

Irrigation strategies on crop and water productivity of sunflowers based on field experiments and modeling¹

Estratégias de irrigação na produtividade da água e da cultura do girassol com base em experimentos de campo e modelação

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HIGHLIGHTS:

The SIMDualKc model simulated soil water content for sunflowers in different irrigation management strategies.

Simulation models and crop coefficients are crucial for optimizing water resources and maximizing crop yields.

The study allowed the calibration of sunflower crop coefficients, which are important parameters for irrigation management.

ABSTRACT: Soil water balance models can be a good option for studying crop growth and yield responses under different water supply levels. The aim of this study was to evaluate the effect of different irrigation strategies on sunflower yield and water productivity using field experiments and soil water balance simulations. Two field experiments were performed. In 2018/19, four irrigation strategies (aimed at maintaining soil available water at 80, 70, 60, and 50% of total available water) were evaluated. In 2020/21 an irrigated and a rain-fed treatment were evaluated. The SIMDualKc model was calibrated and validated to simulate soil water balance and derive the dual coefficients using plant variables from field observations. Grain yield was highest in the treatment maintained at 70% of total available water in Study I, suggesting that a water replenishment reduction strategy may be an alternative to irrigation management, especially in locations where water is scarce. The statistical indicators showed good performance of the model in simulating the water available in the soil, with the coefficient of determination > 0.90 and modeling efficiency above 0.86 for all cases. The study allowed the calibration of the single and basal crop coefficients of sunflower, which are important parameters for irrigation management.

Key words: *Helianthus annuus*, SIMDualKc, evapotranspiration, crop coefficients, water deficit

RESUMO: Os modelos de balanço hídrico do solo podem ser uma boa opção para estudar o crescimento das culturas e as respostas de rendimento sob diferentes níveis de fornecimento de água. O objetivo deste estudo foi avaliar os efeitos de diferentes estratégias de irrigação na produtividade do girassol e na produtividade da água usando experimentos de campo e simulações de balanço hídrico do solo. Dois experimentos de campo foram realizados. Em 2018/19, foram utilizadas quatro estratégias de irrigação (mantida a água disponível no solo em 80, 70, 60 e 50% da água total disponível). Em 2020/21 foi utilizado um tratamento irrigado e de sequeiro. O modelo SIMDualKc foi calibrado e validado para simular o balanço hídrico do solo e derivar os coeficientes duais usando variáveis da planta a partir de observações de campo. A produtividade de grãos foi maior no tratamento mantido a 70% do total de água disponível no Estudo I, sugerindo que a redução da reposição de água pode ser uma alternativa para o manejo da irrigação, principalmente em locais onde a água é escassa. Os indicadores estatísticos mostraram um bom desempenho do modelo na simulação da água disponível no solo, com coeficiente de determinação > 0,90 e eficiência de modelagem acima de 0,86 para todos os casos. O estudo permitiu a calibração do coeficiente de cultura simples e basal do girassol, que são parâmetros importantes para o manejo da irrigação.

Palavras-chave: *Helianthus annuus*, SIMDualKc, evapotranspiração, coeficientes de cultura, estresse hídrico

INTRODUCTION

Sunflower (*Helianthus annuus*) is one of the most important oilseed crops worldwide. Its oil stands out for its high nutritional value, due to the presence of essential fatty acids (Cabral et al., 2022). The sunflower crop responds well to water supply, showing significant increases in grain yield and biomass when its water needs are met. The impact of periods of water deficit can be calculated through the water balance (WB), using meteorological data, which also allows the need for irrigation to be determined.

Accurate estimation of crop water requirements is crucial for efficient water use in agriculture. The current discrepancy between crop demand and water availability in agriculture has led to the search for improvements in this area. Crop simulation models are essential tools for optimizing agricultural management, predicting crop growth and estimating yields, as well as for improving the management of water resources. Pereira et al. (2020) point out that these models are fundamental to helping farmers make decisions, allowing them to evaluate scenarios and cultivation strategies.

Several authors have reported soil water balance models using FAO56 dual crop coefficients (Kc). An approximation to derive the dual Kc for sunflower using the SIMDualKc model was presented by Bondok et al. (2016) in Egypt. Giménez et al. (2017) and Petry et al. (2020, 2023) used the model for soybean in Uruguay and Brazil, respectively. Liu et al. (2022b) in China and Martins et al. (2013) in Southern Brazil used the method to determine evapotranspiration in maize, and Petry et al. (2024) used it for aerobic rice in Southern Brazil. However, only a few studies such as Howell et al. (2015) and Bondok et al. (2016) have referred to evapotranspiration, water use and irrigation strategies for sunflower.

