ΦYTON
REVISTA INTERNACIONAL DE BOTÁNICA EXPERIMENTAL
INTERNATIONAL JOURNAL OF EXPERIMENTAL BOTANY
FUNDACION ROMULO RAGGIO
Gaspar Campos 861, 1638 Vicente López (BA), Argentina
www.revistaphyton.fund-romuloraggio.org.ar

Evapotranspiration and energy balance measurements over a soybean field in the semiarid sowthwestern region of Buenos Aires province (Argentina)

Evapotranspiración y balance energético de un cultivo de soja en la región semiárida de Buenos Aires (Argentina)

Cargnel MD[1], AL Orchansky[2], RE Brevedan[2], SS Baioni[2], MN Fioretti[2]

Abstract. Two field experiments were carried out in a semiarid region of Argentina over a soybean (*Glycine max* L. Merrill) field. The sites of study were San Adolfo (39° 23' S, 62° 22' W, 22 m.a.s.l.) and Nueva Roma (38° 29' S, 62° 39' W, 70 m.a.s.l.). Soybeans were planted on Jan 4 (San Adolfo) and Nov 27 (Nueva Roma) in 0.75 m wide rows and at 400000 pl/ha during two consecutive growing seasons. Energy balance and evapotranspiration (ET) were estimated during the reproductive stages from full bloom (R2) to full maturity (R8). In Nueva Roma ET or latent heat flux (LE) was estimated using the Bowen ratio-energy balance (BREB) (LEβ) and the Priestley-Taylor equation (LE_{PT}) with α_{PT}=1.26, 48 h after irrigation or rain. Both methods could be used to predict ET since the ratio LEβ/LE_{PT} ranged between 0.83 and 0.95. The observed Bowen ratio values were almost 0 during and after rain and increased to approximately 0.45 several days after rain. In San Adolfo LE was estimating using the Priestley-Taylor equation. For both sites the regression analysis for comparison available energy (Rn-G) and LE using BREB or LE_{PT} indicated that, approximately 90% of the available energy was consumed by LE without detecting significative advective conditions.

Keywords: Evapotranspiration; Soybean; Bowen; Priestley-Taylor; Energy balance.

Resumen. Se realizaron dos experimentos a campo en la región semiárida de Argentina, en un cultivo de soja (*Glycine max* L. Merrill). Los sitios de estudio fueron San Adolfo (39° 23' S, 62° 22' W, 22 msnm) y Nueva Roma (38° 29' S, 62° 39' W, 70 msnm). Se sembró el 4 de enero (San Adolfo) y el 27 de noviembre (Nueva Roma) con una separación de 0,75 m y una densidad de 400000 pl/ha durante dos estaciones de crecimiento consecutivas. Se estimaron el balance energético y la evapotranspiración (ET) durante el estado reproductivo desde plena floración (R2) a madurez (R8). En Nueva Roma la ET o el flujo latente de calor (LE) fue estimado usando el cociente de Bowen (BREB) (LEβ) y la ecuación de Priestley-Taylor (LE_{PT}) con α_{PT}=1,26, 48 h luego de la irrigación o precipitación. Ambos métodos podrían ser usados para predecir la ET dado que el cociente LEß/LE_{PT} varió entre 0,83 y 0,95. Los valores del cociente de Bowen observados fueron aproximadamente 0 durante y luego de una precipitación y aumentaron a aproximadamente 0,45 varios días luego de ella. En San Adolfo, LE fue estimado usando la ecuación de Priestley-Taylor. Para ambos sitios el análisis de regresión para la comparación de la energía disponible (Rn-G) y LE usando BREB o LE_{PT} indicaron que aproximadamente el 90% de la energía disponible fue consumida por LE sin que se hayan detectado condiciones advectivas significativas.

Palabras clave: Evapotranspiración; Soja; Bowen; Priestley-Taylor; Balance energético.

[1] Facultad de Agronomía, Universidad de Buenos Aires, C1417DSE Buenos Aires, Argentina.
[2] Depto. Agronomía, Universidad Nacional del Sur (UNS), 8000 Bahía Blanca. Argentina.
Address correspondence to: Miriam Cargnel, *e-mail:* mcargnel@agro.uba.ar
Received 15.VIII.2017. Accepted 30.IX.2017.

INTRODUCTION

Soybean in Argentina has expanded considerably since the early '70s, before which it was considered only a minor crop. During the 1970-75 period a mean annual area of 290000 ha was sown to soybean, and since then production has expanded rapidly to the point where it is now the major crop in Argentina and the principal crop for exportation. Nowadays the area of soybean cultivation reaches 20.2 million ha. The expansion of the area under soybean production is largely the outcome of land being diverted away from other cultivated crops in humid and sub humid temperate zones. However, production is now spreading to marginal zones in the semiarid region, and it is here where there is a need for more information regarding the convenience of alternative planting patterns and the advantages of irrigation, where this is possible (Ramírez et al., 2008).

A potentially suitable region for soybean cultivation is the southwest of Buenos Aires's province but the main limiting factor is water. To manage limited water resources it is crucial to quantify actual crop water use. Although regional studies are useful for large scale planning, ultimately, water is managed at the field scale. The estimation of actual evapotranspiration (ET) is essential to estimate crop water use efficiency under irrigated or rainfed conditions. Unfortunately, the estimation of ET is one of the most difficult tasks in hydrology and soil science due to complex interactions among the components of the soil-plant-atmosphere continuum. Several models for estimating ET have been introduced in the literature. Direct measurements of ET can be obtained using the Bowen ratio-energy balance (BREB) (Hatfield et al., 1996; Steduto & Hsiao, 1998 a, b; Rana & Katerji, 2000; Saylan, 2000; Zhang et al., 2004, Hernandez-Ramirez et al., 2009). This method has the advantage that is not necessary to measure turbulence or wind speed, it is low cost relative to other micrometeorological techniques and it is independent of atmospheric stability (Cellier & Brunet, 1992), nonetheless is open to question whether or not correction is needed for air stability conditions (Allen et al,. 2011a). The two most commonly used methods to measure ET rates are the BREB and the Eddy covariance and a good agreement between the estimates from both methods was found (Pauwels & Samson, 2006; Kosugi et al., 2007).

