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Actual evapotranspiration and the pattern of soil water extraction of a soybean (*Glycine max*) crop

Evapotranspiración real y patrones de extracción de agua del suelo de un cultivo de soja (*Glycine max*)

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Abstract

Crop evapotranspiration knowledge during different phenological stages helps determine crop water requirements and water use efficiency. This study was intended to estimate evapotranspiration of soybean grown under field conditions using the water balance equation and to characterize root water extraction across different soil layers analyzing daily values of its availability. In order to estimate the crop daily water consumption, temporal and spatial variability (vertical) of soil water content up to a depth of 1.10 m was investigated. At the beginning of the experiment, measurements showed that the soybean crop extracted water from the upper levels, and as it continued to grow, water uptake at deeper levels increased. The highest water uptake occurred during reproductive growth stages, which matched the period of highest atmospheric demand. The crop showed a better response to atmospheric demand under water availability, whereas under stress conditions, both evapotranspiration and soil water content decreased.

Keywords
soil water balance • rainfed • Argentina • water stress • water uptake • soybean

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Resumen

Conocer la evapotranspiración de un cultivo durante sus distintos estadios fenológicos ayuda a determinar los requerimientos de agua del mismo y la eficiencia del uso de agua. Los objetivos de este trabajo fueron estimar la evapotranspiración de un cultivo de soja desarrollado bajo condiciones de campo, utilizando la ecuación de balance hídrico, y caracterizar la extracción de agua por parte de las raíces en las distintas capas del suelo, analizando los valores diarios de su disponibilidad. Para determinar los consumos diarios del cultivo se estudió la variabilidad temporal y vertical del contenido de agua en el suelo hasta 1.10 m de profundidad. Al comienzo de las mediciones, el cultivo de soja extrajo agua de los niveles superiores, y a medida que se desarrollaba, aumentó el consumo en niveles más profundos. El mayor consumo de las plantas se dio en los estadios reproductivos, coincidiendo con el período de mayor demanda atmosférica. El cultivo mostró una mejor respuesta a la demanda atmosférica bajo la disponibilidad de agua, mientras que, en condiciones de estrés, tanto la evapotranspiración como el contenido de agua en el suelo disminuyeron.

Palabras clave
balance de agua en el suelo • secano • Argentina • estrés hídrico • consumo de agua • soja

Introduction

The high growth rates of global population demand a substantial increase of food production. Soybean is one of the most important crops in terms of production, worldwide trade and harvested area (35). Argentine soybean harvested area has grown at an average rate of 7.3 x 10^5 ha/year from 1997 to 2016 which leads to 1.95 x 10^7 ha and 5.88 x 10^7 t in 2016 (21). The increased demand of agricultural food production requires a clever analysis of water needs over the crop cycle to ensure its maximum efficiency (36). Significant importance has been given to studies on evapotranspiration at different phenological stages, particularly in critical periods of yield determination (3, 15, 20, 46). These researches allow quantifying, under different management conditions, the amount of crop irrigation water needed to achieve optimal growth or the expected yield loss (10, 29).

Soil water balance is a method used for the estimation of actual evapotranspiration (ET_a) which considers the water balance within the soil depth explored by plant roots, and analyzes only the vertical components of water movements (26). Though this is not the method recommended by FAO (2006) for evapotranspiration estimation, it has virtually no restrictions for use. Besides, it facilitates decision-making on water management, since production in Argentina is mostly under rainfed agricultural systems (34). The use of this methodology requires rainfall and soil moisture measurements at appropriate scales in space and time. Soil moisture, the most difficult of both variables to measure, is critical for the evolution of meteorological variables, as its controls the water and energy exchanged by a surface with the atmosphere (23, 26).

The study on soil water extraction patterns (*WEP*) is used to obtain information about the spatial and temporal plant water consumption variability. Plant water uptake is affected by soil texture and vertical root distribution (5, 43). However, these authors (32) consider learning of *WEPs* is more useful than observing root density. Some researches focuses on the vertical distribution of water extraction in the soil profile (2, 5, 11), while others analyze temporal rate of water extraction (7, 14, 31, 38, 43).

Most water-extraction studies were performed in experimental plots or in the laboratory in controlled environments (39), which can hardly represent real field conditions. There is a gap between actual yields obtained by growers and the potential yield of the best-adapted crop varieties, under good management conditions and in absence of biotic and abiotic stresses (24). It is therefore important to record in productive plots the evolution of variables that are usually measured in controlled experiments, considering that their behavior should not change. Therefore, the objectives of this research are: (a) to learn of the daily ET_a in a field soybean plot, its variability compared to crop evapotranspiration under standard conditions, and its correlation to other meteorological variables, and (b) to study *WEPs* in order to investigate the relative contribution to ET_a of each soil layer.