In a previous study by Paredes et al. (2014) estimates of grain yield as a function of water availability were examined by relating yield and evapotranspiration. The aim of the current study was to evaluate the effect of different irrigation strategies on sunflower yield and water productivity using field experiments and soil water balance simulations, to determine the best water supply strategy for the crop.

MATERIAL AND METHODS

The research was carried out in the 2018/19 (Study I) and 2020/21 (Study II) growing seasons, at two locations in an experimental area at the Department of Rural Engineering of

the Universidade Federal de Santa Maria (DRE/UFSM), in the city of Santa Maria, (29° 43' 39" S and 53° 43' 12" W, with an average elevation of 104 m). The soil is classified as Argissolo Vermelho Distrófico (EMBRAPA, 2006) and Ultisol (Soil Survey Staff 2022). The physical and hydraulic characteristics of the soil of the experimental sites (Table 1) were determined in the Soil Physical Analysis Laboratory at Sistema Irriga[®], according to the procedures described by Martins et al. (2013).

The climate is characterized as humid subtropical "Cfa", according to the Köppen-Geiger classification (Kottek et al., 2006). In this type of climate, there is no dry season, but rather hot summers and cold winters (Binarti et al., 2020). During the two experimental seasons, meteorological data (Figure 1) were obtained from an automatic weather station belonging to the National Institute of Meteorology (INMET), located approximately 200 m from the experimental site. The daily weather data included maximum and minimum air temperature (T_{max} and T_{min}, °C), global solar radiation (R_s, MJ m⁻² per day), wind speed measured at 2 m height (U₂, m s⁻¹), maximum and minimum relative air humidity (RH_{max} and RH_{min}, %), and rainfall (mm). The reference evapotranspiration was computed daily using the FAO-PM (ET_o, mm) equation (Allen et al., 1998).

Study I, sown in 2018/19, was carried out in a rainout shelter measuring 16 × 10 m, moving on rails and with a mechanical drive. This structure allows the ingress of water from precipitation to be controlled within the experimental site. The sunflower hybrid M-734 used has a cycle of about 120 days and is dual-purpose, being used for oil production or as bird feed, and was sown on October 11, 2018, spaced at 0.50 m between rows and at a sowing density of 50,000 plants ha⁻¹. After plant emergence, soybean straw with a volume of approximately 6 t ha⁻¹ was distributed among the experimental units. The crop was harvested on February 6, 2019, with a total crop cycle of 118 days.

The irrigation system used was micro-sprinklers in Study I and conventional sprinklers in Study II. Irrigation was carried out according to the system's operating time and application rate, seeking to meet the need for irrigation to maintain soil moisture within the total available water (TAW) range required for each treatment in Study I. In Study II, irrigation followed the recommendations of the Sistema Irriga[®] application, an irrigation management service, which recommends irrigation when the available water in the soil (ASW) reaches approximately 60% of the TAW.

Table 1. Physical and hydraulic attributes of the soil at experimental sites

Layers (cm)	Ds (g cm ⁻³)	Dp (g cm ⁻³)	Texture (%)			θ (cm ³ cm ⁻³)		TAW
			Sand	Silt	Clay	FC	PWP	
Study I								
0 – 10	1.35	2.54	35	37	21	0.34	0.14	20
10 – 25	1.25	2.59	36	44	22	0.33	0.15	27
25 – 55	1.13	2.61	33	45	22	0.33	0.17	48
55 – 70	1.29	2.65	23	35	44	0.30	0.18	36
Study II								
0 – 30	1.42	2.47	46	28	26	0.35	0.15	60
30 – 60	1.36	2.52	36	29	35	0.34	0.14	58
60 – 100	1.25	2.50	19	23	58	0.42	0.22	60

Ds - Soil density (g cm⁻³); Dp - Particle density (g cm⁻³); θ - Volumetric water content (cm³ cm⁻³); FC - Field capacity (-10 kPa); PWP - Permanent wilting point (-1500 kPa), obtained in laboratory and TAW - Total available water in the soil