Another alternative to direct estimations of ET is the use of models that include empirical or semi-empirical equations like the Penman-Monteith (Monteith, 1965) and the Priestley-Taylor (Priestley & Taylor, 1972) equations. The Priestley-Taylor (PT) approach to estimating ET depends on accurate determination of PT parameter α which is a function of the Bowen ratio (β) and evaporative fraction (EF). Screening out the data for days with minimum advection and a rainfall of at least 20 mm in the previous 1-3 days, in the case of land surfaces, PT found α to vary between 1.08 and 1.34. A value of α=1.26 is usually adopted for wet surfaces (Priestley & Taylor, 1972; Stannard, 1993). Zhang et al. (2004) found that the seasonal trend of α was negatively correlated with β and positive correlated with midday EF. Other authors agreed with the PT model in determining actual ET in spite of its relative simplicity (Sumner & Jacobs, 2005; Fisher et al., 2005; Pereira, 2004; Gavin, 2004). The objectives of this study were to (1) evaluate the accuracy of daily ET estimates from the Bowen ratio-energy model and Priestley-Taylor equation, and (2) estimate daily seasonal soybean energy balance.

MATERIALS AND METHODS

Site description. The study was carried out in the southwest of Buenos Aires's province. This area falls within the semiarid region, where the annual water ranges between 300 and 500 mm. Rains usually occur in spring and at the end of summer-early autumn, this latter period coinciding with pod development and seed production. The annual average temperature is 15 °C, and the absolute minimum and maximum temperatures are -10 and 44 °C. The usual planting date in this area is mid-november, a period when the possibility of frozen days is avoided.

Two field experiments were conducted, one at San Adolfo (39° 23' S, 62° 22' W, 22 m.a.s.l.) and the other at Nueva Roma (38° 29' S, 62° 39' W, 70 m.a.s.l.), both sites are located in the irrigation zone of Colorado and Sauce Chico rivers. The soils were primarily an Ustipsament and Mollic Ustifluvent, respectively. The planophile soybean cultivars ASGROW 3127 were planted on Jan 4 and Nov 27 in 0.75 wide rows during two consecutive growing seasons. Stand density measured during reproductive growth stages was 400000 pl/ha. Irrigation was applied to assure uniform emergence over the experimental area. Furrow irrigation was used and water was applied at the R2 stage (Fehr & Caviness, 1977). Total rainfall during the reproductive seasons was 91 and 185 mm, respectively. Soybeans were harvested on May 14 and April 4, respectively.

Soybean energy balance. The main variables measured at the micrometeorological station were the incoming (Rs_{IN}) and reflected (Rs_{OUT}) solar radiation above the soybean canopy measured with pyranometers (LI-COR LI 200-Z). Net radiation (Rn) was measured using a Frietschen's radiometer (REBS Q5). Soil heat flux at 0.01 m (G) was measured with transducers (REBS HFT-1). Air temperature (Ta) and relative humidity (RH) were measured with the HMP45C probe (Campbell Scientific Inc.). Wind speed (u) was measured with an anemometer (RM Young 03101-5) 2 m above soil level. Signals from these sensors were recorded every 1 min and 30 min average were kept on data loggers (Campbell Scientific CR-21XL). A pluviometer was used to measured precipitations. In Nueva Roma actual evapotranspiration (ET) was calculated by using Bowen ratio method (Bowen, 1926). The latent heat (LE) and sensible heat (H) fluxes were determined with forced ventilated reversible psychrometers that were located at different heights within the dynamic equilibrium boundary layer. The lowest psychrometer was positioned at 0.2 m above the top of the canopy and the distance between the two psychrometers was 1 m. Signals from these sensors were recorded every 10 s, integrated every 5 min. and reversed the sensors position every 15 min.

The energy balance above an active surface like a crop canopy can be expressed as:

$$Rn\text{-}G=LE+H \quad (1)$$

where left and right sides in Eq. (1) are conventionally defined as available energy (Rn-G) and turbulent fluxes (H+LE), G is subtracted from Rn to reflect the maximum quantity of energy possible at the surface; Rn is net radiation flux (W/m^2), G is soil heat flux (W/m^2), LE is the latent heat flux of evapotranspiration from the canopy and soil (W/m^2), H is sensible heat flux from the canopy and soil (W/m^2). The Bowen ratio β is defined as H/LE; knowing β allows estimation of LE using:

$$LE_{\beta}=(Rn\text{-}G)/(1+\beta) \quad (2)$$

Bowen ratio was calculated using averaged values of H and LE during midday.

In San Adolfo the actual ET was calculated by using Priestly-Taylor equation with α_{PT}=1.26 for 48 h after rain or an irrigation event. The equation of Priestly-Taylor (P-T) is defined as:

$$LE_{PT}=\alpha\ (Rn\text{-}G)\ S/(S+\gamma) \quad (3)$$

Where α is the P-T parameter, S is the slope of the function relating saturation vapor pressure to temperature (KPa /K) and γ is the psychrometric constant (KPa/K).

Crop components of energy balance were evaluated during pod filling from growth stage R5 to full maturity (R8) (Table 1). Growth stages of development were evaluated using Fehr & Caviness scale (1977).

Soil water content. Soil water content (SWC) was determined in the surface layer by gravimetry and by a neutron probe (Troxler 1255) at different depths. The neutron probe readings were calibrated with gravimetric soil moisture data. Depth of sampling was every 0.20 m up to 1.00 m. Soil water content at each depth was calculated using the following equation:

$$SWC_d(mm)=\theta v\ g/cm^{3}*z\ cm*\theta w\ (\%)/10 \quad (4)$$

where θv and θw are soil volumetric and weight water content, respectively and z is sampling depth.

Soil water content was measured twice a week during the reproductive stages from early bloom (R2) to full maturity (R8).

RESULTS AND DISCUSSION

Environmental conditions and soil moisture. Table 2 shows the daily averaged weather variables during the two growing seasons studied in San Adolfo (SA) and Nueva Roma (NR), respectively. Rainfall at the field sites, from January to April sum up to 91 and 185.4 mm while the annual average is approximately 450 mm; and it was well distributed during the end of summer-early autumn (Sánchez et al., 1998). Air temperature reached its maximum value in January and February at approximately 30 and 32 °C, while the minimum values occurred during April (10 °C). Relative humidity values were 10% higher in Nueva Roma than in San Adolfo's. Wind speed from January to April was moderated, reached 2.69 and 2.61 m/s in San Adolfo and Nueva Roma, respectively.

