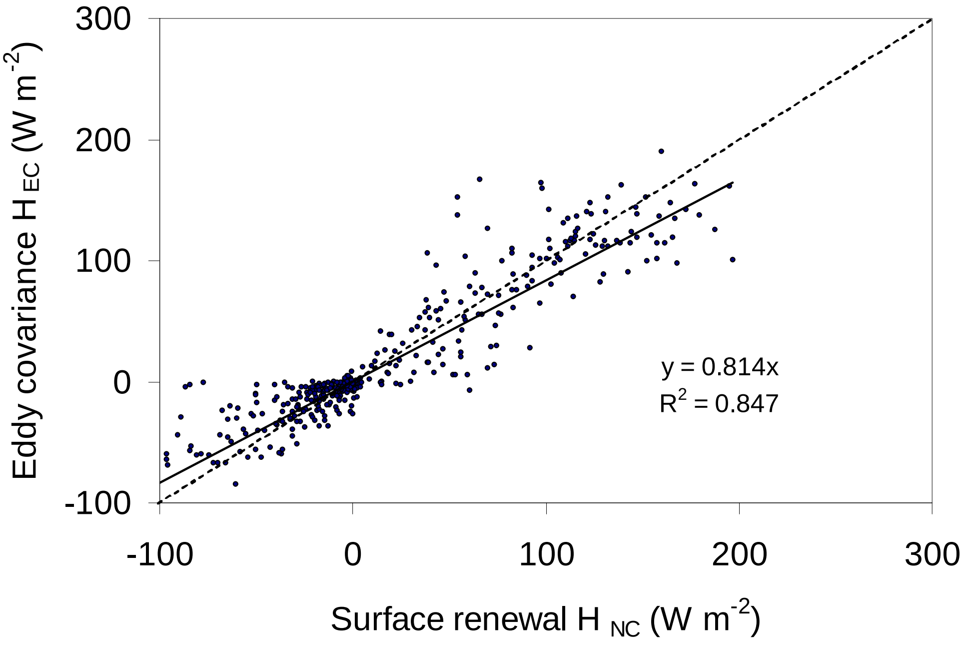

Fig 4. Eddy covariance (H_{EC}) versus non-calibrated surface renewal sensible heat flux (H_{NC}) at a height of 1.0 m above ground for the period 12 to 21 September 2003. Solid line represents the linear regression forced through the origin.

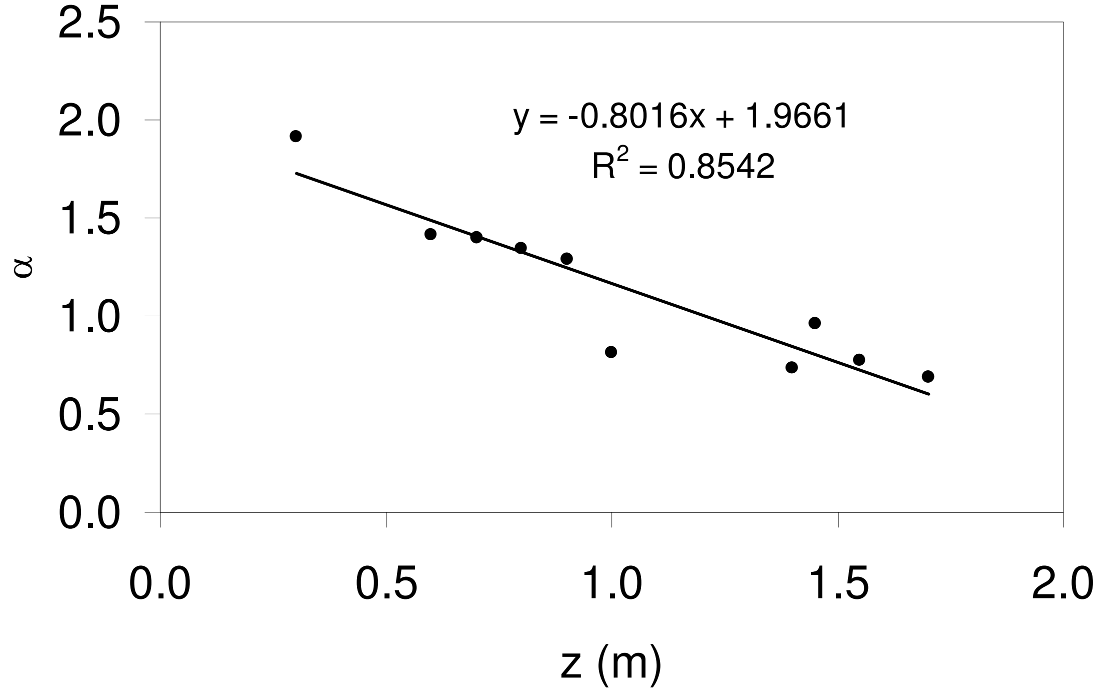

Fig 5. Linear regression between the calibration factor α of the surface renewal sensible heat flux and the measurement height (z) of the high frequency air temperature during 2002 and 2003.