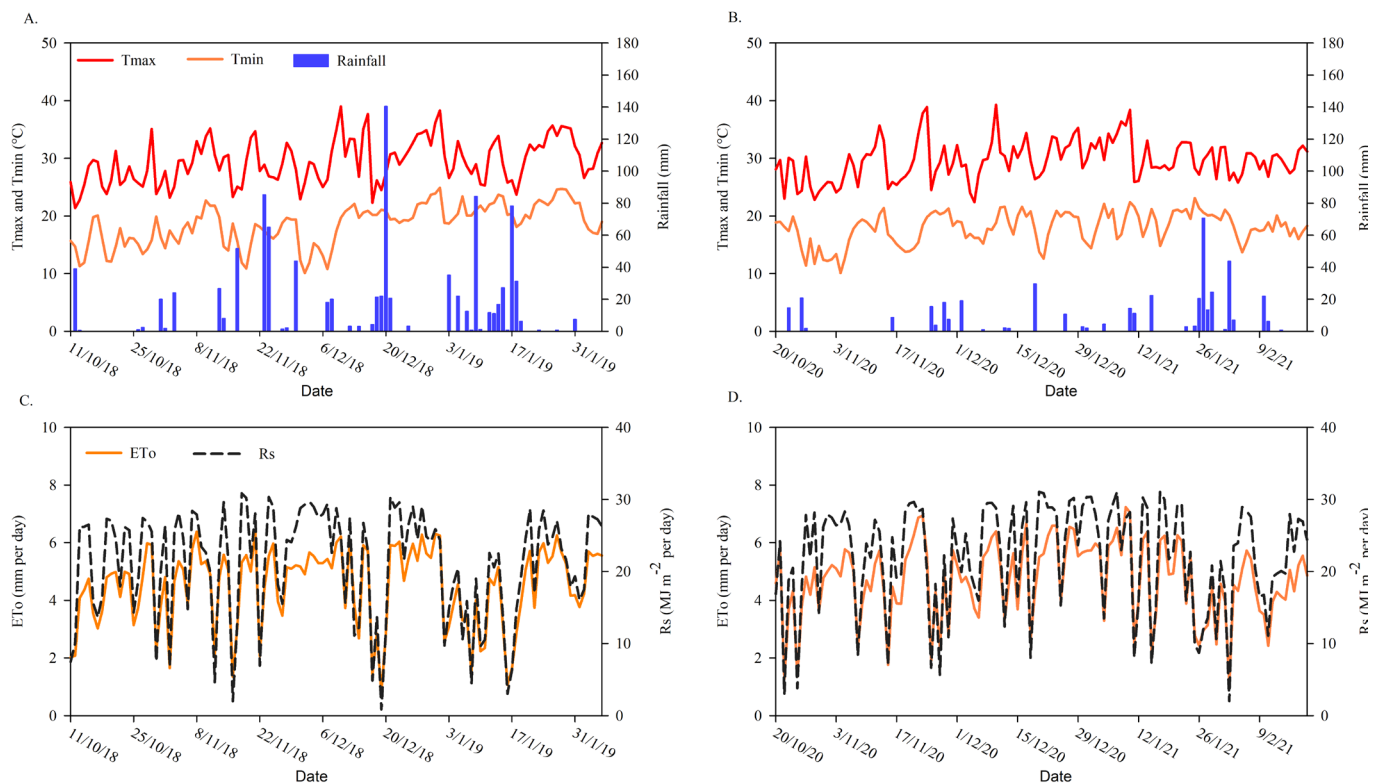


Figure 1. Meteorological data for the two study periods: maximum and minimum air temperature (Tmax and Tmin) and precipitation (P) for Study I (2018/19) (A) and Study II (2020/21) (B); reference evapotranspiration (ETo) and solar radiation (Rs) for Study I (2018/19) (C) and Study II (2020/21) (D)

The total experimental area (EA) was 297 m² (33 × 9 m), with each experimental unit corresponding to 9 m² (3 × 3 m), organized in simple blocks, with six replicates per block for each treatment evaluated, where each block represented a different irrigation treatment. The experiment consisted of four irrigation strategies, based on the percentage of total soil available water (TAW), with irrigation carried out whenever TAW reached the pre-defined percentage for each treatment: 80% of TAW (without deficit); 70% of TAW (mild deficit); 60% of TAW (moderate deficit); 50% of TAW (severe deficit).

Study II was conducted under field conditions, using two water management strategies: irrigated and rain-fed. The Rhino sunflower hybrid, which has a hyper-early cycle and is used for confectionery and bird feed, was hand-sown on October 20, 2020, at a row spacing of 45 cm and a depth of 4 cm.

The experiment was conducted in two blocks, in strips, each strip being an irrigation treatment, with four replicates of each treatment. The factor A consisted of two irrigation treatments (irrigated and rainfed), and factor B consisted of different densities of plant population (45, 50 and 55 thousand plants ha⁻¹). In this study, the different population densities were not taken into account, as the water balance simulations carried out did not show any significant differences. Each experimental plot was 5.5 m long by 5 m wide (27.50 m²). Irrigation treatments were applied following the information automatically provided by the Sistema Irriga[®] (<https://www.sistemairriga.com.br/>), in relation to each treatment.

Soil water content (θ , cm³ cm⁻³) was measured automatically using frequency domain reflectometer (FDR) sensors (model CS-616), connected to a multiplexer (model AM16/32) and

datalogger (model CR1000) (Campbell Scientific, Logan, UT, USA). There were four sensors in each experimental unit, in the 0–0.10, 0.10–0.25, 0.25–0.55, and 0.55–0.85 m layers in Study I. Measurements were taken hourly and automatically stored throughout the crop cycle. In Study II soil moisture measurements were taken once a week throughout the cycle. The observed available soil water (ASW) was calculated from the actual water content in the root zone up to 0.70 m (observed root depth) minus the water content at the permanent wilting point.