The averaged soil water content from R2 to R8 at each sampling depth is shown in Figure 1. The near-surface water content averaged 34.16 mm in San Adolfo and 43.67 mm in Nueva Roma. Error bars indicate the largest SWC variation at the 0-0.20 m depth because soil evaporation is largest at this depth. In Nueva Roma the increased in SWC between 0.20 and 0.40 m depth was due to the irregular distribution of organic matter, and the high value of SWC at 1.0 m depth at the San Adolfo's site was due the presence of ground water.

Energy balance. Total energy fluxes of Rs_{IN}, Rs_{OUT} and Rn were calculated from the summation of diurnal values (8-21 local hour) at each study site (Fig. 2). The values were as expected in the southern hemisphere, lower from January to April in conjunction with the development of the crop. The possible reason of the declined values of Rs_{OUT} was due to the reflective characteristics of the surface, the albedo.

Table 1. Day of year (DOY) of soybean´s reproductive growth stages at San Adolfo (SA) and Nueva Roma (NR) sites.
Tabla 1. Día del año (DOY) correspondiente a los estadios reproductivos del cultivo de soja en las localidades de San Adolfo (SA) y Nueva Roma (NR).

	Stage [day of year (DOY)]							
	R1	R2	R3	R4	R5	R6	R7	R8
SA	51	58	65	69	81	91	101	111
NR	20	29	38	42	51	60	71	83

Table 2. Comparison of environmental conditions in San Adolfo (SA) and Nueva Roma (NR). J-A (January to April), n.d. (no data).
Tabla 2. Tabla comparativa de las condiciones climáticas registradas en las localidades de San Adolfo (SA) y Nueva Roma (NR). J-A (enero a abril), n.d. (sin datos).

Variable	Site	January	February	March	April	J-A
Temperature (°C)						
Mean daily max.	SA	(n.d.)	30.00	27.00	23.10	26.70
	NR	32.00	28.90	27.50	(n.d.)	29.45
Mean daily min.	SA	(n.d.)	11.80	12.50	10.00	11.50
	NR	16.50	13.15	13.90	(n.d.)	14.50
Mean daily temp.	SA	(n.d.)	21.20	19.80	12.20	17.75
	NR	24.00	21.00	20.15	(n.d.)	21.70
Rel. humidity (%)						
Mean daily max.	SA	(n.d.)	86.70	89.67	94.79	90.38
	NR	89.97	90.00	90.06	(n.d.)	90.01
Mean daily min.	SA	(n.d.)	21.26	33.24	41.46	31.98
	NR	31.77	32.74	43.73	(n.d.)	36.08
Mean daily RH.	SA	(n.d.)	51.50	61.42	72.39	61.77
	NR	64.28	65.86	71.98	(n.d.)	67.37
Mean daily wind speed (m/s)	SA	(n.d.)	3.06	2.64	2.38	2.69
	NR	2.56	2.74	2.55	(n.d.)	2.61
Total precipitation (mm)	SA	(n.d.)	(n.d.)	42.20	48.80	91.00
	NR	5.08	79.25	101.08	(n.d.)	185.41

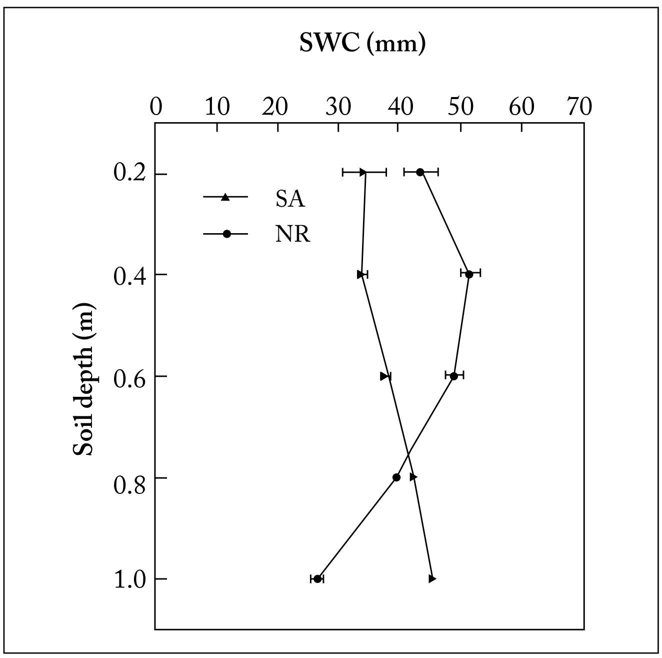

Fig. 1. Average soil water content (mm) at each depth in San Adolfo (SA) and Nueva Roma (NR) locations.
Fig. 1. Contenido de agua, promedio, del suelo (mm) en función de la profundidad en las localidades de San Adolfo (SA) y Nueva Roma (NR).

The regression line between Rn and Rs_{IN}, was significant at both sites, and the r^2 was 0.99. The slopes indicate that approximately 70% of the Rs_{IN} is available for Rn (Fig. 3). The magnitude of the slope Rn/Rs_{IN} agrees with Fritschen (1967) and Kaminsky & Dubayah (1997) for complete covered canopies under irrigation.

Three conditions for three different days were selected to compare the daily diurnal trends of the components of the surface energy balance above soybean canopies in San Adolfo and Nueva Roma. Figure 4 presents the days differentiated by irrigation time during the reproductive stage R2-R3: a) Before irrigation day, b) Irrigation day and c) After irrigation day. The maximum solar radiation flux (Rs_{IN}) occurred between 14:00 to 16:00 local time. At both sites, soil water content affected the diurnal flux of G, especially in San Adolfo. Unfortunately, due to mechanical sowing problems, midday G values increased before and after irrigation, reaching approximately 22% of Rn. G fluxes during irrigation day showed slight net heat loss.

Irrigation water caused a decrease of G flux near soil surface keeping the soil thermal conductivity high (Guan et al., 2009). When soil surface dried, G (24 h) flux increased (net heat gain), and represented less than 10% of Rn (24 h) before irrigation and during the whole period studied. These results agreed with Saylan (2000) and Ventura et al. (1999). The available energy was used mainly for latent and sensible heat fluxes, heating the air and evaporating water.

