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PARTIÇÃO DA EVAPOTRANSPIRAÇÃO DA CULTURA DA SOJA EM DIFERENTES CULTIVARES EM CADA ESTÁDIO FENOLÓGICO

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1 RESUMO

A soja é a principal cultura no Brasil, tanto em área, como em volume produzido. As condições meteorológicas durante o ciclo têm considerável efeito sobre o rendimento, principalmente relacionadas às precipitações ao longo do ciclo de desenvolvimento. O suprimento de água via irrigação suplementar requer o conhecimento da evapotranspiração da cultura (ET_c) para que o manejo dos recursos hídricos seja racional, com conhecimento sobre a evaporação e a transpiração. Teve-se por objetivo no presente trabalho fracionar a ET_c em transpiração da cultura (T_c) e evaporação do solo (E_s) por estádio fenológico, para diferentes cultivares de soja, em condição irrigada e de sequeiro. O experimento foi conduzido a campo, na área didático-experimental do Instituto Federal do Rio Grande do Sul – Ibirubá/RS durante a safra 2018/2019, em dois regimes hídricos (sequeiro e irrigado), utilizando quatro cultivares de soja (Raio IPRO, Elite IPRO, Lança IPRO, Ícone IPRO). O modelo SIMDualKc foi utilizado para simular o balanço hídrico, particionando os valores de ET_c nos estádios fenológicos e condições de cultivo. Observou-se maior ET_c ($T_c + E_s$) para as cultivares de soja irrigada, em comparação às mesmas cultivares em regime de sequeiro. O particionamento da ET_c nos diferentes estádios fenológicos, permitiu observar diferentes comportamentos de E_s e T_c entre as cultivares, principalmente durante os estádios de germinação-emergência e florescimento-enchimento de grãos, sendo o modelo SIMDualKc eficaz no estabelecimento do regime hídrico da cultura da soja, bem como, na representação das frações de Es e Tc.

Palavras-chave: *Glycine max*, irrigação, evaporação do solo, transpiração da cultura, estádios fenológicos.

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PARTITION OF EVAPOTRANSPIRATION OF SOYBEAN CULTURE IN DIFFERENT CULTIVARS IN EACH PHENOLOGICAL STADIUM

2 ABSTRACT

Soy is the main crop in Brazil, both in area and in volume produced. Meteorological conditions during the cycle have a considerable effect on yield, mainly related to rainfall during the development cycle. The supply of water via supplementary irrigation requires knowledge of crop evapotranspiration (ETc) so that the management of water resources is rational, with knowledge about evaporation and transpiration. The objective of the present work was to fractionate the ETc in transpiration of the crop (Tc) and evaporation of the soil (Es) by phenological stage, for different soybean cultivars, under irrigated and rainfed conditions. The experiment was conducted in the field, in the didactic-experimental area of the Federal Institute of Rio Grande do Sul - Ibirubá / RS during the 2018/2019 harvest, in two water regimes (rainfed and irrigated), using four soybean cultivars (Raio IPRO, Elite IPRO, Launches IPRO, IPRO Icon). The SIMDualKc model was used to simulate the water balance, partitioning the ETc values in the phenological stages and cultivation conditions. The higher ETc (Tc + Es) was observed for irrigated soybean cultivars, compared with the same cultivars under rainfed conditions. The partitioning of ETc, in the different phenological stages, allowed to observe different behaviors of Es and Tc among the cultivars, mainly during the stages of germination-emergence and flowering-filling of grains, the SIMDualKc Model is effective in establishing the water regime of the crop. soybean, as well as, in the representation of the Es and Tc fractions.

Keywords: *Glycine max*, irrigation, soil evaporation, crop transpiration, phenological stages.

3 INTRODUCTION

Soybean productivity is highly dependent on environmental factors, and water deficit is the main factor affecting yield, as crops require approximately 650 mm of water during their development cycle to achieve the expected yields (SENTELHAS et al., 2015). Other factors, such as soil and plant management, appropriate sowing time for each relative maturity group (RMG) (BATTISTI et al., 2017), and irrigation management, are important elements to consider in advance for crop success. Understanding the morphological and physiological behavior of each RMG when faced with environmental adversities, such as high temperatures and water stress, is essential to reduce the differences between potential yields and those achieved at the producer level (BOOTE et al., 2011).

Knowledge of the GMR should also be considered when planning soybean cultivation, as it allows estimation of the number of days it will take for the cultivar to reach maturity, from sowing to physiological maturity. The time (days) is determined by the photoperiod and temperature conditions (ZANON et al., 2015), influencing the crop's water requirements and, consequently, variations in production response, both in rainfed and irrigated agriculture.

Soybean is highly responsive to water; however, for maximum crop yield, a satisfactory water supply throughout the development cycle is needed. Montoya et al. (2017) noted that moderate water stress during the vegetative phase may not result in a significant reduction in yield. On the other hand, medium- to long-term deficits during the reproductive period can lead to a severe reduction in yield (LICHT; WRIGHT; LENSSEN, 2013).

However, the responses of different soybean GMRs to different water availability in the subtropical conditions of southern Brazil still raise doubts due to the lack of knowledge of crop evapotranspiration (ETc) in the different phases of the development cycle.

Understanding water consumption at various phenological stages of plant development allows for more rational irrigation management according to crop requirements. In dryland agriculture, understanding water demand allows for adjusting sowing times on the basis of the region's average water availability, enabling greater use of rainfall (FERNANDES; TURCO, 2003).

Linking crop evapotranspiration to each of the phenological stages that soybeans go through during their development is extremely important for irrigation planning, as it can identify periods of greatest water need. Furthermore, planning the crop cycle according to these periods of greatest water need during periods with more suitable climatic conditions is a strategy for optimizing water resources in dryland agriculture.