Two representative uniform plants were tagged in each plot to assess the morphological and phenological variables of the crop in the two experiments. The variables assessed were: plant height, phenological stage, average plant stem diameter perpendicular to the soil, and leaf width and length.

The height of plants was measured with a tape measure, from the soil surface to the top of the plants. The phenological stage was evaluated using the scale proposed by Schneiter & Miller (1981) as a reference. This scale is divided into two crop stages: vegetative and reproductive. The vegetative stage begins when the seedling emerges and is represented by the letter V, followed by a number ranging from one (V1) to n (Vn), where the number indicates the number of fully expanded leaves. The reproductive stage, represented by the letter R, consists of nine phases and begins with the emergence of the flower bud until physiological maturity. Stem diameter was determined using a digital caliper, taking the measurement between the first and second pairs of leaves.

Based on the width and length of leaves measured with a ruler, the leaf area (LA) of each plant was calculated, according to the method proposed by Maldaner et al. (2009). Leaf area

index (LAI) was determined from the LA data using the following Eq. 1:

$$LAI = \frac{LA}{GA} \quad (1)$$

Where LA is the leaf area (cm²) and ground area (GA) is the soil area occupied by the plant (cm²). Sunflower accumulated growing degree days (AcGDD) were calculated from the average daily temperature, subtracted from a base temperature (T_{base}) of 8 °C (Soltani & Sinclair, 2012). The crop development cycle was divided into different periods, associated with growing degree days according to the phenology of the crop: beginning of rapid vegetative growth (V8); start of the intermediate period (R1); start of senescence (R6). Grain yield was determined after harvesting the central area of each experimental unit (4 m² - Study I; 18 m² - Study II), manually threshing the material, and weighing it on a precision balance. The values obtained were corrected to 13% moisture and the grain yield was calculated in kg ha⁻¹.

The plant variables observed in Study II were the same as those described in Study I. The root depth was observed by opening a trench up to 1 m deep. No roots were observed below 0.70 m. At the end of the cycle, when the plants had reached physiological maturity (R9), the plant capitulum were collected in the central area of each plot (18 m²) to determine the grain yield.

The soil water balance (SWB) was simulated for each irrigation strategy in both studies, using the SIMDualKc model, from a set of observed and standard input data (Rosa et al., 2012). The model, as described by Allen et al. (1998),

uses the dual crop coefficient methodology, which partitions crop evapotranspiration (ET_c) into its components, plant transpiration (T_c) and soil evaporation (E_s).

The water productivity (WP, kg m⁻³) was calculated for the different irrigation strategies. The total water productivity (WP_t, kg m⁻³) is the ratio between the achieved yield (Y_a, kg) and the total water used (TWU, m³) (Pereira et al., 2012). TWU is the sum of the rainfall, soil water storage, capillary rise and gross irrigation applied (m³). Meanwhile, irrigated water productivity (WP_i, kg m⁻³) is the ratio between the yield achieved by the crop (Y_a, kg) using only irrigation water (IWU, m³).

In this study, the simulations carried out by the SIMDualKc program assumed a linear variation of the relative yield loss with the relative transpiration deficit of the crop, since T_c is the component of ET directly responsible for the yield (Paredes et al., 2014).

To calibrate the model, initial values (standard) of all parameters were used for crop, soil, deep percolation and surface runoff (Table 2). The calibration methods followed those of Pereira et al. (2015), resulting in the calibrated values also shown in Table 3.

The SIMDualKc model was calibrated based on the treatment maintained at 80% of TAW in Study I (2018/19 growing season), and the other data-sets were used to validate the model. The first stage of calibration consisted of parameterizing the non-observed crop characteristics, i.e. the crop's basal coefficients (K_{cb ini}, K_{cb mid}, and K_{cb end}) and the depletion fractions for no water stress (p_{ini}, p_{mid}, and p_{end}). The initial values used were those proposed by Pereira et al. (2020). The runoff number curve (CN) and the deep percolation

Table 2. Initial (standard) and calibrated values of the SIMDualKc model, with the data maintained at 80% of TAW for the treatment in Study I, during the 2018/19 growing season

Parameters	Initial, standard	Calibrated values	Source of the initial parameter values
Crop parameters			
K _{cb ini}	0.15	0.20	Pereira et al. (2021)
K _{cb mid}	1.15	1.05	Pereira et al. (2021)
K _{cb end}	0.35	0.25	Pereira et al. (2021)
Water depletion for no stress (p)	0.45	0.45	Pereira et al. (2021)
Soil evaporation			
TEW (mm)	49	22	Soil characteristics
REW (mm)	12	9	
Z _e (m)	0.15	0.10	
Deep percolation			
a _{DP}	353	340	Liu et al. (2006)
b _{DP}	- 0.022	- 0.022	Martins et al. (2013)
Runoff (CN)	75	75	Martins et al. (2013)