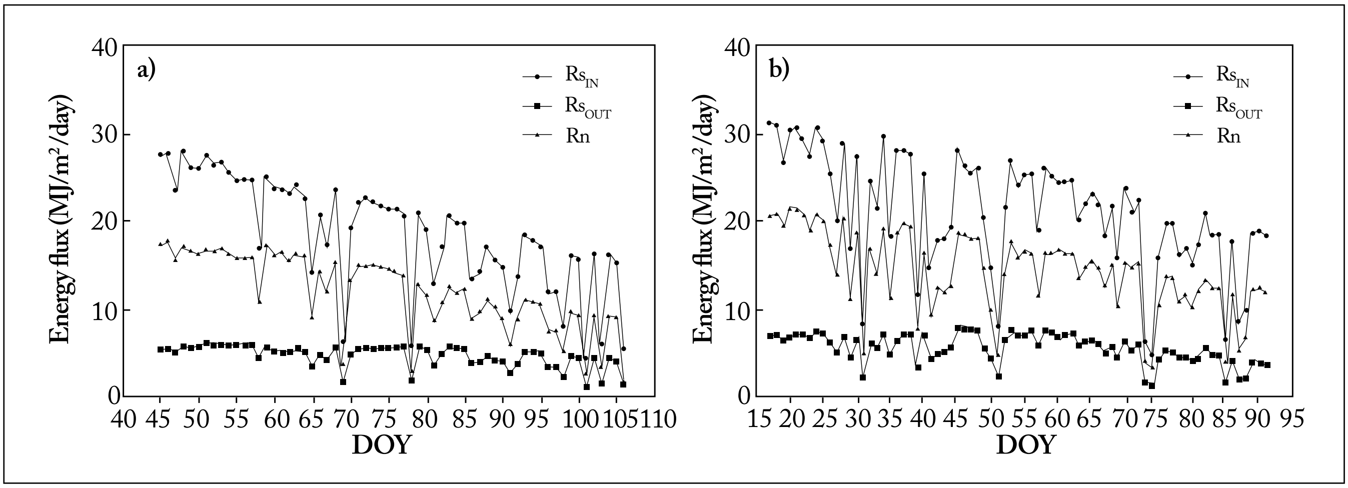

Fig. 2. Energy fluxes (MJ/m²/day) at a) San Adolfo and b) Nueva Roma from January to April.
Fig. 2. Flujos diarios de energía (MJ/m²/day), desde los meses de enero a abril, en las localidades de a) San Adolfo (SA) y b) Nueva Roma (NR).

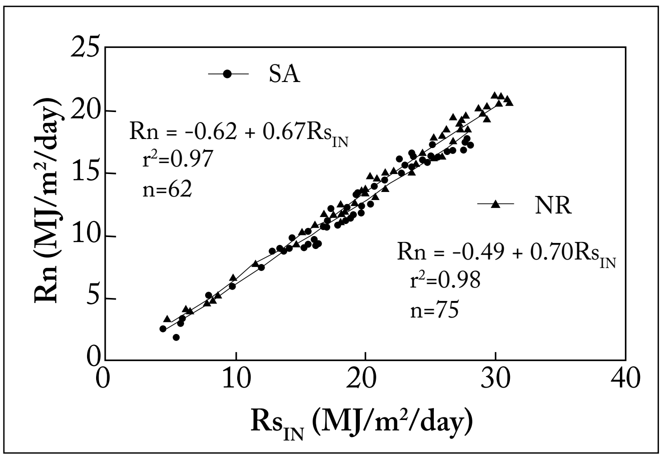

Fig. 3. Net radiation (Rn, MJ/m²/day) versus Incident radiation (Rs_{IN}, MJ/m²/day).
Fig. 3. Radiación neta diaria (Rn, MJ/m²/day) en función de la Radiación incidente diaria (Rs_{IN} , MJ/m²/day). San Adolfo (SA) y Nueva Roma (NR).

The Albedo. The Albedo ($\alpha_S = Rs_{OUT}/Rs_{IN}$) was calculated using the diurnal values (8-21 local hour). Figure 5 shows the albedo during the reproductive growth at San Adolfo (a) and Nueva Roma (b). Albedo increased as soil was covered with green plant material and then declined when the crop matured. Maximum values of surface albedo were reached when the LAI was greater than 3, during the R5-R6 growth stages. Vegetation cover is one of the parameters that affect surface albedo (Hollinger et al., 2010). Higher albedos are associated with various plant-surface structures that reduce cuticular conductance to the extent that leaf temperature and transpiration are reduced without a reduction in stomatal conductance and maximizing soil moisture use (Blum, 2005; Serban et al., 2011). Recent studies show an interesting point of view of higher crop albedos so as to absorb less energy and potentially cool regional air temperatures (Doughty et al., 2011).

In San Adolfo, due to incomplete soil cover, the results showed that soil moisture plays an important role in albedo´s values as indicated in the irrigation day (DOY 60). The presence of free water in the soil decreased surface albedo. Guan et al. (2009) found an exponential relationship between albedo and soil moisture.

Figure 6 shows the relationship between midday ratio of soil heat flux to net radiation and daily surface albedo observed at SA and NR. To show accurately the influence of the surface albedo on the ratio G/Rn daily differences such as rain and irrigation have been excluded in order to minimize the effect of water on soil heat flux and surface albedo. At both sites, the ratio of soil heat flux to net radiation showed a linear decrease as the surface albedo increased, reaching a value around 0.1, when surface albedo was near 0.28 in SA. In Nueva Roma the ratio G/Rn reached values less than 0.1, for albedos greater than 0.20, indicating a full cover. In this case a constant midday value for G/Rn works reasonably well, regardless of surface conditions. These results agree with Ogee et al. (2001) and Santanello & Friedl, (2003). In San Adolfo the ratio G/Rn reached up to 0.30, indicating the presence of a sparse canopy. In the same time surface albedo values were near 0.20, showing a dependence on surface conditions, such as soil type, vegetation amount and height (Kustas et al., 1993).