The individual components of ETc allow for improved irrigation management, as transpiration (Tc) is usually associated with productivity, whereas evaporation (Es) is undesirable (KOOL et al., 2014). Direct measurements of Tc and Es are difficult and require adequate instrumentation; therefore, they are estimated through the soil water balance. Es is separated from ETc by soil moisture and meteorological conditions because of its dependence on energy and moisture. Therefore, the objectives of this study were to fractionate ETc into crop transpiration (Tc) and soil evaporation (Es) at different development stages and to identify the water requirements of soybean cultivars with distinct GMRs at different phenological stages under irrigated and rainfed conditions.

4 MATERIALS AND METHODS

4.1 Description of the site and experiment

The experiment was conducted during the 2018/2019 agricultural year in the municipality of Ibirubá/RS, which is located in the physiographic region of the middle plateau (28°37'39"S and 53°05'23"W) and has an altitude of approximately 400 m above sea level. The soil in the region is classified as a typical Dystrophic Red Latosol belonging to the Cruz Alta mapping unit (STRECK et al., 2008).

Soybean was sown via a no-tillage system on November 13, 2018, via wheat crop residues. A two-factor randomized block design was used, arranged in four blocks, with eight replicates and 64 experimental units, each measuring 9.45 m². The factors consisted of four cultivars under two water conditions (irrigated and rainfed).

The treatments consisted of four cultivars from different relative maturity groups (RMG): RMG 5.0 (Raio 50I52RSF IPRO), RMG 5.5 (Elite 58I55RSF IPRO), RMG 5.8 (Lança 58I60 RSF IPRO), and RMG 6.8 (Ícone 68I70 RSF IPRO). Each cultivar was divided into two fractions to compose the irrigated and rainfed treatments. A conventional sprinkler irrigation system with Agropolo NY-25-type sprinklers spaced every 12 m was used. The uniformity coefficient and distribution coefficient (CHRISTIANSEN, 1942) were 90% and 85%, respectively. The system evaluation indicated an application rate of 9.42 mm hour $^{-1}$.

The irrigated water depth was applied with variable irrigation shifts and determined via the Irriga® System, an irrigation management platform that determines the timing and quantity of water to be applied. The Irriga® system uses crop agronomic parameters, soil characteristics, local weather conditions, and irrigation equipment as inputs, combined with mathematical models for determining the soil water balance.

4.2 Simulation model

The SIMDualKc simulation model was used to simulate crop evapotranspiration for soybean. The SIMDualKc model adopts the dual-Kc approximation proposed by Allen et al. (2005) to calculate ETc in the field, considering soil evaporation (Es) and crop transpiration (Tc) separately, and is described in detail by Rosa et al. (2012). The necessary input parameters are determined in situ or adjusted and calibrated. In the present work, the following data were used:

a) Soil data: physical and water characterization of the soil, with determination of texture, field capacity, and permanent wilting point, in the root layer (0–0.60 m), which allows the calculation of total available soil water (TAW, mm) and easily available soil water (RAW, mm) and the values for total evaporable water (TEW, mm), easily evaporable water (REW, mm) and thickness of the evaporation soil layer (Ze, m), as defined by Allen (2000).

b) Crop data: sowing date, duration of the different development phases, considered by SIMDualKc (sowing, beginning of the rapid growth period, beginning of the intermediate stage, beginning of senescence/maturation and harvest), depth of the root system, plant height, leaf area index (LAI), and fractions of soil cover by vegetation, which were determined in the field, in addition to the fractions of soil wetted by rain and irrigation.

The parameters considered as standards, such as the basal crop coefficient (K_{cb}) for each stage and the fraction of water depleted in the soil to avoid water deficit (RAW=TAW.p), were objects of calibration.

c) Meteorological data: minimum and maximum daily air temperature (°C), wind speed at 2 m height (m/s), solar radiation, daily relative air humidity (%), precipitation (mm), and reference evapotranspiration (ET_o), which were obtained via the Penman–Monteith method (ALLEN et al., 1998).

d) Irrigation data: data relating to the irrigated surface and respective irrigation dates.

e) Observation data on crop residues, which consist of the soil cover fraction and cover density, as well as the percentage reduction in soil evaporation in relation to the percentage of the soil surface covered by plant residue.

4.3 Observations and evaluations

Phenological development observations were carried out twice a week, according to the phenological scale of Fehr and Caviness (1977). The fractions of soil cover, plant height, and leaf area index (LAI) were determined weekly until full flowering. The maximum depth of the root system was determined at full flowering, with the trench digging. Whenever possible, field observations were related to the development phases used by the model, with the phenological stages of the crop defined as follows: initial period (sowing to V3); rapid growth (V3 to V7); intermediate period (R1 to R6); and final period (R7 to harvest). The fraction of cover of plant residues and the dates of occurrence of the crop development stages were determined according to Martins et al. (2013).

A set of frequency domain reflectometry (FDR) probes was installed to determine the soil moisture. Readings were taken hourly, and 24 records were collected per day. Volumetric moisture determination was performed by 16 sensors in the 0–30 cm layer and 4 sensors in the 30–60 cm layer in different experimental plots, i.e., irrigated and rainfed.

The meteorological data came from an automatic INMET station installed approximately 100 m from the experimental site. ETo was determined on the basis of climate information collected at the meteorological station via the FAO Penman–Monteith method for quantification (ALLEN et al., 1998).

4.4 Calibration and validation

In the SIMDualKc calibration procedures, unobserved parameters were adjusted. The aim was to minimize the difference between the soil water content simulated with the model and that observed by field sensors (GIMÉNEZ; PAREDES; PEREIRA, 2017; ROSA et al., 2012). Model calibration and validation must use independent datasets. In this case, for each cultivar, the irrigated system was used for calibration, and the model was validated for rainfed conditions.

The calibration and validation of the model were evaluated with the indicators used by Rosa et al. (2012), Martins et al. (2013) and Paredes et al. (2014): linear regression coefficient (b0), coefficient of determination (R²), root mean square error (RMSE), mean absolute error (AAE), mean relative error (ARE) and modeling efficiency (EF).