MATERIALS AND METHODS

Sampling site and data collection

The study was carried out in the Unidad Integrada Balcarce [Unidad Integrada Balcarce] (UIB, Facultad de Ciencias Agrarias de la Universidad Nacional de Mar del Plata - Estación Experimental Agropecuaria Balcarce del Instituto Nacional de Tecnología Agropecuaria), located in the southeast of the Province of Buenos Aires. (37°45' S; 58°18' W), Argentina. The meteorological and edaphic variables need to estimate crop evapotranspiration were measured in a 19-ha soybean plot during the 2012-2013 summer season. The soil is classified as a typical Argiudoll, with a loamy clayey texture up to 0.30 m depth and between 0.80 to 1.10 m, and clayey between 0.30 and 0.80 m depth (41). The land has a slope of 1:50 oriented NE to SW. A caliche layer was found at 1.00 m to 1.20 m depth and the water table was considered to be beneath that level. The soybean variety used was DM 3810, Maturity Group III with indeterminate growth habit. The crop was sown on November 21, 2012, and emergence occurred on December 1. The crop was grown under rainfed conditions. Soy growing stages were identified on a weekly basis following phenological scale from these authors (22), the evolution of which is shown in table 1 (page 128).

The information used in this study included daily precipitation records and reference crop evapotranspiration (ET_0) estimated for the 2013 January-March period at the INTA-Balcarce Estación Experimental, located about 1 km away from the experimental site.

A database resulting from soil water content (*SWC*) readings measured with an array of Sentek EnviroSCAN capacitive sensors (Sentek Sensor Technologies, Stepney, Australia), and a Troxler neutron probe Model 4300 Depth Moisture Gauge (Troxler Electronics Laboratories Inc., Research Triangle Park, USA) was previously presented (12).

Table 1. Soybean Phenological Stages (21). Most significant events and dates are shown.

Tabla 1. Estadios fenológicos de soja (21). Se indican los eventos más significativos y las fechas de ocurrencia respectivas.

Phenological stage	**Description**	**Date**
	Sowing	November 21
VE	Emergence	December 1
V3	Third-node	January 7
R1 - V8	Beginning bloom	January 25
R3 - V12	Beginning pod	February 5
R5 - V15	Beginning seed	February 22
R7	Full maturity	April 6

The vertical spatial resolution of the database was a depth range of 0.01 m to 1.10 m and the temporal resolution was 15 minutes. The study period started on January 6 and ended on March 15, 2013 (69 days, phenological stages V3 to R5, table 1).

Methodology

Water balance within a soil thickness in a time interval Δt is expressed as Hiilel (1998):

$$\boldsymbol{SWC_t = SWC_{t-\Delta t} + PP_t - ET_t - Per_t - R_t} \qquad (1)$$

where:

SWC_t and $SWC_{t-\Delta t}$ = the soil water content measured at time points t and $t-\Delta t$, respectively

PP_t = precipitation

ET_t = evapotranspiration

Per_t = deep percolation

R_t = surface runoff, all of them for time t

Soil water content, precipitation, percolation and runoff measurements can be used to estimate soil water loss to the atmosphere by evapotranspiration, clearing this variable from Equation (1) and integrating at successive time intervals. Equation (1) could include other terms, which were not considered in this work such as irrigation, horizontal flow of water in soil and water movement from water table through capillary rise due to the fact that the crop grows under rainfed conditions, and the contributions of water horizontal fluxes and capillarity are neglegible.

For the estimation of *SWC,* high-resolution humidity profiles interpolated at 12:00 UTC (9:00 local time) were selected to coincide with the time at which precipitation was measured. This data was considered day-representative. A 24 h time interval (Δt) was used. Estimation of *SWC* for the soil profile ([0;1.1m]) was done by numerical integration of soil moisture profiles using the trapezoidal rule and expressing the result as water depth units (mm). Using the same methodology, the field capacity *(FC)* and permanent wilting point *(PWP)* values from this author (6) were integrated for the soil profile to estimate the available water *(AW)* (13).

In order to characterize soil water variability across different layers, four regular partitions were taken from the profile: 0-0.275, 0.275-0.55, 0.55-0.825 and 0.825-1.10 m. Partitions do not match with the soil stratigraphy (12). Soil water content (SWC_k) and soil water availability (AW_k) series for each layer were obtained using the same method as for the entire profile with the information in table 2 (page 130). Decline in SWC_k was used to detect plant water uptake while increases were associated to water inflow. These values were integrated on a daily basis and for the V3-V8, R1-R2 and R3-R4 crop growth periods (table 1, page 128). Additionally, the percentage share contributed by each layer to the total water consumption, previously defined as *WEP*, was estimated. Also, average daily consumption was assessed for each individual level at the phenological periods mentioned before.

For the estimation of ET_a, Equation 1, (page 128), was solved for the total soil profile considering the *SWC* value integrated up to 1.10 m ($SWC_{0\text{-}1.10\ m}$). No estimations of surface runoff were done. Deep percolation and capillary rise from the water table were neglected due to their low incidence in the soil water balance. On days with precipitation, evapotranspiration was not estimated since temporal scales of processes represented by each term of Equation 1 (page 128), are different (37). The days in which an increase in $SWC_{0\text{-}1.10\ m}$ was found without previous rainfall record were also excluded.