Evapotranspiration. Measurement of evapotranspiration of agricultural crops is a basic tool to compute water balances and to estimate water availability and requirements. Table 3 shows the parameters of linear regressions of available energy (Rn-G) and LE using Priestley-Taylor (LE_{PT}) and BREB (LEβ) methods. The slopes (0.89-0.94) indicated that approximately 90% of the available energy is consumed by LE,

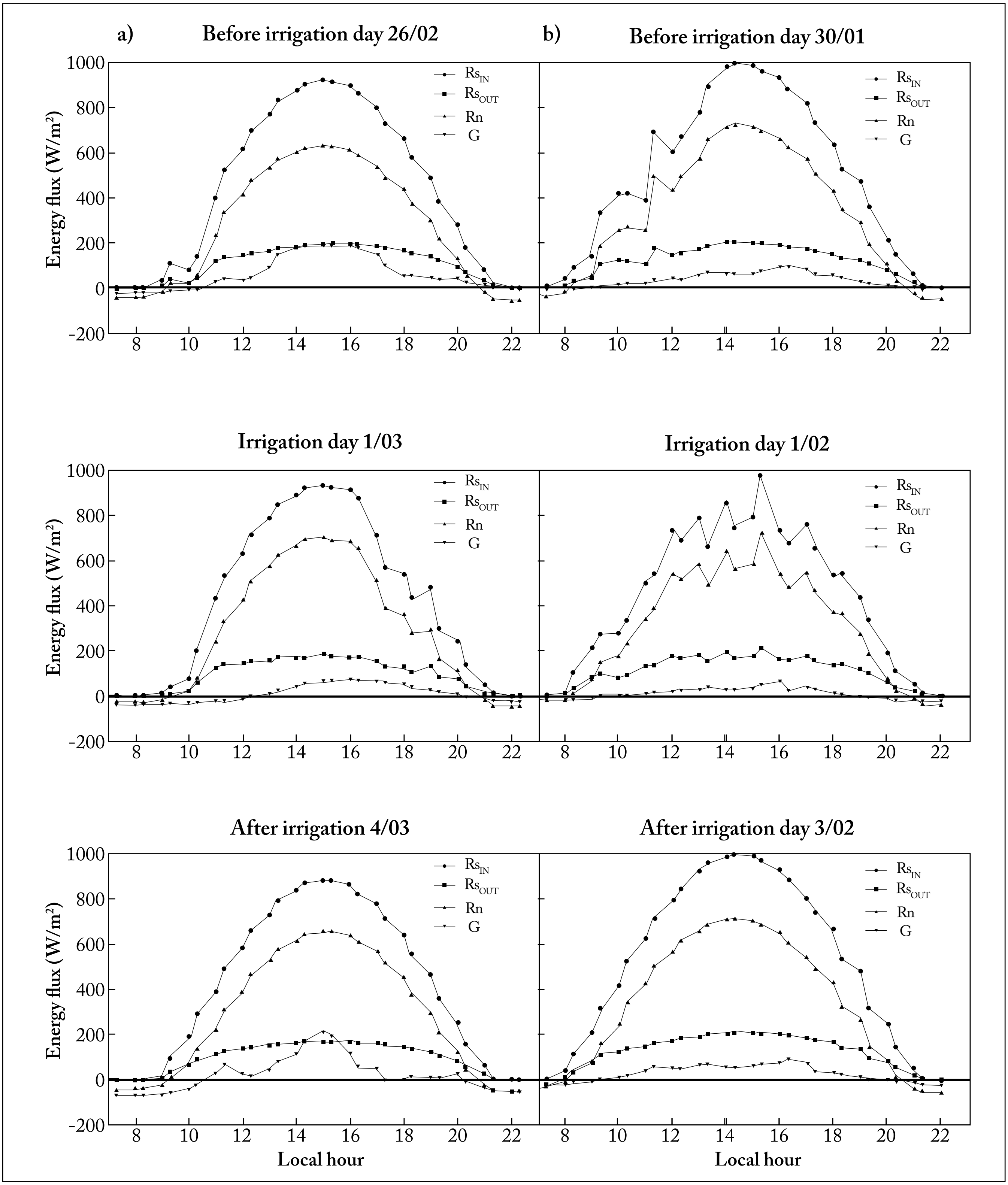

Fig. 4. Diurnal energy fluxes (W/m[2]) during three days according irrigation time, at R2-R3 reproductive stages. a) San Adolfo and b) Nueva Roma.

Fig. 4. Flujos diarios de energía (W/m[2]) de tres días diferentes según el momento de realización del riego, durante los estadios reproductivos R2-R3. a) San Adolfo (SA) y b) Nueva Roma (NR).

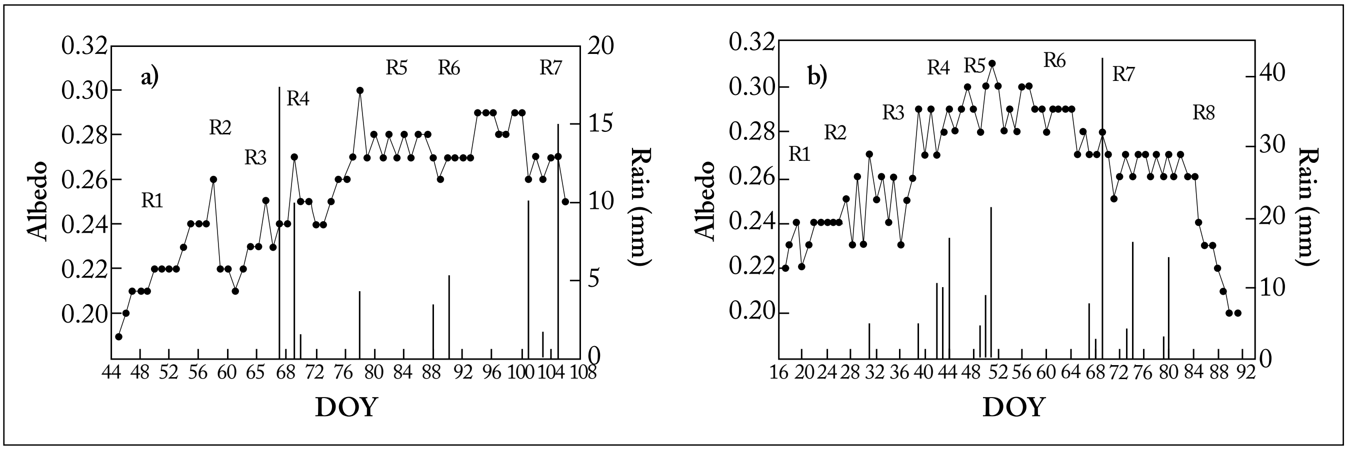

Fig. 5. Albedo ($\alpha_S = Rs_{OUT}/Rs_{IN}$) during the reproductive season. Narrow bars indicate recorded precipitation. a) San Adolfo (SA) and b) Nueva Roma (NR).