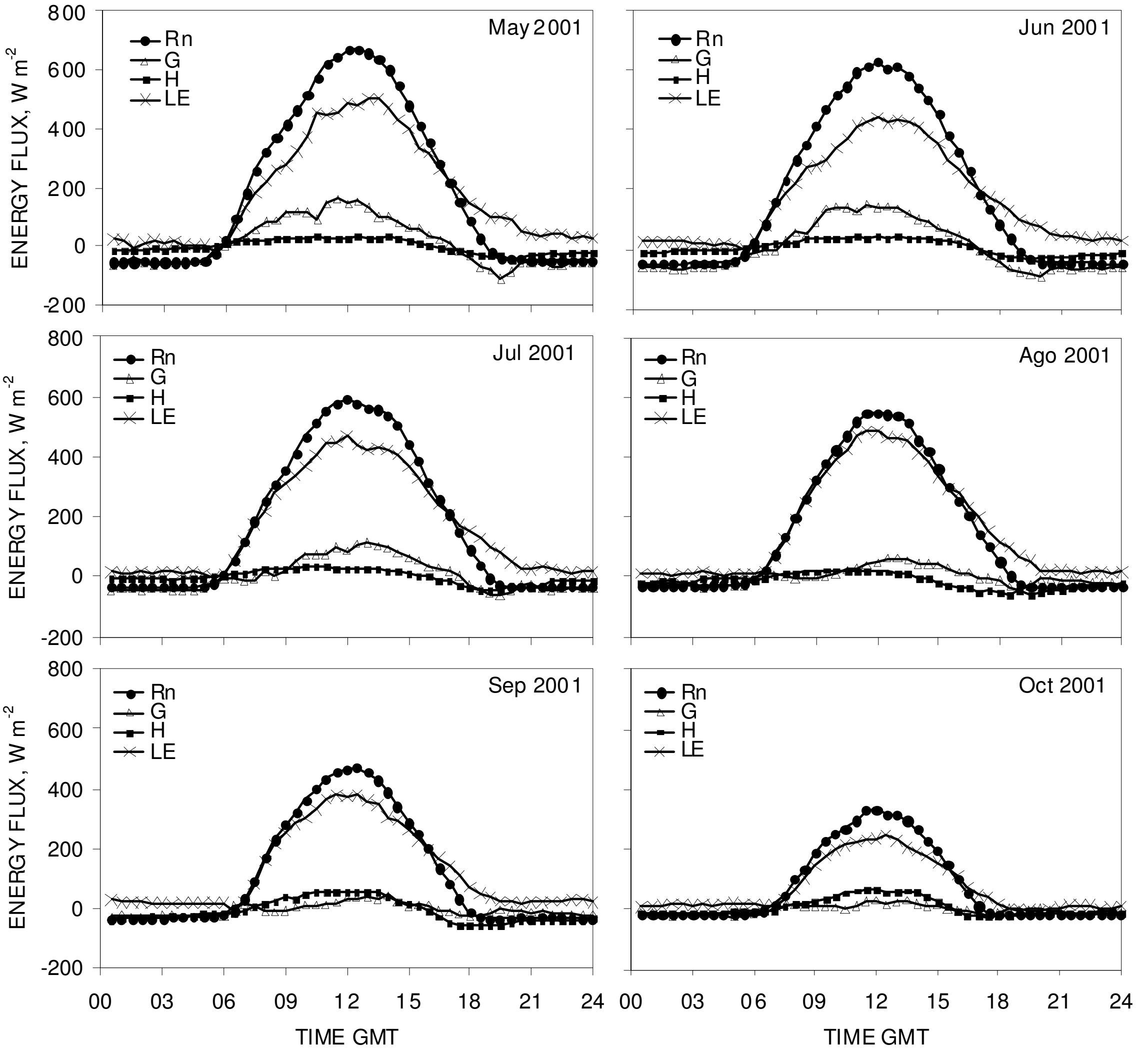

Fig. 6. Monthly averages of half –hour values of net radiation (R_n), and latent (LE), sensible (H) and soil (G) heat flux obtained for 2001.