A regression analysis between ET_a, crop evapotranspiration under standard conditions (ET_c) and $SWC_{0\text{-}1.10}$ was carried out in order to characterize the dominant drivers of actual evapotranspiration. Crop evapotranspiration under standard conditions was estimated as $ET_c = K_c\ ET_0$, where K_c is the crop coefficient (1). K_c values were obtained using the empirical equation developed by these authors (17) for soybean grown in Balcarce:

Water stress was studied for those cases where ET_a resulted lower than ET_c.

The Mann-Whitney U Test (9) was used to determine whether the crop was under water stress and to identify periods where plants suffered stress. *SWC* - ET_a/ET_c pairs were ordered by increasing magnitude of *SWC.* By using increasing *SWC* thresholds, the data set was divided into two groups that were sequentially tested to find the threshold value that best represented the difference between the two groups.

RESULTS AND DISCUSSION

Soil water content

Measurements showed from the beginning a decreasing $SWC_{0\text{-}1.10\ m}$ (figure 1a, page 130), with occasional increases associated to precipitation events. At the early stages of senescence, this general decreasing trend reverted as a result of the gradual decrease of crop water uptake and the occurrence of long-duration precipitation events. The soil water content measured up to 1.10m depth was always higher than *PWP,* which was estimated at 206 mm.

At the beginning of the study period (January 6 through 25), $SWC_{0\text{-}1.10\ m}$ was above field capacity (369 mm; figure 1a, page 130). Its distribution in the profile showed that the largest soil water storage occurred at the 0.275 - 0.825 m depth range ($SWC_{0.275\text{-}0.55\ m}$ and $SWC_{0.55\text{-}0.825\ m}$, figure 2a, page 131 and table 2, page 130) reaching in some cases more than 100% AW_k for both levels (figure 2b, page 131) and for the entire profile ($AW_{0\text{-}1.10\ m}$; figure 1b, page 130).

$$Kc = 2.30\ x10^{-8}(DAE)^4 - 7.29x10^{-6}(DAE)^3 + 5.62\ x\ 10^{-4}(DAE)^2 + 4.93x10^{-5}(DAE) + 0.32 \quad (2)$$

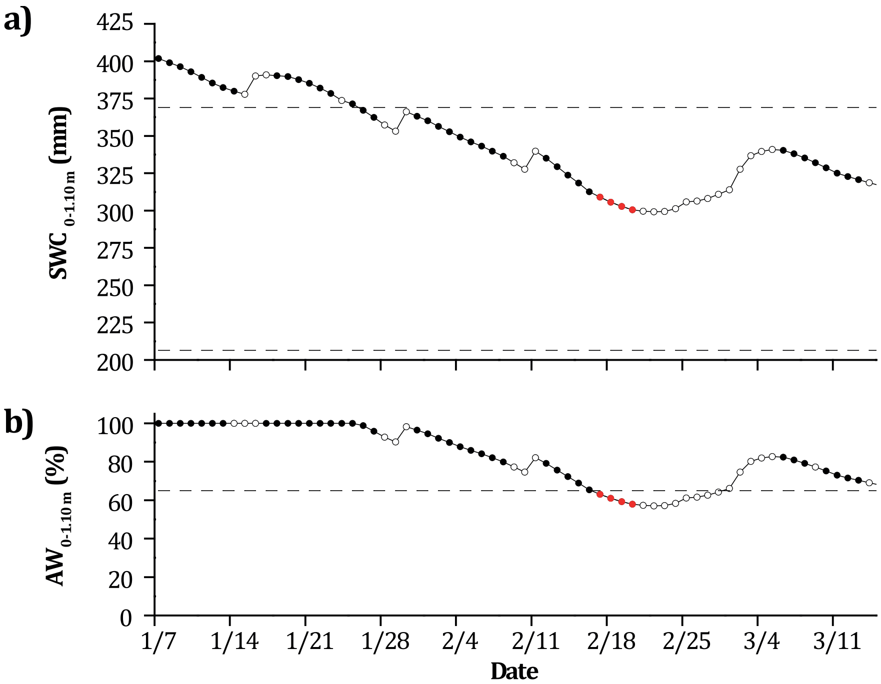
where:

DAE = days after emergence

Table 2. Field Capacity (FC_k), Permanent Wilting Point (PWP_k) and Saturation Point (SAT_k) expressed as depth of water (mm) for Balcarce at different soil depths (6, 39). Variables are expressed in average values for the defined layers.

Tabla 2. Capacidad de campo (CC_k), punto de marchitez permanente (PMP_k) y punto de saturación (SAT_k) expresados como lámina de agua (mm) para la localidad de Balcarce a distintas profundidades (6, 39). Los valores de las variables son promedios para las capas definidas.