Fig. 5. Albedo ($\alpha_S = Rs_{OUT}/Rs_{IN}$) durante la etapa reproductiva del cultivo de soja. Barras angostas indican los registros de precipitación (mm). a) San Adolfo (SA) y b) Nueva Roma (NR).

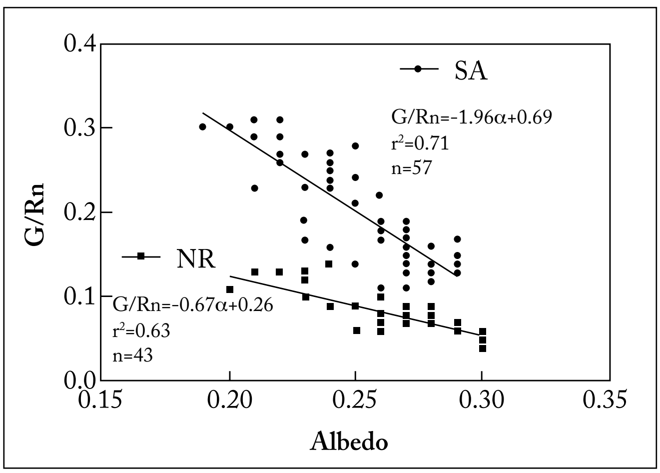

Fig. 6. Midday ratio of soil heat flux to net radiation (G/Rn) against daily surface albedo (α_S) observed in San Adolfo (SA) and Nueva Roma (NR) locations.

Fig. 6. Relación flujo de calor en el suelo: radiación neta (G/Rn), al mediodía, en función de los valores diarios de albedo (α_S) registrados en las localidades de San Adolfo (SA) y Nueva Roma (NR).

without detecting significant advective conditions. Therefore, the energy for LE was supplied by the energy balance. Sauer et al. (2007) reported that under the full canopy conditions, nearly 90% of the shortwave and net radiation was attenuated by the canopy, with over 80% of the available energy utilized by ET. The BREB and Priestley-Taylor methods accurately measured ET in semiarid conditions. In Nueva Roma, the observed ratio values of $LE\beta/LE_{PT}$ ranged between 0.83 and 0.95, which corroborated the use of both methods. Ünlü (2010) agreed with the use of BREB in semiarid conditions. McAneney & Itier (1996) indicated that α_{PT} is fairly insensitive to wind speed and saturation deficit over a reasonable range of conditions with daily mean saturation deficit of 10 g/m^3, as a probable upper limit of validity. In our study, the saturation vapor deficit (SDV) was $2.02 \leq SDV \leq 13.09$ g/m^3 in Nueva Roma and $2.80 \leq SDV \leq 13.04$ g/m^3 in San Adolfo.

In Nueva Roma the Priestley-Taylor equation was solved for the Priestley-Taylor constant (α_M) by replacing LE_{PT} for $LE\beta$. The midday averaged values were calculated during 12 to 16 h local time. The α_M ranged $0.91 < \alpha_M < 1.4$ during irriga-

Table 3. Parameters of a linear regressions between evapotranspiration, using Priestley-Taylor equation (LE_{PT}, $MJ/m^2/day$) and Bowen ratio ($LE\beta$, $MJ/m^2/day$), and available energy (Rn-G, $MJ/m^2/day$) during the reproductive stages of a soybean crop in San Adolfo (SA) and Nueva Roma (NR) locations.

Tabla 3. Parámetros de las regresiones lineales realizadas entre la evapotranspiración, calculada según la ecuación de Priestley-Taylor (LE_{PT}, $MJ/m^2/day$) y cociente de Bowen ($LE\beta$, $MJ/m^2/day$), y la energía disponible (Rn-G, $MJ/m^2/day$) en las localidades de San Adolfo (SA) y Nueva Roma (NR) durante la etapa reproductiva del cultivo de soja.

Site	Stages	n	Slope	Intercept	Adjusted r^2	Model
SA	R4-R7	36	0.94	-0.53	0.97	LEPT
NR	R5-R8	35	0.94	-0.39	0.96	LEPT
NR	R5-R8	35	0.89	-0.84	0.82	BREB

[a] Intercept was significantly different from 0 at the P<0.001 level.

tion day or after rain (>10 mm). A correlation analysis for comparison the partition of available energy (LEβ/(Rn-G)) or evaporative fraction and α_M showed that $\alpha_M \approx 1.34$ when total irradiative energy is consumed by LE (Fig. 7). This α_M was consistent with a well-watered canopy cover (IAF≥3), and this value represented 10% up of α_{PT} what corroborated the validity of the Priestley-Taylor model under our experimental conditions.

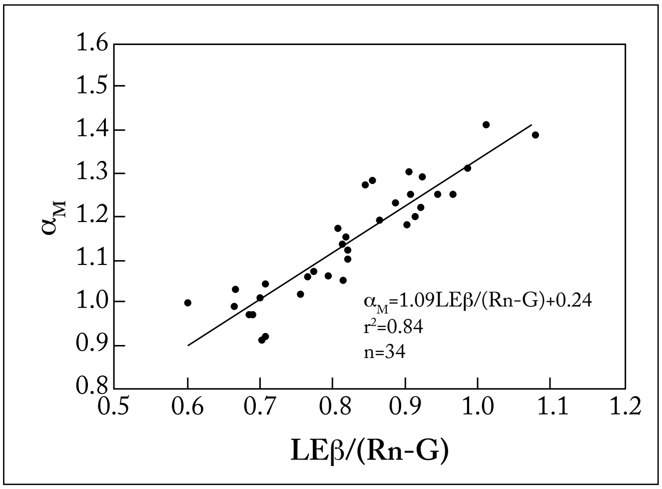

Fig. 7. Relationship between α_M (Priestley-Taylor constant calculated from LEβ) and available energy for evaporation (LEβ/(Rn-G)) in Nueva Roma.