K_{cb ini}, K_{cb mid} and K_{cb end} - K_{cb} basal crop coefficient for the initial, mid and final period, respectively; Z_e - Depth of the soil's evaporable layer; TEW - Total evaporable water; REW - Readily evaporable water; a_{DP} and b_{DP} - Parameters of the percolation equation; CN - Curve number

Table 3. Growing degree days (GDD, °C) at the beginning of each sunflower development stage, for the different irrigation strategies in the two field experiments

Crop season	Irrigation strategy	Crop stages				
		Sowing date	Start of growth stage	Start of intermediate stage	Start of senescence	Harvest
2018/19	80% TAW	2018/10/11	338	718	1281	1793
	70% TAW		338	718	1281	1793
	60% TAW		338	718	1281	1793
	50% TAW		338	718	1281	1793
2020/21	Irrigated	2020/10/20	403	688	1494	1862
	Rainfed		403	787	1494	1862

TAW - Total available water

(DP) parameters (a_{DP} and b_{DP}) used were those determined by Martins et al. (2013) at the same experimental site.

Following the procedures proposed by Pereira et al. (2015), the K_{cb} and depletion fraction (p) values were adjusted through trial and error, intending to minimize the differences between the observed and simulated available soil water data. A qualitative analysis was performed using graphs to determine if and when there were trends towards over or underestimation by the model. After reducing the estimation errors from one interaction to another, the trial-and-error method was applied to the parameters related to soil evaporation, deep percolation and surface runoff to adjust them accordingly.

To assess the accuracy of the model, a set of indicators described in previous studies was used (Pereira et al., 2015; Giménez et al., 2017; Liu et al., 2022a) and their target values were: (a) the regression coefficient (b_0) forced to the origin, looking for values close to 1.0 indicating that the predicted and observed values were statistically similar; (b) the coefficient of determination (R^2), with values close to 1.0 showing that the model explained most of the total variance of the observed values; (c) the root mean square error (RMSE), with values between 0.0 and a positive value, attempting to achieve a value below the average of the observations; (d) the normalized RMSE (NRMSE), which is the ratio of the RMSE to the mean of the observed data; and (e) the modeling efficiency (EF, dimensionless), which aims for values close to 1.0, to determine the quality of the modeling, as it represents the magnitude of the residual variance compared to the variance of the measured data. For the statistical analysis of grain yield, regression analysis was carried out for Study I and the values obtained in Study II were subjected to the Skott-Knott test at $p \leq 0.05$.

RESULTS AND DISCUSSION

Table 3 shows the growing degree days (GDD, °C) for the main stages of the sunflower. In Study I, there were no differences in the duration of the main stages between the different irrigation strategies, due to the milder temperatures and relative humidity than in Study II, which allowed the plants to adapt to the lower water content in the soil. In Study II, the lower distribution and occurrence of rainfall decreased the development of rainfed sunflowers, reducing the onset of the intermediate phase by 99 °C per day (5 days) compared to the irrigated treatment. The different hybrids used in each of the two studies may partially explain these differences. These results showed that counting the duration of the crop

cycle using GDD was important for estimating plant water requirements, which is in line with the reports of Pereira et al. (2015).

Plant height observations are listed in Table 4, with average values observed on specific days for each segment of the crop coefficient curve. In the initial stage, the plants in Study I had a lower plant height than in Study II, which can be attributed to the fact that they were different hybrids, with different growth characteristics. Due to weather conditions, the rainout shelter remained closed for 9 consecutive days in the initial phase of Study I to prevent water ingress from rainfall. Thus, the plants were also protected from other weather conditions, such as: solar radiation, air temperature, relative humidity and wind circulation in the area. The fact that taller plants were observed in the irrigated crops in Study II may be due to the variety and delay in sowing date compared to Study I. The lower plant height caused by water stress is related to the reduction in soil water content and, consequently, the reduction in leaf water potential, stomatal closure and loss of turgor, which can reduce and/or interrupt cell growth (Jaleel et al., 2009).

The observed leaf area index (LAI) data for each irrigation strategy and the two studies are shown in Figure 2. The highest observed LAI values in Study I were obtained in the treatments where the TAW was maintained at 80 and 70% (Figures 2A and B), demonstrating that soil moisture was conserved at levels that were readily available to plants, allowing them to increase maximum LAI and thus contribute to plant growth. In Study II, there was a visible contrast in maximum LAI between the irrigated and the rainfed treatments, at 3.8 and 2.2 respectively. As LAI decreases, there is also a reduction in the translocation of photoassimilates to the other plant organs (Garofalo & Rinaldi, 2015), affecting grain yield. This illustrates how water deficit influences plant growth, and that a greater LAI allows greater radiation absorption through the larger leaf area, with greater biomass and a higher rate of photosynthesis for grain production.