The linear regression coefficient (b0) and the coefficient of determination (R²) were determined via the following equations:

$$b_0 = \frac{\sum_{i=1}^{n} O_i - P_i}{\sum_{i=1}^{n} O_i^2} \quad (1)$$

$$R^2 = \left\{ \frac{\sum_{i=1}^{n} \left(O_i - \overline{O}\right)\left(P_i - \overline{P}\right)}{\left[\sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2\right]^{0.5} \left[\sum_{i=1}^{n} \left(P_i - \overline{P}\right)^2\right]^{0.5}} \right\}^2 \quad (2)$$

The error residuals were estimated from the source square of the error mean error (RMSE) (Equation 3) and the mean absolute error (AAE) (Equation 4), which express the variance of the errors and the average size of the estimated errors, according to the methodology described by Martins et al. (2013). The error relative average (ARE) (Equation 5) is used to indicate the size average of the errors estimated according to the following equation:

$$RMSE = \left[\frac{\sum_{i=1}^{n} \left(P_i - O_i\right)^2}{n} \right]^{0.5} \quad (3)$$

$$AAE = \frac{1}{n} \sum_{i=1}^{n} \left| O_i - P_i \right| \quad (4)$$

$$ARE = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{O_i - P_i}{O_i} \right| \quad (5)$$

Furthermore, another indicator was used to assess modeling quality: model efficiency (FE). This measure determines the relative magnitude of the residual variance compared with the variance of the measured data, defined as the ratio of the mean squared error to the variance of the observed data. When the FE value is close to zero or negative, the average of the observed values is as good as or better than those simulated by the model, according to equation (6):

$$EF = 1.0 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \quad (6)$$

5 RESULTS AND DISCUSSION

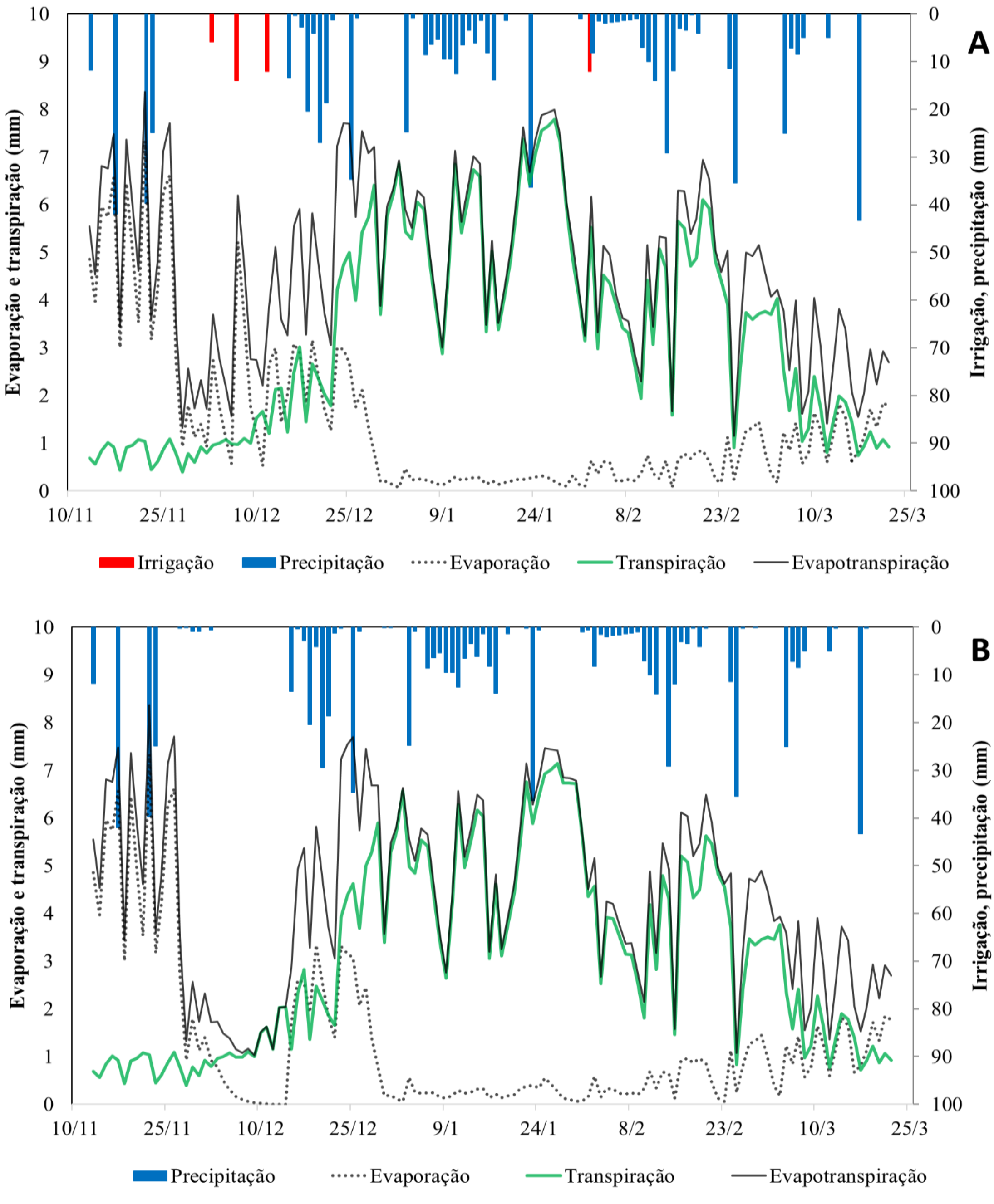
In the 2018/2019 agricultural year, adequate rainfall was distributed in the state of Rio Grande do Sul, reducing the risk of water deficit. The actual rainfall during the crop development cycle was 640 mm (Figure 1), with a total precipitation of 852.9 mm. This precipitation volume exceeded the climatological normal for the period (SILVA, 2013; INMET, 2022). High rainfall reduces the need for supplemental irrigation. Four irrigations were carried out, totaling 44 mm of net irrigated water depth (Figure 1).