Soil depth (m)	PWP_K	FC_k	SAT_k
0 - 0.275	41.3	94.9	145.6
0.275 - 0.55	56.0	102.0	162.3
0.55 - 0.825	57.6	95.6	169.0
0.825 - 1.10	52.3	77.0	143.0

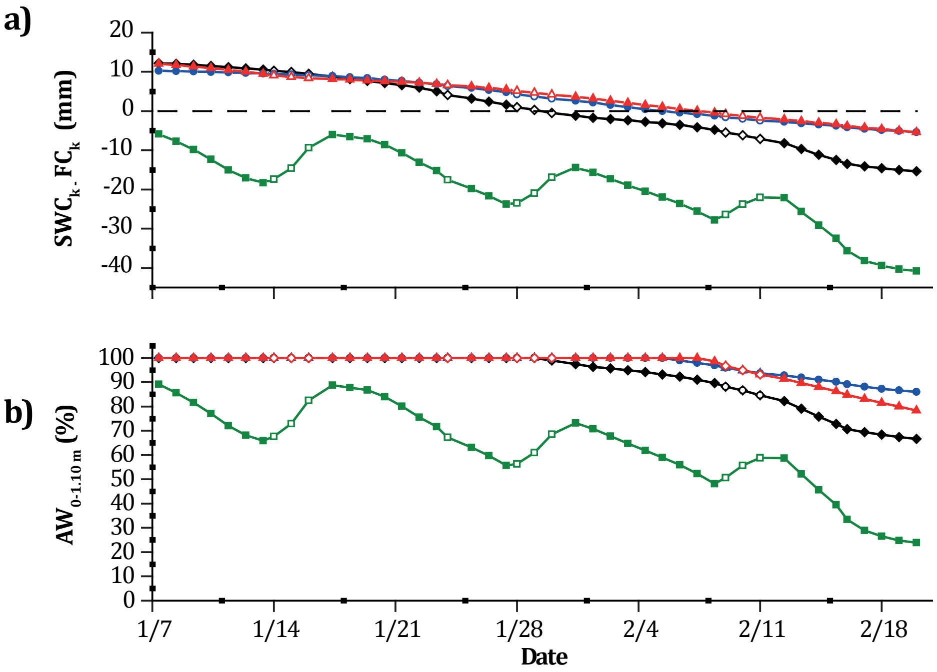


The dotted lines in (a) represent the field capacity (*FC*) and permanent wilting point (*PWP*) values. The dotted line in (b) indicates the $AW_{0\text{-}1.10m}$ threshold for plant stress (65% $AW_{0\text{-}1.10\ m}$); red icons show cases in that condition. The empty icons indicate the days not considered for the estimation of evapotranspiration (ET_a), where precipitations or an increase in the daily soil water storage occurred.

Las líneas punteadas en (a) representan los valores de capacidad de campo (*CC*) y punto de marchitez permanente (*PMP*). Los íconos rojos y la línea punteada en (b) indican el valor a partir del cual la humedad del suelo se encuentra en condiciones de estrés (65% $AU_{0\text{-}1,10\ m}$). Los íconos vacíos indican los días que no se consideraron para las estimaciones de evapotranspiración (ET_r), por ser días con precipitación o con aumento del almacenaje diario de agua en el suelo.

Figure 1. Water Content Evolution ($SWC_{0\text{-}1.10\ m}$; a) and soil water availability ($AW_{0\text{-}1.10\ m}$; b), integrated for each date in the entire soil profile.

Figura 1. Evolución del contenido de agua ($CAS_{0\text{-}1,10\ m}$; a) y porcentaje de agua útil ($AU_{0\text{-}1,10\ m}$; b), integrado para cada fecha en el total del perfil del suelo.



The empty icons indicate the days not considered for the estimation of evapotranspiration (ET_a), where precipitations or an increase in the daily soil water storage occurred.

Los íconos vacíos indican los días que no se consideraron para las estimaciones de evapotranspiración (ET_r), por ser días con precipitación o con aumento del almacenaje diario de agua en el suelo.

Figure 2. Difference between the soil water content and the field capacity value (SWC_k- FC_k; a) and soil water availability (AW_k; b) for the 0-0.275 (green squares), 0.275-0.55 (black diamonds), 0.55-0.825 (blue circles) and 0.825-1.10 m (red triangles) layers.

Figura 2. Diferencia entre el contenido de agua en el suelo y el valor de capacidad de campo (CAS_k- CC_k; a) y del porcentaje de agua útil (AU_k; b) para los estratos de 0-0,275 (cuadrados verdes), 0,275-0,55 (rombos negros), 0,55-0,825 (círculos azules) y 0,825-1,10 m (triángulos rojos).

A number of edaphic, biological and meteorological factors can explain this behavior. In the first place, precipitation in December was 239.9 mm, which included heavy rainfall events on December 19 and 24 (77 mm and 88 mm, respectively).

In addition, precipitation recorded on January 1 and 5 was 26.5 mm and 20 mm, respectively. Secondly, there is an assumption of shallow rooting during the heavy precipitation period (31, 43) because crop emergence occurred in the early days of December.