Fig. 7. Constante de Priestley-Taylor, calculada a partir de LEβ, (α_M) en función de la fracción disponible de energía para evaporación (LEβ/(Rn-G)) en la localidad de Nueva Roma (NR).

The values of the evaporative fraction were consistent with those reported by Zhang et al. (2004) for well-irrigated winter wheat and maize canopies when LAI varied from 2.0 to 6.0. For agricultural crops, under low-to-moderate VPD conditions (0<VPD<4KPa), Agam et al. (2010) found that initializing the TSM (thermal-based two-source model) with a α_{PT}=1.30 did not significantly degrade model performance in estimating the latent heat flux. We found the same conditions in our research area.

Maximum rates of evapotranspiration were recorded during the reproductive stages (R5-R6) (Fig. 8). In Nueva Roma, LEβ averaged 4.68 mm/day. In San Adolfo, LE_{PT} averaged 3.87 mm/day. The elevated LE values in Nueva Roma were due to higher precipitation during the season compared with San Adolfo. The Bowen ratio values observed in Nueva Roma ranged from -0.108<β<0.67, β≈0 values were recorded during and after the rain. Negative values occurred in a well-watered canopy due to decrease in the canopy temperature compared with the reference temperature of the air.

According to the soil available water data in full canopies, the crop acts as a source of sensible heat flux. An estimation of canopy temperature could be done by knowing the β values (Orchansky, 1993).

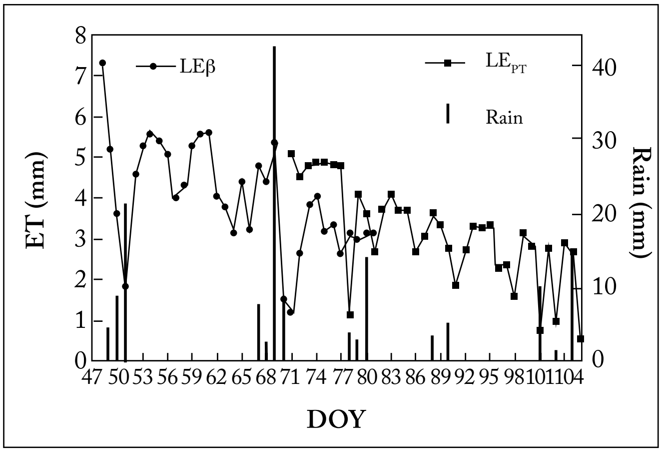

Fig. 8. Soybean evapotranspiration (LE_{PT} y LEβ, mm/day) and rainfall (mm) during R5-R8 reproductive growth stages in San Adolfo (SA) and Nueva Roma (NR) locations, respectively.

Fig. 8. Evapotranspiración del cultivo de soja (LE_{PT} y LEβ, mm/day) y precipitaciones (mm) registradas durante los estadios reproductivos R5-R8, en las localidades de San Adolfo (SA) y Nueva Roma (NR), respectivamente.

The results obtained in this study proved that the Bowen ratio and the Priestley-Taylor equation could be used to estimate actual evapotranspiration over a soybean crop in the semiarid conditions of the southwestern Buenos Aires province, when there is no information available on seasonal patterns of the energy balance components. The estimations of LEβ or LE_{PT} indicated that approximately 90% of available energy was consumed by LE without detecting advective conditions. Moreover, the Bowen ratios were near zero during and after rain events, and these values could estimate the temperature of a full canopy cover.

At both sites Rs_{IN} was approximately 70% of Rn. This value agreed with complete covered canopies under irrigation and the ratio of soil heat flux to net radiation linearly decreased in conjunction with surface albedo, and reached value around 0.1 for a full canopy cover. The components of the energy balance were similar in both years, even when G reached 22% of Rn before and after irrigation due to incomplete soil cover.

This work will help in future irrigation scheduling research and will introduce a soybean crop that will be of special interest to farmers in this semiarid region of Argentina.

REFERENCES

Agam, N., W.P. Kustas & M.C. Anderson (2010). Application of the Priestley-Taylor approach in a two-source surface energy balance model. *Journal of Hydrology* 11: 185-198.

Allen, R.G., L.S. Pereira, T.A. Howell & M.E. Jensen (2011). Evapotranspiration information reporting: I. Factors governing measurement accuracy. *Agricultural Water Management* 98: 899-920.

Blum, A. (2005). Drought resistance, water-use efficiency, and yield potential-are they compatible, dissonant, or mutually exclusive? *Australian Journal of Agricultural Research* 56: 1159-1168.

Bowen, I.S. (1926). The ratio of heat losses by conduction and by evaporation from any water surface. *Physiological Research* 27: 779-787.

Cellier, P. & Y. Brunet (1992). Flux-gradient relationships above tall plant canopies. *Agricultural and Forest Meteorology* 58: 93-117.

Doughty, C.E., C.B. Fied & A.M.S. McMillan (2011). Can crop albedo be increased through the modification of leaf trichomes, and could this cool regional climate? *Climatic Change* 104: 379-387.

Fehr, W.R. & C.E. Caviness (1977). Stages of soybean development. Iowa Agric. Home Econ. Exp. Stn. IOWA Coop. Est. Serv. Epec. 80.

Fisher, J.B., T.A. De Biase, Y. Qi, M. Xu & A.H. Goldstein (2005). Evapotranspiration models compared on a Sierra Nevada forest ecosystem. *Environmental Modelling and Software* 20: 783-796.

Fritschen, L.J. (1967). Net and solar radiation relations over irrigated field crops. *Agricultural Meteorology* 4: 55-62.

Gavin, H. & C.A. Agnew (2004). Modelling actual, reference and equilibrium evaporation from a temperate wet grassland. *Hydrological Processe,* 18: 229-246.

Guan, X., J. Huang, N. Guo, J. Bi & G. Wang (2009). Variability of soil moisture and its relationship with surface albedo and soil thermal parameters over the loess plateau. *Advances in Atmospheric Sciences* 26: 692-700.