The calibration and validation of SIMDualKc demonstrate, through the evaluated statistical parameters (linear regression coefficient (b0), coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (AAE), mean relative error (ARE), and modeling efficiency (EF)), that the simulation performed by the model well represented the observations made at the field level. The average b0 value was 0.93, with an R^2 ranging from 0.90--0.94, for all the cultivars, demonstrating the good performance of the model in simulating the soil water content (MARTINS et al., 2013; ÁVILA, 2016). The average RMSE was 8.92 mm, which represents approximately 10% of the total water available in the root layer. The mean absolute error (AAE) was 7.96 mm, and the mean relative error (ARE) was 12.93%, with a modeling efficiency (EF) of 0.70.

The range of values found for the statistical parameters is considered adequate since other studies that used SIMDualKc reported statistical values similar to those reported in this study (ÁVILA, 2016; MARTINS et al., 2013; PETRY et al., 2020). Properly calibrated water simulation models are valuable tools that can be used to calculate crop irrigation needs, support irrigation management practices, and assess the impacts of water stress on crop yield (MARTINS et al., 2013).

The good results achieved in terms of model fit and evapotranspiration estimation ensure that the partitioning of crops evapotranspiration using the dual crop coefficient approach in SIMDualKc is appropriate (WEI et al., 2015). After calibration and validation, the SIMDualKc model allows for the analysis of soil evaporation (Es, mm) and plant transpiration (Tc, mm) with greater precision. This method allows for the verification of the impacts of variations in soil water availability, addressing the daily variability in the volume of water available to plants according to evapotranspiration (PAÇO et al., 2012; ZHAO et al., 2012). The results for the respective daily evaporation and transpiration values for the cultivars with a GMR of 5.0, irrigated and rainfed are presented in Figures 1A and 1B.

Figure 1. Daily variation in crop evapotranspiration (mm), soil evaporation (mm), crop transpiration (mm), effective precipitation (mm) and irrigation (mm) for the cultivars with GMR 5.0, (Raio 50I52RSF IPRO) irrigated (A), and without irrigation (B).



Es was greater than Tc during the initial crop phase, which comprises the period from sowing to V3 or the second fully expanded trifoliate leaf (November 13 to December 10), representing 85% of the evapotranspiration that occurs during this period. This higher Es is due to the high water content in the evaporative layer of the soil, the frequency of precipitation, and the reduced fraction of soil shaded by the crop canopy and reduced straw on the soil surface. Plant residues, as well as crop overgrowth, reduce the solar energy available for evaporation at the soil surface (ALLEN et al., 2005). Soil water evaporation is influenced by several factors that influence soil surface conditions, no-tillage practices, cover cropping, especially crop residues, soil shading by crops, planting density and crop height, soil surface moisture, and wetting frequency (ALLEN; PEREIRA, 2009).

After the initial crop phase, there is a progressive reduction in Es and an increase in Tc due to crop growth and development, with increases in leaf area and canopy height. After complete canopy coverage of the soil surface, Es remains very low. The effects of soil wetting events on Es are also visible, mainly during the initial and final periods of crop development, with evaporation peaks after rainfall (November 13, November 17, November 22, and November 23) and irrigation (December 3, December 17, and December 12).

During the intermediate development period, between the beginning of flowering (R1) and complete granulation (R6), the fraction of moist soil exposed to solar radiation was reduced because of the coverage of the soil surface by the plant canopy, with a coverage fraction of 100%. Thus, Es during this period was practically zero, with transpiration being the fraction responsible for evapotranspiration.

These behaviors of Es and Tc throughout crop development are in agreement with works by Silva et al. (2022) in Brazil, Giménez; Paredes and Pereira (2017) in Uruguay and Paredes et al. (2014) in China, where Es also obtained practically null data for the time interval between the phenological stages of R1 to R6.

The average percentage of soil evaporation in crop evapotranspiration (Es/ETc) was 31.5% across all the treatments (Table 1). Considering the irrigated treatments, the ratio was 32.6% greater than that of the nonirrigated conditions, which had a ratio of 30.4%, which is representative of the total volume of water evaporated in this situation during the crop development cycle. Soil water evaporation was high because of the high rainfall during the crop cycle, with straw contributing to maintaining soil moisture. Es was greater for the irrigated condition because of the greater frequency of soil wetting, keeping the soil moist longer.

Table 1. Soil water evaporation (Es, mm) and crop transpiration (Tc, mm) for each crop development stage.

	Initial Period *		Rapid Growth		Intermediate Period		Final Period		Total cycle	
	It is	Tc	It is	Tc	It is	Tc	It is	Tc	It is	Tc
					Irrigated					
GMR5.0	98.33	22.84	43.39	100.46	9.93	186.23	35.84	112.99	187.48	422.52
GMR5.5	102.13	16.29	50.53	83.62	15.63	183.40	41.24	145.73	209.59	429.04
GMR5.8	102.16	16:31	49.34	87.47	13.05	183.41	42.13	160.15	206.69	447.34
GMR6.8	125.61	20.50	47.91	67.8	14.09	191.52	37.62	134.80	225.24	414.62
					Dryland					
GMR5.0	83.45	22.84	35.86	93.18	9.67	177.04	37.05	106.29	166.05	399.35
GMR5.5	85.76	16.32	40.09	87.47	12.56	174.62	42.04	159.78	180.44	438.19
GMR5.8	85.73	16:30	41.24	83.62	15.05	175.22	41.15	145.41	183.17	420.55
GMR6.8	98.18	20.49	47.91	67.80	13.60	182.30	37.54	134.30	197.24	405.29

*Initial period = (sowing to V3); rapid growth = (V3 to V7); intermediate period = (R1 to R6); and final period = (R7 to harvest). Fehr and Caviness (1977) phenological scale. GMR 5.0 = Cultivate Radius 50I52RSF IPRO; GMR 5.5 = Cultivar Elite 58I55RSF IPRO; GMR 5.8 = Cultivar Spear 58I60 RSF IPRO; GMR 6.8 = Grow Icon 68I70 RSF IPRO.