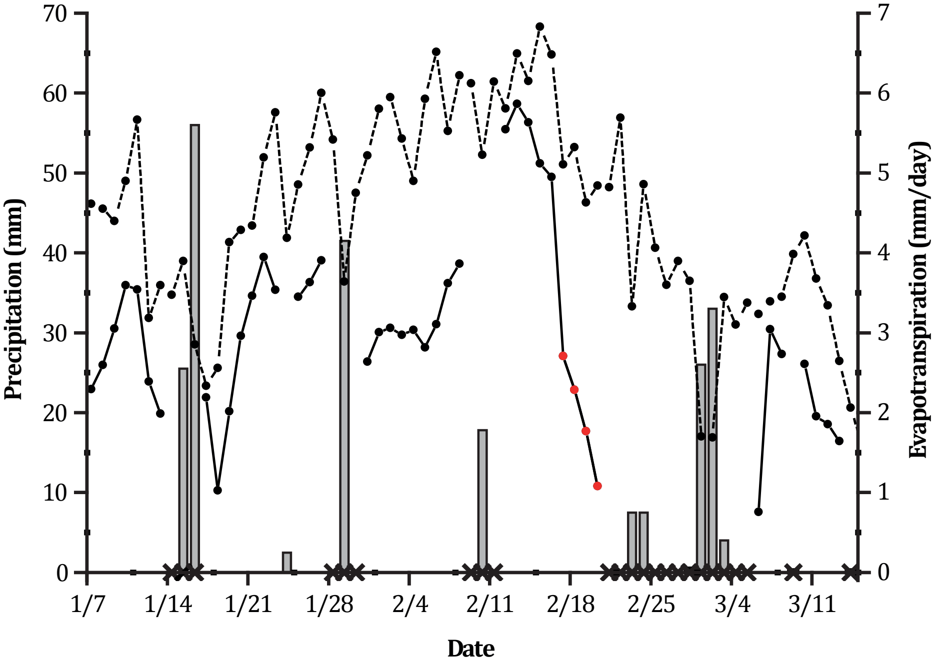
Lastly, the presence of clay in the intermediate soil layers (41) and caliche in the lower levels may have slowed down water movement and reduced percolation to deeper levels. These factors could prevent precipitation from rapidly flowing out of the system by percolation or evapotranspiration.

Actual Evapotranspiration

ET_a increased gradually to reach a maximum value between February 12 and 15, and then decreased (figure 3, page 133). The highest estimated value was 5.9 mm/day on February 13. The highest ET_c value recorded for soybean was 6.8 mm/day on February 15 (77 DAE). This result is similar to that obtained by these authors: Della Maggiora *et al.* (2000), for a soybean crop in Balcarce of approximately 7 mm/day 70 DAE. The mean and median ET_a values for the complete period were both at 3.0 mm/day, with a standard deviation of 1.2 mm/day and an interquartile range of 1.3 mm/day.

ET_a was always lower than *ETc*, even during the periods when $AW_{0\text{-}1.10m}$ was 100%, which suggests that there has been another factor limiting evapotranspiration other than water availability. The dry biomass value for the V3/V4 stage was 308 kg/ha, with a row spacing of 0.38 m and a plant density of 383000 plants/ha. For a soybean crop, at the same development stage and in the same region, under controlled water conditions and without limitations, Della Maggiora *et al.* (2006), obtained 324 kg/ha with a row spacing of 0.70 m and plant densities between 240000 and 309000 plants/ha. But Andriani *et al.* (1991) found values above 500 kg/ha in rainfed conditions with a row spacing of 0.70 m and plant densities between 270000 y 330000 plants/ha. This information confirmed that the crop growth rate declined during the growing season. It failed to achieve complete coverage thus limiting the evapotranspiration.

The results for the different phenological stages show that the $SWC_{0\text{-}1.10m}$ value decreased to a rate of about 5.5 mm/day until February 21 (figure 1a, page 130), whereas ET_a and ET_c increased until February 13 and 15, respectively. Until then, the crop developed from the V3 stage up to pod formation at R3, passing through the flowering stage (table 1, page 128). As already mentioned, the high water requirements of plants at these stages plus the increased atmospheric demand (table 3, page 134) contributed to a higher evapotranspiration causing therefore a reduction in soil water content. Grain filling at R5 started on February 22. At this stage, plants start to translocate nutrients to the pods in formation (40) and senescence starts. As of this moment, ET_a and ET_c started to decrease (figure 3, page 133), and as a result of the 63 mm rainfall between February 25 and March 7, $SWC_{0\text{-}1.10m}$ increased (figure 1, page 130). ET_a values obtained from Equation 1 (page 128), showed a better correlation with ET_c (r^2=0.62, p<0.01; figure 4a, page 135) than with ET_0 (r^2=0.43, p<0.01).



Crosses indicate the days not considered for the estimation of evapotranspiration (ETa), where precipitations or an increase in the daily soil water storage occurred. Red dots indicate the cases where soil water availability in the 0 - 1.10 m ($AW_{0\text{-}1.10\ m}$) profile was below 65%.

Las cruces indican los días que no se consideraron para las estimaciones de ET_r por ser días con precipitación o con aumento del almacenaje diario de agua en el suelo. Los puntos rojos indican los casos en los que el agua útil en el perfil 0 - 1,10 m ($AU_{0\text{-}1,10\ m}$) fue inferior a 65%.