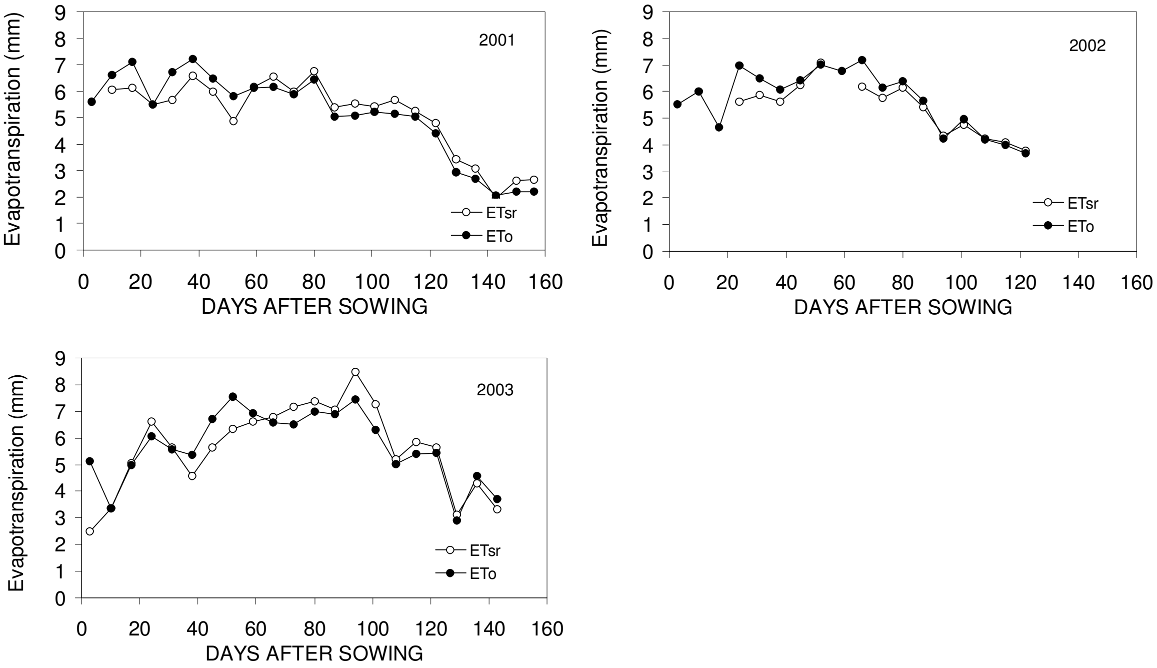

Fig. 7. Weekly averages of rice evapotranspiration (ET_{SR}) and reference evapotranspiration (ET_o) during 2001 to 2003. Sowing dates were May 18 in 2001, May 21 in 2002 and April 28 in 2003