The values of the ratio (Es/ETc) found in the present study are similar to those reported by Petry et al. (2020), who reported Es/ETc values of 22 to 35% in the central depression region of Rio Grande do Sul. However, Ávila (2016), for the same region, presented an Es/ETc ratio of 23%. Barbieri et al. (2020) reported that Es/ETc varies from 33 to 39%, depending on the amount of crop residue on the soil surface. Wei et al. (2015) reported Es/ETc values ranging from 28--26% for northern China.

Distinct ETc values were observed depending on the crop development cycle and its GMR. The accumulated ETc was 610 mm and 565 mm for the cultivar with a GMR of 5.0 under irrigated and rainfed conditions, respectively (Table 1). For the cultivar with a GMR of 6.8, values of 640 mm and 603 mm were observed for irrigated and rainfed conditions, respectively. However, the cultivar with a GMR of 5.8 presented ETc, Es, and Tc values very similar to those of the cultivar with a GMR of 6.8. The results indicate that the water requirements of a cultivar depend mainly on the duration of each development subperiod and not only on the total duration of the development cycle. For GMR5.5, the values ranged from 654.02 mm to 618.635 mm under irrigated and rainfed conditions. Finally, for the cultivar with a GMR of 6.0, values between 639 mm (irrigated) and 604 mm (rainfed) were found.

For a GMR 6.0 cultivar grown in São Paulo, Silva et al. (2022) reported an ETc ranging from 629 to 983 mm. Alfonso et al. (2020), for a GMR 3.8 cultivar, reported an ETc ranging from 445 to 467 mm for the Argentine Pampa region. Anapalli et al. (2022), for a GMR 4.0 cultivar in Mississippi, reported an ETc ranging from 539 to 562 mm. Matzenauer, Barni, and Maluf (1999) reported that the average values of total evapotranspiration in the crop cycle vary from 664 mm in December for the middle plateau of Rio Grande do Sul Cruz to 930 mm in October. Ávila (2016) reported values ranging from 244.2 mm to 351.4 mm for the central depression region of Rio Grande do Sul.

The accurate partitioning of ETc allowed for improved irrigation management and management practices, as it determined the moments in which Es should be taken into consideration as the main factor of ETc and the moments in which Tc becomes the main factor, thus making it possible to establish agronomic strategies that aim at better use of water stored in the soil.

The average daily evapotranspiration throughout the crop development cycle (Table 2) under irrigated conditions was 4.69 mm day $^{-1}$ (GMR 5.0), 4.15 mm day $^{-1}$ (GMR 5.5), 4.24 mm day -1 (GMR 5.8) and 4.14 mm day $^{-1}$ (GMR 6.8). Under rainfed conditions, average daily evapotranspiration values of 4.34 mm day $^{-1}$ (GMR 5.0), 3.94 mm day $^{-1}$ (GMR 5.5), 3.95 mm day $^{-1}$ (GMR 5.8) and 3.95 mm day $^{-1}$ (GMR 6.8) were observed.

The average daily evapotranspiration found for soybean is in agreement with that reported by Moreira et al. (2013) for the middle plateau of Rio Grande do Sul, who reported an average ETc of 3.20 mm day $^{-1}$ in the no-tillage system via measurements with *eddy covariance*. In the central depression of Rio Grande do Sul, Ávila (2016) reported an average daily evapotranspiration of 2.85 mm day $^{-1}$ for the same crop. However, the average evapotranspiration at each development stage varies.

The R2 stage (full flowering) is the moment in which the crop presented the greatest demand, with an average demand among the treatments of 6.84 mm day $^{-1}$ and a maximum value of 7.47 mm day $^{-1}$. The R3 (beginning of legume formation) and R1 (beginning of flowering) stages presented demands of 6.30 mm day $^{-1}$ and 5.95 mm day $^{-1,}$ respectively (Table 2). This behavior was observed in all the cultivars, regardless of their GMR.

Table 2. The variation in ETc (mm day $^{-1}$) during the different phenological stages, considering their duration, irrigated (irr.) and rainfed (seq.) conditions for cultivars with different relative maturity groups (RGMs).

	GMR 5.0		GMR 5.5		GMR 5.8		GMR 6.8	
	Irr.	**Seq.**	**Irr.**	**Seq.**	**Irr.**	**Seq.**	**Irr.**	**Seq.**
Seeding-VC	3.22	3.15	2.79	2.79	2.79	2.79	2.80	3.03
V1-V3	3.22	1.28	3.71	3.71	3.72	3.72	3.61	1.02
V4-V6	5.31	4.43	5.45	5.45	5.52	5.52	5.37	4.85
V7	6.10	6.06	5.15	5.15	5.3	5.3	4.87	4.87
R1	5.99	5.56	5.50	5.50	6.29	6.29	6.85	5.61
R2	6.94	6.39	7.19	7.19	6.03	6.03	7.47	7.47
R3	6.71	6.63	5.78	5.78	7.47	7.47	5.80	4.73
R4	5.09	4.65	5.04	5.04	5.80	5.80	4.94	4.75
R5	4.77	4.56	5.01	5.01	4.88	4.88	4.33	4.32
R6	4.08	3.90	3.55	3.55	3.70	3.7	4.13	4.12
R7	3.75	3.70	2.86	2.86	3.03	3.03	2.86	2.86
R8	2.75	2.72	2.24	2.24	2.43	2.43	2.12	2.12
Average	4.69	4.34	4.14	4.14	4.24	4.24	4.15	3.91

Fehr and Caviness (1977) phenological scale. GMR 5.0=(Cultivar Raio 50I52RSF IPRO); GMR 5.5=(Cultivar Elite 58I55RSF IPRO); GMR 5.8=(Cultivar Lança 58I60 RSF IPRO); GMR 6.8=(Cultivar Ícone 68I70 RSF IPRO)

According to Tagliapietra et al. (2022), the highest water demand for soybean crops occurs between R1 and R5 (beginning of flowering and grain filling), with an evapotranspiration of 6.9 mm day $^{-1}$. Souza et al. (2016) reported average ETc values between 4.1 and 4.5 mm day $^{-1}$ in the state of Pará, with maximum peaks in the grain-filling phase (R3--R5). From the full grain-filling phase (R6) onward, there was a rapid decline in evapotranspiration, reaching values below 1 mm day $^{-1}$, close to harvest. Báez et al. (2020) reported that water requirements increase with soybean crop development, reaching maximum requirements in the flowering and grain-filling phases, with values between 6 and 7 mm day $^{-1}$.