The available soil water (ASW) dynamics observed and simulated after model calibration are shown in Figure 3, with the calibration data-set (Figure 3A) and other validation sets shown in the other figures. The observed and simulated ASW values were above the readily available water (RAW) limit (59 mm) throughout the crop cycle in the 80% TAW treatment in Study I, and in the irrigated treatment in Study II. In the other treatments, observation and simulation suggested at least one period of water stress, in some specific periods, with the ASW decreasing to values below the RAW. In Figure 3B, the treatment maintained at 70% TAW showed moments when the

Table 4. Average values of plant height observations (m) for the different stages of sunflower development in the different irrigation strategies of the two field experiments

Crop Year	Irrigation strategy	Stages of crop development			
		Sowing date	Start of growth stage	Start of intermediate stage	Start of senescence
2018/19	80% TAW	0.07	1.50	1.80	1.60
	70% TAW	0.07	1.30	1.50	1.20
	60% TAW	0.07	1.30	1.40	1.10
	50% TAW	0.07	1.10	1.28	1.00
2020/21	Irrigated	0.25	1.70	1.90	1.80
	Rainfed	0.18	1.40	1.70	1.30

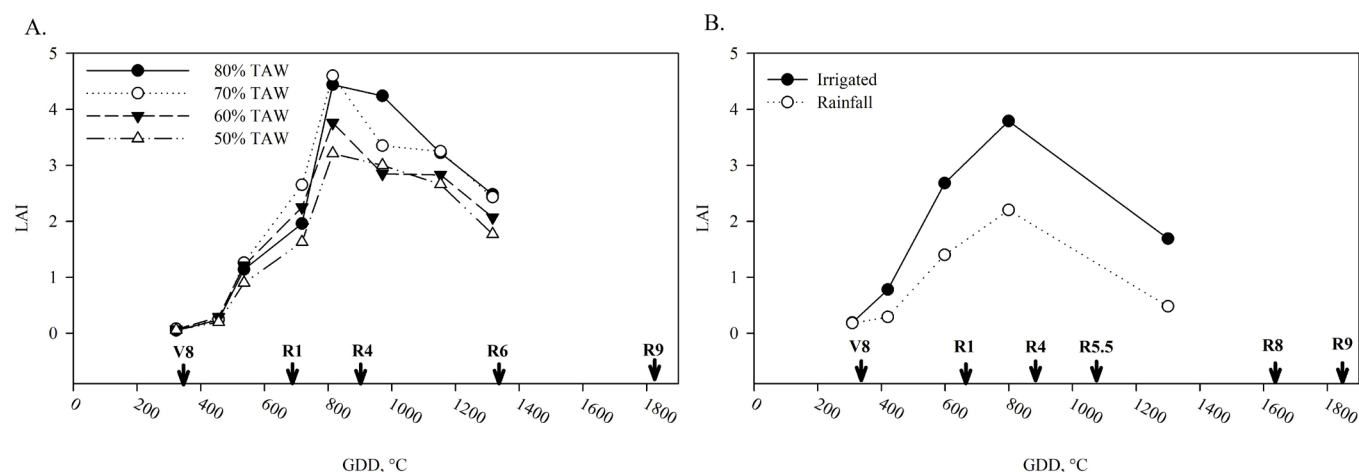


Figure 2. Leaf area index (LAI) observations for each irrigation strategy evaluated for Study I (A) and Study II (B), highlighting the observed plant phenological stages