Figure 3. Soybean crop evapotranspiration under standard conditions (ET_c, dotted line), actual evapotranspiration (ET_a, solid line) and precipitation (grey bars).

Figura 3. Evapotranspiración de un cultivo de soja bajo condiciones estándar (*ETM*, línea punteada), evapotranspiración real (ET_r, línea llena) y precipitación (barras grises).

Table 3. Actual Crop Evapotranspiration (ET_a), Reference Crop Evapotranspiration (ET_0) and soybean crop evapotranspiration under standard conditions (ET_c), average (mm/day) and accumulated (mm) for Balcarce, for each phenological period.

Tabla 3. Evapotranspiración real del cultivo (ET_r), evapotranspiración de cultivo de referencia (ET_0) y evapotranspiración para un cultivo de soja bajo condiciones estándar (ETM) promedio (mm/día) y acumulada (mm) para la localidad de Balcarce, para cada período fenológico.

	Phenological stage		
	V3-V8	**R1-R2**	**R3-R4**
ET_a (mm)	59.6	28.5	60.6
ET_0 (mm)	82.0	53.2	86.7
ET_c (mm)	68.9	54.6	96.9
ET_a (mm/day)	3.3	2.6	3.8
ET_0 (mm/day)	4.6	4.8	5.1
ET_C (mm/day)	3.8	5.0	5.7

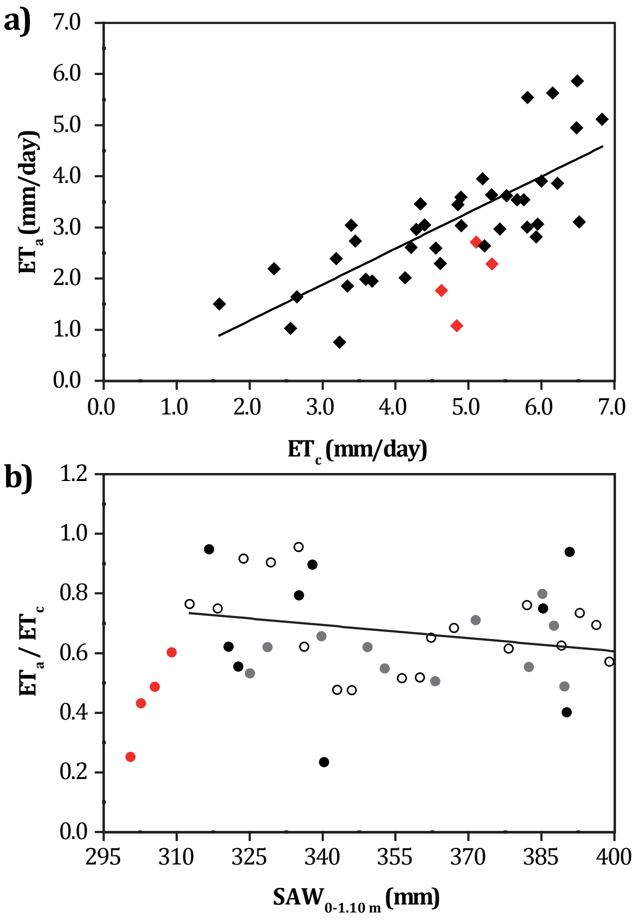
This is an indication that the K_c coefficient, which summarizes the evolution of crop characteristics, had a significant impact on the results.

Mechanisms controlling the relationship between evapotranspiration and water availability in the soybean crop can be diverse. The most important one is associated with the stomatal regulation, controlled by hormone signals coming from the roots and by leaf turgor loss (11, 30, 45).

Some authors suggest an effect resulting from the reduction of soil hydraulic conductivity associated to drying, particularly in clayey soils with high impedance to water flow (19, 38, 39). An additional difficulty for water extraction in this type of soils is associated to root clumping (14). It has also been suggested that there is another effect associated to root contraction caused by drying, which increases the resistance to water flow in the soil-root interface (44).

In association to these mechanisms, the behavior usually found in some evapotranspiration and soil moisture variables is a process regulated by a limiting factor (8, 27, 33, 42). However, in other studies (7, 14, 19) there is no clear evidence of this kind of response.

According to the proposed method, the threshold value established for water stress of $SWC_{0\text{-}1.10\ m}$= 312 mm was used to identify groups with $p < 0.01$. This threshold value correlates to an approximate $AW_{0\text{-}1.10\ m}$ value of 65%, and a mean matric potential for the soil moisture profile of -1.4 MPa, as per retention curves from these authors (18). The data set for water stress included findings of four consecutive days (February 17-20, around R4 stage), during which $SWC_{0\text{-}1.10m}$ and ET_a/ET_c decreased simultaneously (red dots in figure 1 (page 130), figure 3 (page 133) and figure 4b (page 135).



Red icons indicate the cases where soil water availability in the 0 - 1.10 m (AU0-1.10 m) profile was below 65%. These were not included in the estimation of linear regressions shown. Black, grey and empty dots show first, second and third tercile for the reference crop evapotranspiration (ET_0).