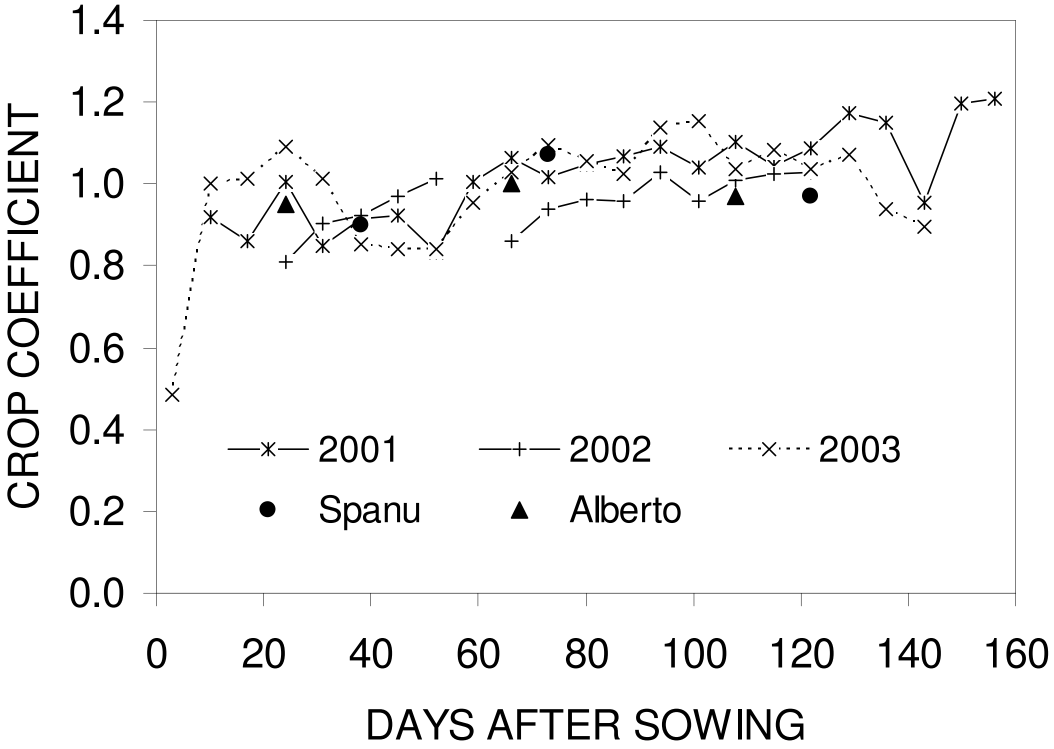

Fig. 8. Weekly values of experimental rice crop coefficient during 2001 to 2003. Sowing dates were May 18 in 2001, May 21 in 2002 and April 28 in 2003. Included are also crop coefficient values reported by Spanu et al. (2009) at Sasari (Sardinia, Italy) (Spanu), and Alberto et al. (2011) at Los Baños (Phillipines) (Alberto).

Table 1. Measurement height (z) of thermocouples used to estimate sensible heat flux by means of the surface renewal method during 2001, 2002 and 2003. DAS, days after sowing.

DAS(1)	2001			2002		2003		
	Z1	Z2	Z3	Z1	Z2	Z1	Z2	Z3
0-37	1.3	1.7	2.1	0.7	1.5	0.3	0.6	0.9
37-59	1.3	1.7	2.1	0.7	1.5	0.4	0.7	1.0
59-65	1.3	1.7	2.1	0.7	1.5	0.5	0.8	1.1
65-71	1.3	1.7	2.1	0.7	1.5	0.6	0.9	1.2
71-102	1.3	1.7	2.1	0.8	1.6	0.6	0.9	1.2
102-113	1.3	1.7	2.1	0.8	1.6	0.7	1.0	1.3
>113	1.3	1.7	2.1	0.8	1.6	1.0	1.4	1.7

(1) Sowing dates: May 18 in 2001, May 21 in 2002 and April 28 in 2003.

Table 2 Monthly and total irrigation water (mm) applied during 2001 to 2003.

Years	May	Jun	Jul	Aug	Sep	Total
2001	71.3	145.5	206.1	220.8	114.3	758.0
2002	38.8	170.4	155.6	208.5	86.5	659.8
2003	105.6	159.7	294.3	230.0	-	789.6

Table 3. Fraction F of fluxes (F1, F2, F3) sensed at the different measurement heights (Z1, Z2, Z3) during 2001, 2002 and 2003. DAS, days after sowing; h_c,the crop height (m).