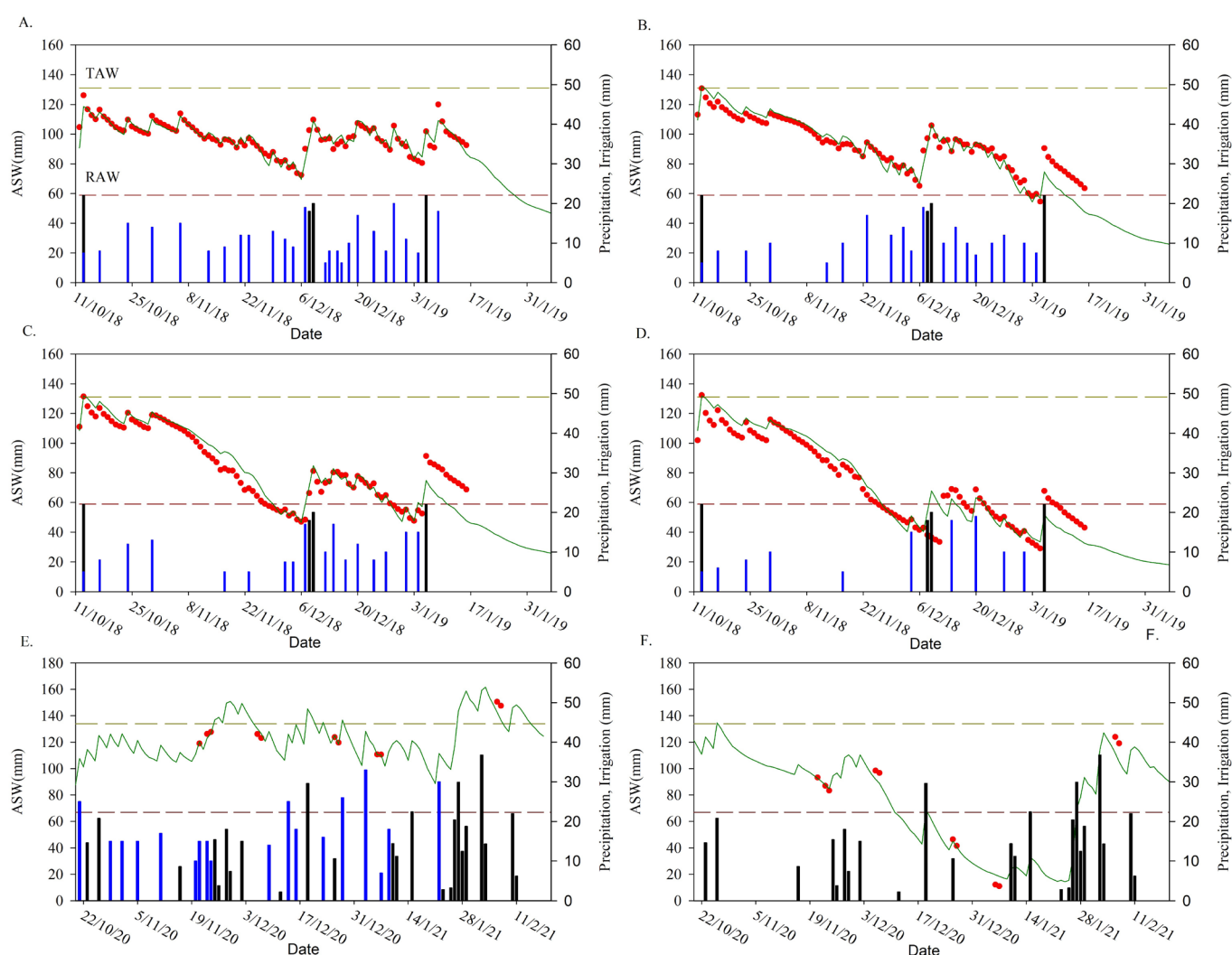


Figure 3. Calibration and validation of the SIMDualKc model for the treatments in Study I, maintaining the TAW percentage for model calibration at (A) 80% TAW and for validation at (B) 70% TAW, (C) 60% TAW and (D) 50% TAW, in the 2018/19 growing season; (E) irrigated, (F) rainfed, during the 2020/21 growing season, where ● ASW observed; — ASW simulated; | precipitation; | irrigation

simulated ASW curve was under the RAW when the crop was in the grain filling stage, with an ET_c exceeding 5 mm per day.

It can be seen that more periods with a water content lower than the TAW were observed in the 2018/19 growing season, i.e., below the RAW (Figures 3C, D), due to the imbalance

between irrigation and the crop's water requirement. The irrigation schedules of treatments in Study I maintained the TAW close to the desired threshold on average, with only the treatment that maintained TAW at 80% having a final average TAW below target, at 74% of TAW.

In general, compared to the daily data observed in Study I, the model was able to accurately reproduce the behavior of water available in the soil throughout the crop cycle; this was also the case in Study II, even with the smaller number of observations made. The statistical indicators for the two crop years are shown in Table 5. In Study I, b_0 values remained around 1.0 for all cases analyzed, with no trends towards over or underestimation of ASW, showing good fit between the observed and simulated values. The coefficient of determination (R^2) was significantly high (> 0.90) in all situations, indicating that the model has good ability to explain the variation in the observations. Miao et al. (2016) found b_0 values between 1.01 and 1.07 and RMSE between 9.4 and 16.4 mm when they studied 3 years of strip-irrigated sunflower in China. These results contributed to a high modeling efficiency coefficient for most treatments, suggesting that the variability of the residuals was lower than in the ASW observations. The estimation errors were small, with RMSE values ranging from 3.34 to 8.89 mm. These results are comparable to other studies conducted in the Santa Maria region. Martins et al. (2013) found average RMSE values relative to TAW of 2.6% for maize, with a range of 2.0 to 3.2%. Paredes et al. (2018) determined RMSE values between 4.2 and 5.2 mm during calibration and between 5.0 and 7.2 mm during validation for the Tifton 85 variety.