Under irrigated or rainfed conditions, ETc presented high values in the stages between the beginning of flowering and grain filling (R1--R5). However, ETc stands out in the interval between sowing and the cotyledonary stage (CV). Despite being a short phase, measured in days, this period determines initial establishment and plant distribution and density in the crop, one of the main components of crop productivity (WINCK et al., 2020). During germination, both excess and a lack of water are detrimental to crop establishment.

The results of this study clearly show that soybean crops have periods of development in which water needs are greater than during the rest of the cycle, namely, full flowering and grain filling. Salinas et al. (1989) and Licht, Wright, and Lenssen (2013) corroborate that soybeans have two well-defined critical periods in relation to water shortages: from sowing to emergence and grain filling.

Separating the soybean development cycle into phases according to crop phenology is useful for evaluating ET determination methods, particularly for understanding the influence of daily variation in ET in relation to these phases (SILVA et al., 2022).

6 CONCLUSION

Soil evaporation (Es) represented 32% of crop evapotranspiration (ETc) throughout the soybean development cycle. In the initial development phase, Es contributed 85% of ETc.

Regardless of the relative maturity group of the cultivar and the water availability condition, the R2 stage (full flowering) was the phenological moment in which the crop indicated the greatest demand, with an ETc of 6.84 mm day $^{-1}$. The phenological stages R3 (beginning of legume formation) and R1 (beginning of flowering) resulted in ETc values of 6.30 mm day $^{-1}$ and 5.95 mm day $^{-1,}$ respectively.

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8 REFERENCES

ALFONSO, C.; BARBIERI, PA; HERNÁNDEZ, MD; LEWCZUK, NA; MARTÍNEZ, JP; ECHARTE, MM; ECHARTE, L. Water productivity in soybean following a cover crop in a humid environment. **Agricultural Water Management** , Amsterdam, v. 232, p.106045, 2020. DOI: https://doi.org/10.1016/j.agwat.2020.106045. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0378377419309345. Accessed on: December 1, 2022.

ALLEN, RG Using the FAO-56 dual crop coefficient method over an irrigated region as part of an evapotranspiration intercomparison study. **Journal of Hydrology** , Amsterdam, v. 229, no. 1/2, p. 27-41, 2000. DOI:

https://doi.org/10.1016/S0022-1694(99)00194-8. Available at: https://www.sciencedirect.com/science/article/pii/S0022169499001948. Accessed on: December 5, 2022.

ALLEN, RG; PEREIRA, LS Estimating crop coefficients from fraction of ground cover and height. **Irrigation Science** , Berlin, v. 28, p. 17-34, 2009. DOI: 10.1007/s00271-009-0182-z. Available at: https://link.springer.com/content/pdf/10.1007/s00271-009-0182-z.pdf?pdf=button. Accessed on: December 5, 2022.

ALLEN, RG; PEREIRA, LS; SMITH, M.; RAES, D.; WRIGHT, JL FAO-56 dual crop coefficient method for estimating evaporation from soil and application extensions. **Journal of Irrigation and Drainage Engineering** , Reston, vol. 131, p. 2-13, 2005. DOI: 0.1061/(ASCE)0733-9437(2005)131:1(2). Available at: https://ascelibrary.org/doi/epdf/10.1061/%28ASCE%290733-9437%282005%29131%3A1%282%29. Accessed on: December 5, 2022.

ALLEN, RG; PEREIRA, LS; RAES, D.; SMITH, M. **Crop evapotranspiration** : Guidelines for computing crop water requirements. Rome: FAO, 1998. (Irrigation and Drainage paper, 56).
ANAPALLI, SS; PINNAMANENI, SR; REDDY, KN; SUI, R.; SINGH, G. Investigating soybean (Glycine max L.) responses to irrigation on a large-scale farm in the humid climate of the Mississippi Delta region. **Agricultural Water Management** , Amsterdam, v. 262, p. 107432, 2022. DOI: https://doi.org/10.1016/j.agwat.2021.107432. Available at: https://www.sciencedirect.com/science/article/pii/S0378377421007095. Accessed on: 4 Dec. 2022.

ÁVILA, VS **Soil water balance and evapotranspiration partitioning of Soybeans, Corn, and Beans subjected to deficit irrigation in southern Brazil** . 2016. Dissertation (Master in Agricultural Engineering) – Universidade Federal de Santa Maria, Santa Maria, 2016.

BÁEZ, MSA; PETRY, MT; CARLESSO, R.; BASSO, LC; ROCHA, MR; RODRIGUEZ, GJ Water balance and productivity of soybean grown under different levels of water deficit in Southern Brazil. **Investigación Agraria** , Asunción, v. 22, n. 1, p. 3-12, 2020. DOI: https://doi.org/10.18004/investig.agrar.2020.junio.03-12. Available at: https://www.agr.una.py/revista/index.php/ria/article/view/504/433. Accessed on: December 5, 2022.

BARBIERI, JD; FREITAS, PSL; DALLACORT, R.; REZENDE, R.; SILVA, ALBR; FENNER, W.; CARVALHO, MAC Influence of Soil Coverage on Evapotranspiration and Dual Crop Coefficients on Soybean. **Journal of Experimental Agriculture International** , Reston, v. 42. n. 6, p. 111-125, 2020. DOI: 10.9734/JEAI/2020/v42i630546. Available at: https://www.researchgate.net/publication/343392588_Influence_of_Soil_Coverage_on_Evapotranspiration_and_Dual_Crop_Coefficients_on_Soybean. Accessed on: December 5, 2022.