Hatfield, J.L., J.H. Prueger & T.J. Sauer (1996). Comparison of evapotranspiration equations over different surfaces. Proceedings of the International ASAE Evapotranspiration and Irrigation Scheduling Conference. San Antonio, Texas USA, pp. 1065-1070.

Hernández-Ramírez, G., J.L. Hatfield, J.H. Prueger & T.J. Sauer (2009). Energy balance and turbulent flux partitioning in a corn-soybean rotation in the Midwestern US. *Theoretical and Applied Climatology* 100: 79-92.

Hollinger, D.Y., S.V. Ollinger, A.D. Richardson, T.P. Meyers, D.B. Dail, M.E. Martin, N.A. Scott, T.J. Arkebauer, D.D. Baldocchi, K.L. Clark, P.S. Curtis, K.J. Davis, A.R. Desai, D. Dragoni, M.L. Goulden, L. Gu, G.G. Katul, S.G. Pallardy, K.T. Paw U, H. Schmid, P.C. Stoy, A.E. Suyker & S.B. Verma (2010). Albedo estimates for land surface models and support for a new paradigm based on foliage nitrogen concentration. *Global Change Biology* 16: 696-710.

Kaminsky, K.Z. & R. Dubayah (1997). Estimation of surface net radiation in the boreal forest and northern prairie from shortwave flux measurements. *Journal of Geophysical Research* 102: 707-716.

Kosugi, Y., S. Takanashi, H. Tanaka, S. Ohkubo, M. Tani, M. Yano & T. Katayama (2007). Evapotranspiration over a Japanese cypress forest. I. Eddy covariance fluxes and surface conductance characteristics for 3 years. *Journal of Hydrology* 337: 269-283.

Kustas, W.P., C.S.T. Daughtry & P.J. Van Oevelen (1993). Analytical treatment of the relationships between soil heat flux/net radiation ratio and vegetation indices. *Remote Sensing Environment* 46: 319-330.

McAneney, K.J. & B. Itier (1996). Operational limits to the Priestley-Taylor formula. *Irrigation Science* 17: 37-43.

Monteith, J.L. (1973). Principles of Environmental Physics. American Elsevier Publishing Company Inc. New York, 241 p.

Ogee, J., E. Lamaud, Y. Brunet, P. Berbigier & J.M. Bonnefond (2001). A long-term study of soil heat flux under a forest canopy. *Agricultural and Forest Meteorology* 106: 173-186.

Orchansky, A.L. (1993). El microclima de un cultivo ralo bajo condiciones de riego: Balance energético, Transpiración y Evaporación. Tesis Doctorado en Cs. Agrarias. Universidad Nacional del Sur.

Pauwels, V.R.N. & R. Samson (2006). Comparison of different methods to measure and model actual evapotranspiration rates for a wet sloping grassland. *Agricultural Water Management* 82: 1-24.

Pereira, A.R. (2004). The Priestley-Taylor parameter and the decoupling factor for estimating reference evapotranspiration. *Agricultural and Forest Meteorology* 125(3-4): 305-313.

Priestley, C.H.B. & R.J. Taylor (1972). On the assessment of surface heat flux and evaporation rates measured by the energy balance method. *Agricultural Meteorology* 11: 261-267.

Ramírez, L., J.C. Porstmann & G. López (2008). La expansión de la frontera agrícola argentina. 2º Congreso Regional de Economía Agraria, 2º Congreso Rioplatense de Economía Agraria. XXXIX Reunión Anual AAEA.

Rana, G. & N. Katerji (2000). Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: a review. *European Journal of Agronomy* 13: 125-153.

Sánchez, R., N. Pezzola & J. Cepeda (1998). Caracterización edafoclimática del area de influencia del INTA. EEA Hilario Ascasubi. Boletín de Divulgación 18. INTA, Buenos Aires.

Santanello Jr., J.A. & M.A. Friedl. (2003). Diurnal covariation in soil heat flux and net radiation. *Journal of Applied Meteorology* 42: 851-862.

Sauer, T.J., J.W. Singer, J.H. Prueger, T.M. Desutter & J.L. Hatfield (2007). Radiation balance and evaporation partitioning in a narrow-row soybean canopy. *Agricultural and Forest Meteorology* 145: 206-214.

Saylan, L. (2000). The effects of the environmental factors on the evapotranspiration in different growth phases of soybean. *Australian Journal of Agricultural Research* 51: 127-134.

Serban, G., D.T. Cotfas & P.A. Cortas (2011). Significant differences in crop albedo among Romanian winter wheat cultivars. *Romanian Agricultural Research* 28: 11-15.

Stannard, D.I. (1993). Comparison of Penman-Monteith, Shuttleworth-Wallace, and Modified Priestley-Taylor Evapotranspiration Models for wildland vegetation in semiarid rangeland. *Water Resources Research* 29: 1379-1392.

Steduto, P. & T. Hsiao (1998 a). Maize canopies under two soil water regimes II. Seasonal trends of evapotranspiration, carbon dioxide assimilation and canopy conductance, and as related to leaf area index. *Agriculture and Forest Meteorology* 89: 185-200.

Steduto, P. & T. Hsiao (1998 b). Maize canopies under two soil water regimes III. Variation in coupling with the atmosphere and the role of leaf area index. *Agriculture and Forest Meteorology* 89: 201-213.

Sumner, D.M. & J. Jacobs (2005). Utility of Penman-Monteith, Priestley-Taylor, reference evapotranspiration, and pan evaporation methods to estimate pasture evapotranspiration. *Journal of Hydrology* 308: 81-104.

Ünlü, M., R. Kanber & B. Kapur. (2010). Comparison of soybean evapotranspiration measured by weighing lysimeter and Bowen ratio-energy balance methods. *African Journal of Biotechnology* 9: 4700-4713.

Ventura, F., D. Spado, P. Duce P. & R.L. Snyder (1999). An evaluation of common evapotranspiration equations. *Irrigation Science* 18: 163-170.

Zhang, Y., C. Liu, Q. Yu, Y. Shen, E. Kendy, A. Kondoh, C. Tang & H. Sun (2004). Energy fluxes and the Priestley-Taylor parameter over winter wheat and maize in the North China Plain. *Hydrological Processes* 18: 2235-2246.