Los íconos rojos indican los casos en los que el agua útil en el perfil 0-1,10 m fue inferior a 65% ($AU_{0\text{-}1,10\ m}$). Esos casos no fueron incluidos en las estimaciones de las regresiones lineales mostradas. Los puntos negros, grises y vacíos indican pertenencia al primer, segundo y tercer tercil de la evapotranspiración de cultivo de referencia (ET_0).

Figure 4. Actual Evapotranspiration (ET_a) as a function of soybean crop evapotranspiration under standard conditions (ET_c) (mm/day; a) with its linear least squares adjustment ($ET_a = 0.70\ ET_c - 0.23\ mm$, $r^2 = 0.62$, $p < 0.01$). ET_a / ET_c, ratio as a function of soil water content for the 0-1.10 m soil thickness ($SWC_{0\text{-}1.10\ m}$, mm; b) with its linear regression ($ET_a/ET_c = -0.001\ mm^{-1}\ SWC_{0\text{-}1.10\ m} + 1.19$, $r^2 = 0.07$, $p > 0.16$).

Figura 4. Evapotranspiración real (ET_r) en función de la evapotranspiración de un cultivo de soja bajo condiciones estándar (ETM) (mm/día; a) con su respectivo ajuste lineal por cuadrados mínimos ($ET_r = 0,70\ ETM - 0,23\ mm$, $r^2 = 0,62$, $p < 0,01$). Cociente entre ET_r y ETM, en función del contenido de agua en el suelo para el espesor de suelo 0-1,10 m ($CAS_{0\text{-}1,10\ m}$, mm; b) con su respectiva regresión lineal ($ET_r/ETM = -0,001\ mm^{-1}\ CAS_{0\text{-}1,10\ m} + 1,19$, $r^2 = 0,07$, $p > 0,16$).

Functional dependence was not studied in this case because there were not enough available data. Other authors found similar behaviors. These authors (8) detected reduced evapotranspiration in soybean with *AW* values below 48% to 36%, while these others (33) found similar results but only with AW values below 25%. These authors (27) found a decrease in evapotranspiration for pre-dawn plant water potential values of -0.33 MPa. A study aimed at modelling water deficit in Balcarce (15) used *AW* thresholds of 60% for the three decades (10-day periods) of flowering, and 40% for the rest of the cycle. These authors (14) established an *AW* threshold of 62%, and a pre-dawn water potential of -1.4 MPa for the same location, with results similar to those obtained in this study.

However, the different methods used to define *FC*, *PWP* (42), the differences found between different types of soils and evapotranspiration references used in the different studies make comparison of results difficult.

Under no-stress conditions (black, grey and empty dots in figure 4b (page 135), E_a/ET_c showed no significant dependence on $SWC_{0\text{-}1.10\ m}$, and presented high variability (a median of 0.62, interquartile range of 0.22). These authors (7, 45) found a relative reduction in ET_a under potential and high demand conditions, while these others (19) did not find a similar response. Results seem to indicate that the atmospheric demand had no impact on the E_a/ET_c ratio, as represented by the distribution of black, grey and empty dots (terciles of ET_0) in figure 4b, page 135.

Other possible sources of evapotranspiration variability that have not been analyzed can be water balance components not considered in this study, such as surface or subsurface runoff (associated to land slope), deep percolation and ponding. In this regard, an increased $SWC_{0\text{-}1.10\ m}$ was found in days without precipitation (a total of 12 days between January 7 and March 15, with a median increase value of 1.4 mm and interquartile range of 1.4 mm), which could be associated to ponding or horizontal water movement phenomena. These were not taken into account for ET_a estimations.

Water Extraction Patterns (WEP)

Considering the net consumption per level over the different phenological stages, the upper layer (0-0.275 m) is where the crop met most of its water needs (figure 5a, page 137).

The third and fourth layer contributed alternately with smaller amounts of water at different crop phenological stages: 0.55-0.825 m at V3-V8 and R3-R4, and 0.825-1.10 m at R1-R2. It was also found that the vertical profile of water consumption (%) for the vegetative phases was less homogeneous (highest consumption in the first stage), while water uptake was more equally distributed among layers during R1-R2. This might be an indication that, as there is less root development at the beginning of stage V, the crop restricted water extraction to upper levels.

Then, with an increased root development at R1-R2, and with less water content in the surface layer, the relative contribution of deeper layers increased.

At R3-R4, water consumption by the crop increased as a result of a higher atmospheric demand (table 3, page 134) and because the crop was passing through phenological stages in which there is a high demand of water (16). Water use values for this stage were the highest of the three stages under study (figure 5b, page 137).