BATTISTI, R.; SENTELHAS, PC; BOOTE, KJ; CHAMBER, GMS; FARIAS, JRB; BASSO, CJ Assessment of soybean yield with altered water-related genetic improvement traits under climate change in Southern Brazil. **European Journal of Agronomy** , Amsterdam, v. 83, p. 1-14, 2017. DOI: https://doi.org/10.1016/j.eja.2016.11.004. Available at: https://www.sciencedirect.com/science/artic le/pii/S1161030116302155. Accessed on: December 5, 2022.

BOOTE, KJ; IBRAHIM, AMH; LAFITTE, R.; MCCULLEY, R.; MESSINA, C.; MURRAY, SC; SPECHT, JE; TAYLOR, S.; WESTGATE, ME; GLASENER, K.; BIJL, CG; GIESE, JH Position Statement on Crop Adaptation to Climate Change. **Crop Science** , Madson, v. 51, p. 2337-2343, 2011. DOI: https://doi.org/10.2135/cropsci2011.07.0369. Available at: https://acsess.onlinelibrary.wiley.com/doi/full/10.2135/cropsci2011.07.0369. Accessed on: December 5, 2022.

CHRISTIANSEN, JE **Irrigation by sprinkler** . Berkeley: California Agricultural Station, 1942.

FERNANDES, JF; TURCO, JEP Reference evapotranspiration for irrigation management in soybean crops **. Irriga** , Botucatu , v. 8, n. 2, p. 132-141, 2003. DOI: https://doi.org/10.15809/irriga.2003v8n2p132-141. Available at: https://actaarborea.fca.unesp.br/index.php/irriga/article/view/3129/1921. Accessed on: December 4, 2022.

FEHR, WR; CAVINESS, CE **Stages of soybean development** . Ames: Iowa State University, 1977. (Special Report, 80).

GIMÉNEZ, L.; PAREDES, P.; PEREIRA, L. S. Water Use and Yield of Soybean under Various Irrigation Regimes and Severe Water Stress. Application of AquaCrop and SIMDualKc Models. **Water** , Basel, v. 9, n. 6, p. 1-18, 2017. DOI: https://doi.org/10.3390/w9060393. Available at: https://www.mdpi.com/2073-4441/9/6/393. Accessed on: December 5, 2022.

INMET. **Climatological Normals of Brazil** . (1991/2020). Brasília, DF: INMET, 2022. Available at: https://portal.inmet.gov.br/normals. Accessed on: July 19, 2022.

KOOL, D.; AGAM, N.; LAZAROVITCH, N.; HEITMAN, J.L.; SAUER, T.J.; BEN-GAL, A. A review of approaches for evapotranspiration partitioning. **Agricultural and Forest Meteorology,** Amsterdam, v. 184, p. 56–70, 2014. DOI: https://doi.org/10.1016/j.agrformet.2013.09.003. Available at: https://www.sciencedirect.com/science/article/pii/S016819231300230X. Accessed on: December 5, 2022.

LICHT, MA; WRIGHT, D.; LENSSEN, AW **Soybean response to drought** . Ames: Iowa State University, 2013.

MARTINS, JD; RODRIGUES, GC; PAREDES, P.; CARLESSO, R.; OLIVEIRA, ZB; KNIES, AE; PETRY, MT; PEREIRA, LS Dual crop coefficients for maize in southern Brazil: model testing for sprinkler and drip irrigation and mulched soil. **Biosystems Engineering** , Amsterdam, vol. 113. n. 3, p. 291-310, 2013. DOI: https://doi.org/10.1016/j.biosystemseng.2013.03.016. Available at: https://www.sciencedirect.com/science/article/abs/pii/S1537511013000627. Accessed on: December 4, 2022.

MATZENAUER, R.; BARNI, NA; MALUF, JRT Agroclimatic analysis of water availability for soybean crops in the Middle Plateau region of Rio Grande do Sul . **Brazilian Journal of Agrometeorology** , Santa Maria, v. 6, n. 2, p. 263-275, 1998.

MONTOYA, F.; GARCIA, C.; PINTOS, F.; OTERO, A. Effects of irrigation regime on the growth and yield of irrigated soybean in temperate humid climatic conditions. **Agricultural Water Management** , Amsterdam, v. 193, p. 30-45, 2017. DOI: https://doi.org/10.1016/j.agwat.2017.08.001 . Available at: https://www.sciencedirect.com/science/article/abs/pii/S0378377417302573. Accessed on: December 4, 2022.

MOREIRA, VS; ROBERTI, DR; TIMM, A.; WEBLER, G.; DEGRAZIA, GA Analysis of evapotranspiration and leaf area index in a soybean crop under two management systems . **Revista Ciência e Natura** , Santa Maria, v. 35, n. 35, p. 432-435, 2013.

PAÇO, TA; FERREIRA, MI; ROSA, RD; PAREDES, P.; RODRIGUES, GC; CONCEIÇÃO, N.; PACHECO, CA; PEREIRA, LS The dual crop coefficient approach using a density factor to simulate the evapotranspiration of a peach orchard: SIMDualKc model vs. eddy covariance measurements. **Irrigation Scien ce** , Berlin, v. 30, n. 2, p. 115-126, 2012. DOI: 10.1007/s00271-011-0267-3. Available at: https://link.springer.com/content/pdf/10.1007/s00271-011-0267-3.pdf?pdf=button. Accessed on: December 5, 2022.

PAREDES, P.; RODRIGUES, GC; ALVES, I.; PEREIRA, LS Partitioning evapotranspiration, yield prediction and economic returns of maize under various irrigation management strategies. **Agricultural Water Management,** Amsterdam, v. 135, p. 27-39, 2014. DOI: https://doi.org/10.1016/j.agwat.2013.12.010 . Available at: https://www.sciencedirect.com/science/article/abs/pii/S0378377413003521. Accessed on: December 4, 2022.

PETRY, MT; BASSO, LJ; CARLESSO, R.; ARMOA, MS; HENKES, JR. Modeling yield, soil water balance, and economic return of soybean under different water deficit levels. **Agricultural Engineering** , Jaboticabal, v. 40, n. 4, p. 526-535, 2020. DOI: https://doi.org/10.1590/1809-4430-Eng.Agric.v40n4p526-535/2020. Available at: https://www.scielo.br/j/eagri/a/JQZ96jWH8PqMNyk4RQqzyBJ/?lang=en. Accessed on: December 5, 2022.