Year	DAS	h_c (m)	Z1 (m)	Z2 (m)	Z3 (m)	Z1/h_c	Z2/h_c	Z3/h_c	F1	F2	F3
2001	56	0.264	1.30	1.70	2.10	4.9	6.4	8.0	0.81	0.73	0.65
	69	0.316	1.30	1.70	2.10	4.1	5.4	6.6	0.83	0.75	0.68
	76	0.421	1.30	1.70	2.10	3.1	4.0	5.0	0.86	0.79	0.71
	83	0.505	1.30	1.70	2.10	2.6	3.4	4.2	0.88	0.81	0.74
	91	0.571	1.30	1.70	2.10	2.3	3.0	3.7	0.89	0.82	0.76
	98	0.628	1.30	1.70	2.10	2.1	2.7	3.3	0.90	0.84	0.77
	104	0.643	1.30	1.70	2.10	2.0	2.6	3.3	0.90	0.84	0.77
	115	0.626	1.30	1.70	2.10	2.1	2.7	3.4	0.90	0.84	0.77
2002	20	0.050	0.70	1.45	-	14.0	29.0	-	0.84	0.64	-
	30	0.100	0.70	1.45	-	7.0	14.5	-	0.87	0.69	-
	51	0.161	0.70	1.45	-	4.4	9.0	-	0.90	0.73	-
	58	0.146	0.70	1.45	-	4.8	10.0	-	0.90	0.73	-
	64	0.203	0.70	1.45	-	3.5	7.2	-	0.91	0.76	-
	71	0.249	0.70	1.45	-	2.8	5.8	-	0.93	0.78	-
	78	0.299	0.80	1.55	-	2.7	5.2	-	0.92	0.77	-
	84	0.332	0.80	1.55	-	2.4	4.7	-	0.93	0.79	-
	90	0.360	0.80	1.55	-	2.2	4.3	-	0.93	0.79	-
	101	0.436	0.80	1.55	-	1.8	3.6	-	0.95	0.82	-
	122	0.430	0.80	1.55	-	1.9	3.6	-	0.95	0.82	-
2003	30	0.050	0.30	0.60	0.90	6.0	12.0	18.0	0.94	0.85	0.76
	37	0.090	0.35	0.65	0.95	3.9	7.2	10.6	0.95	0.87	0.78
	46	0.150	0.40	0.70	1.00	2.7	4.7	6.7	0.95	0.88	0.81
	59	0.230	0.50	0.80	1.10	2.2	3.5	4.8	0.95	0.89	0.82
	65	0.280	0.55	0.85	1.15	2.0	3.0	4.1	0.95	0.89	0.83
	77	0.300	0.55	0.85	1.15	1.8	2.8	3.8	0.96	0.90	0.84
	91	0.450	0.63	0.93	1.23	1.4	2.1	2.7	0.97	0.92	0.86
	102	0.530	0.73	1.03	1.33	1.4	1.9	2.5	0.97	0.92	0.86
	107	0.550	0.73	1.03	1.33	1.3	1.9	2.4	0.97	0.92	0.87
	113	0.680	1.00	1.40	1.70	1.5	2.1	2.5	0.95	0.88	0.83
	121	0.680	1.00	1.40	1.70	1.5	2.1	2.5	0.95	0.88	0.83
	136	0.620	1.00	1.40	1.70	1.6	2.3	2.7	0.94	0.87	0.82
	147	0.620	1.00	1.40	1.70	1.6	2.3	2.7	0.94	0.87	0.82

Table 4 Calibration values (α) obtained for the comparison between half-hour sensible heat fluxes obtained with the non calibrated surface renewal method (H_{NC}) and the eddy covariance approach (H_{EC}) for different measurement heights and periods.

Year	Height (m)	DAS[a]	α	R^{2}[b]
2002	0.70	20-78	1.395	0.769
	1.45	20-78	0.957	0.773
	0.80	79-128	1.342	0.737
	1.55	79-129	0.776	0.768
2003	0.30	3-37	1.916	0.775
	0.60	3-37	1.417	0.722
	0.90	3-37	1.290	0.777
	1.00	113-147	0.814	0.847
	1.40	113-147	0.733	0.817
	1.70	113-147	0.685	0.807

(a) DAS, days after sowing; sowing dates: May 21 in 2002 and April 28 in 2003.

(b) R^2, coefficient of determination

Table 5 Error analysis statistics of the comparison between weekly averages and cumulative daily measured (ET_{lys}) and estimated (ET_{SR}) rice evapotranspiration during 2001 and 2002. n, sample size; □x, mean of variable x (ET_{lys}); □y, mean of variable y (ET_{SR}); RMSE, root mean square error; R^2, coefficients of determination; RE, error relative; IA, index of agreement.

Periods	n	□x$^{(a)}$	□y$^{(a)}$	□y/□x	RMSE$^{(a)}$	R^2	RE (%)	IA
Weekly	29	5.60	5.38	0.960	0.75	0.783	13.90	0.916
Cumulative	134	222.7	208.2	0.935	13.3	0.996	6.40	0.997

(a) Values of □x, □y, and RMSE are in mmday^{-1} for weekly data and mm for cumulative data.

Table 6 Average values of experimental crop coefficients for sprinkler irrigated rice at the different development stages, initial (K_{cini}), mid-season (K_{cmid}) and end-season (K_{cend})

Years	$K_{c\,ini}$	$K_{c\,mid}$	$K_{c\,end}$
2001	0.90	1.09	1.13
2002	0.92	1.00	-
2003	0.93	1.08	0.92
Average	0.92	1.06	1.03