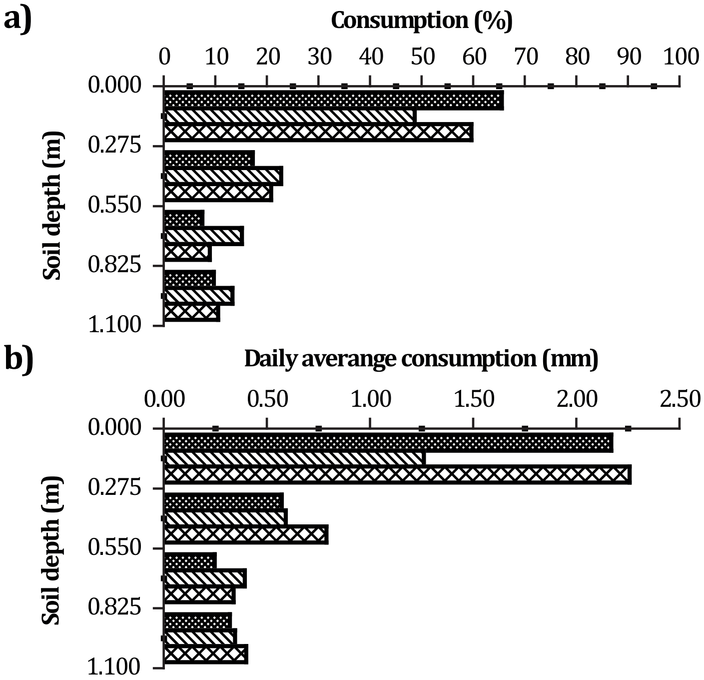


Figure 5. (a) Individual layer share of total water consumption (%) and (b) daily average consumption (mm) in each layer, for V3-V8 (dense grid pattern), R1-R2 (striped pattern) and R3-R4 (spaced grid pattern) phenological periods.

Figura 5. (a) Contribución de cada capa al consumo total de agua (%) y (b) consumo medio diario (mm) de cada capa, para los períodos fenológicos V3-V8 (patrón cuadriculado denso), R1-R2 (patrón a rayas) y R3-R4 (patrón cuadriculado espaciado).

However, consumption percentage increases again in the upper soil level (figure 5a, page 137). As the top soil layer is recharged (figure 4, page 135; 10/2), roots will take up water again from that layer regardless of the moisture in deeper levels (28). Vertical distribution of *WEP* values were in general similar to those found by these authors (25) for the two-year trial on soybean under irrigation in the same location, where most of the water supply came from the upper soil layer.

The water stress event occurred at the end of R3-R4. It consisted in a reduction of water storage, which was reflected in a lower AW_k value even in the two deepest levels (figure 2, page 131), which can be associated to a dominant effect of water extraction by plants (43).

From February 17 to 20, the crop gradually extracted a higher volume of water from deeper soil layers (figure 6), as moisture decreased in the surface layer.

Other authors (2, 4, 11) also reported that higher water extraction records moved to deeper soil levels, as moisture decreased in upper layers.

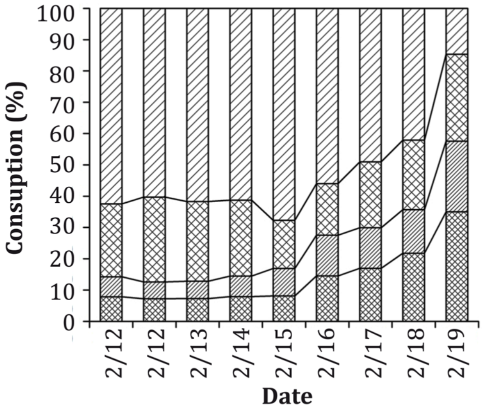


Figure 6. Individual layer share of total water consumption (%) 0-0.275 (spaced striped pattern), 0.275-0.55 (spaced grid pattern), 0.55-0.825 (dense striped pattern) and 0.825-1.10 m (dense grid pattern) strata, for February 12 to 20, which includes the water stress period.

Figura 6. Contribución de cada capa al consumo total de agua (%) para los estratos de 0-0,275 (patrón rayado espaciado), 0,275-0,55 (patrón cuadriculado espaciado), 0,55-0,825 (patrón rayado denso) y 0,825-1,10 m (patrón cuadriculado denso), para los días 12 al 20/2, que incluyen el período en que el cultivo de soja sufrió estrés hídrico.

CONCLUSIONS

This research work studied the ET_a and *WEP* in a soybean crop grown in the productive area of Balcarce, Buenos Aires Province, Argentina, using the soil water balance equation. *SWC* decreased over crop growth stages until the start of grain filling (V3-R5), showing a clear correlation between the root *WEP* and the crop phenological stages. After a stress event in R4, *SWC* increased gradually again until the end of cycle of the crop, as a result of soil water recharge through precipitations and a reduced plant water uptake.

Furthermore, ET_a values under no-water stress conditions were in average as much as 40% lower than the estimated value under standard conditions (ET_c). These results indicate that crop growth and development conditions in a productive scenario can show evapotranspiration values different from those found in an experimental context, even if the crop has no water constraints. This could explain why in some cases crop yields in productive conditions are lower than in controlled conditions, shown in this study by a reduced production of above-ground biomass.

WEPs were similar to those found in field experiments under controlled conditions. The crop modifies the water extraction pattern based on the water availability in the different strata, with a preference for upper rather than deeper layers. When water availability in upper levels declines, plants increase extraction from deeper levels to supply their water needs.

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