ROSA, RD; PAREDES, P.; RODRIGUES, GC; ALVES, I.; FERNANDO, RM; PEREIRA, LS; ALLEN, RG Implementing the dual crop coefficient approach in interactive software: 2. Model testing . **Agricultural Water Management** , Amsterdam, v. 103, p. 8-24, 2012. DOI: https://doi.org/10.1016/j.agwat.2011.10.018 . Available at: https://www.sciencedirect.com/science/article/abs/pii/S0378377411002903. Accessed on: December 4, 2022.

SALINAS, AR; SANTOS, DSB; SANTOS, FO; MELLO, VDC; ZONTA, EP Behavior of soybean genotypes, up to seedling stage, at different moisture levels . *In* : WORLD SOY RESEARCH CONFERENCE, 4th, 1989, Buenos Aires. **Annals** [...]. Buenos Aires: Cornell University, 1989. v. 4. p. 376-382.

SENTELHAS, PC; BATTISTI, R.; CHAMBER, GMS; FARIAS, JR; HAMPF, A.; NENDEL, C. The soybean yield gap in Brazil – magnitude, causes and possible solutions for sustainable production. **Journal of Agricultural Science** , Cambridge, vol. 153, no. 8, p. 1394-1411 , 2015. DOI: https://doi.org/10.1017/S0021859615000313. Available at: http://www.leb.esalq.usp.br/agmfacil/artigos/artigos_sentelhas_2015/2015_JAgricScience_1-18_SoybeanYieldGap.pdf. Accessed on: December 5, 2022.

SILVA, RR **Relationship between rainfall and soybean crop productivity in the**

municipality of Ibirubá-RS . 2013. Dissertation (Master's in Geography and Geosciences/Environment, Landscape and Environmental Quality) – Universidade Federal de Santa Maria, Santa Maria, 2013.

SILVA, EHFM; HOOGENBOOM, G.; BOOTE, KJ; GONÇALVES, AO; MARIN, FR Predicting soybean evapotranspiration and crop water productivity for a tropical environment using the CSM-CROPGRO-Soybean model. **Agricultural and Forest Meteorology** , Amsterdam, v. 323, 2022. DOI: https://doi.org/10.1016/j.agrformet.2022.109075. Available at: https://www.sciencedirect.com/science/article/pii/S0168192322002635. Accessed on: December 5, 2022.

SOUZA, PJOP; FARIAS, SO; ROCHA, EJP; SOUSA, AML; SOUZA, EB Soybean water consumption in northeastern Pará **. Irriga** , Botucatu, v. 1, n. 1, p. 218-231, 2016. DOI: https://doi.org/10.15809/irriga.2016v1n01p218-231. Available at: https://irriga.fca.unesp.br/index.php/irriga/article/view/1879/1529. Accessed on: December 4, 2022.

STRECK, EV; KÄMPF, N.; DALMOLIN, RSD; KLAMT, E.; NASCIMENTO, PC; SCHNEIDER, P. **Soils of Rio Grande do Sul** . Porto Alegre: Pallotti, 2008.

TAGLIAPIETRA, EL; ZANON, AZ; STRECK, NA; BALEST, DS; ROSA, SL; BEXAIRA, K, P.; RICHTER, GL; RIBAS, GG; SILVA, MR Biophysical and management factors causing yield gap in soybean in the subtropics of Brazil. **Agronomy Journal** , Madison, vol. 113, no. 2, p. 1882-1894, 2021. DOI: https://doi.org/10.1002/agj2.20586. Available at: https://acsess.onlinelibrary.wiley.com/doi/full/10.1002/agj2.20586. Accessed on: December 5, 2022.

ZANON, AJ; WINCK, JEM; STRECK, NA; ROCHA, TS M; CERA. JC; RICHTER. GL; SABEL LAGO, I.; SANTOS, PM; MACIEL, LR; GUEDES, JVC; MARCHESAN, E. Development of soybean cultivars according to maturity group and growth type in uplands and lowlands. **Bragantia** , Campinas, v. 74, n. 4, p. 400-411, 2015. DOI: https://doi.org/10.1590/1678-4499.0043. Available at: https://www.scielo.br/j/brag/a/K4nQRyVDfqvys83YWKn6XLv/?lang=pt. Accessed on: December 4, 2022.

WEI, Z.; PAREDES, P.; LIU, Y.; CHI, WW; PEREIRA, LS Modeling transpiration, soil evaporation and yield prediction of soybean in North China Plain. **Agricultural Water Management** , Amsterdam, v. 147, p. 43-53, 2015. DOI: https://doi.org/10.1016/j.agwat.2014.05.004 . Available at: https://www.sciencedirect.com/science/article/abs/pii/S0378377414001450. Accessed on: December 4, 2022.

WINCK, JEM; MARTIN, TN; PINTO, MAB; BRUNING, LA; ARISMENDI, GA Spatial arrangement of plants on leaf growth and development and the yield potential of soybean. **Australian Journal of Crop Science** , Lismore, vol. 14, no. 6, p. 913-922, 2020. DOI: 10.21475/ajcs.20.14.06.p1721. Available at: https://www.cropj.com/martin1721_14_6_2020_913_922.pdf. Accessed on: 5 Dec. 2022.

ZHAO, NN; LIU, Y.; CAI, JB; ROSA, R.; PAREDES, P.; PEREIRA, LS Dual crop coefficient modeling applied to the winter wheat-summer maize crop sequence in North China Plain: basal crop coefficients and soil evaporation component. **Agricultural Water Management** , Amsterdam, v. 117, p. 93-105, 2013. DOI: https://doi.org/10.1016/j.agwat.2012.11.008 . Available at: https://www.sciencedirect.com/science/article/abs/pii/S0378377412003010. Accessed on: December 4, 2022.