Figure 4 shows how the basal crop coefficient (K_{cb}), evaporation coefficient (K_e), of the actual basal crop coefficient ($K_{cb\ act}$) and the single crop coefficient ($K_{c\ act}$) derived by the simulation model change according to the different irrigation strategies. Although the K_c s of the most economically important crops have been studied to better estimate water requirements using direct measurements (lysimetry, eddy covariance, Bowen's ratio), this information is lacking for crops such as sunflower (Pereira et al., 2021).

The standard values of the basal crop coefficients for the initial, mid-season and end season ($K_{cb\ ini}$, $K_{cb\ mid}$ e $K_{cb\ end}$) were calibrated as 0.20, 1.05 and 0.25, respectively, and the $K_{cb\ mid}$ was lower than the 1.15 recommended by Pereira et al. (2021). The $K_{cb\ mid}$ adjusted to the local climatic conditions by the SIMDualKc model was 0.97, 0.75, 0.71 and 0.44 for the treatments with 80, 70, 60 and 50% of TAW, respectively. These values were significantly lower than those reported by Howell et al. (2015) in sprinkler irrigated sunflower and without water stress (1.22). The lower $K_{cb\ mid}$ values adjusted to climate are related to the plant characteristics, lower IAF, lower fraction of ground cover, low wind speed ($1.26\ m\ s^{-1}$)

and relative humidity above 45% (51%) during crop growth and mid-season. The calibrated $K_{cb\ end}$ ($K_{cb\ end} = 0.25$) was similar to that recommended by Pereira et al. (2021). Similar values to the calibrated values were observed for the $K_{cb\ end}$ adjusted to climate. In the study by Howell et al. (2015), the $K_{cb\ end}$ declined to values close to $K_{cb\ ini}$ (0.15) due to the more arid conditions.

The results show that no stress occurred in the treatments maintained at 80% of TAW in Study I (Figure 4A) or in the irrigated treatment in Study II (Figure 4E). The other treatments experienced periods of water stress, which were detected when the $K_{cb\ act}$ curve fell below the potential K_{cb} curve. In treatments with less water replenishment from irrigation or rainfall, these stress periods were longer because the ASW was lower due to the lack of irrigation.

Regarding the evaporation coefficient (K_e), it can be observed that the model was able to capture the dynamics of K_e , and showed an increase after each entry of water into the system, which is represented by the peak values occurring due to the high water availability.

The differences between 2018/19 and 2020/21 (Table 6) were most noticeable during the initial and vegetative growth stages, as well as in the final stage, and were less significant for K_e in the mid-season. Therefore, the fluctuations in $K_{c\ ini}$ and $K_{c\ end}$ values are mainly due to the variability in K_e , which is influenced by the number and intensity of water inputs into the soil via precipitation or irrigation and by water losses due to soil evaporation (Petty et al., 2023). The results indicate that the $K_{c\ ini}$ decreased with decreasing water availability and in Study II the $K_{c\ ini}$ difference between the irrigated and the rainfed treatments was 0.3. The value of $K_{c\ ini}$ is influenced by soil evaporation, which is determined by the ET_0 rate and irrigation frequency (Allen et al., 1998).

Table 7 shows the water balance components for all irrigation strategies during the 2018/19 and 2020/21 growing seasons. Of the total of rainfall that occurred during the 2018/19 growing season (918 mm), 85 mm entered Study I due to three unexpected downpours during the night, which were accompanied by intense winds and electrical discharges that made it impossible to activate the electromechanical system of the mobile structure.

In both studies, the $ET_{c\ act}$ was the main output component of the water balance, depending on soil water availability, crop stage, and atmospheric evaporative demand (ET_0). Whenever ASW was below RAW, the $ET_{c\ act}$ was reduced, as reported by

Table 5. Performance indexes of the simulation of the available water in the soil for the irrigation strategies in Study I and statistical analysis of the water supply situations in Study II

Growing season	Irrigation strategy	b_0	R^2	RMSE (mm)	NRMSE (%)	EF
2018/19	80% TAW	1.00	0.61	3.25	3.30	0.90
	70% TAW	1.00	0.75	6.26	6.80	0.86
	60% TAW	1.01	0.80	8.11	9.70	0.88
	50% TAW	1.03	0.85	8.75	12.0	0.90
2020/21	Irrigated	0.91	0.99	4.46	3.50	0.87
	Rainfed	0.91	0.99	7.17	9.70	0.96

b_0 and R^2 - Regression coefficient forced through origin and determination coefficient, respectively; RMSE - Root mean square error; NRMSE - Normalized root mean square error; EF - Modeling efficiency

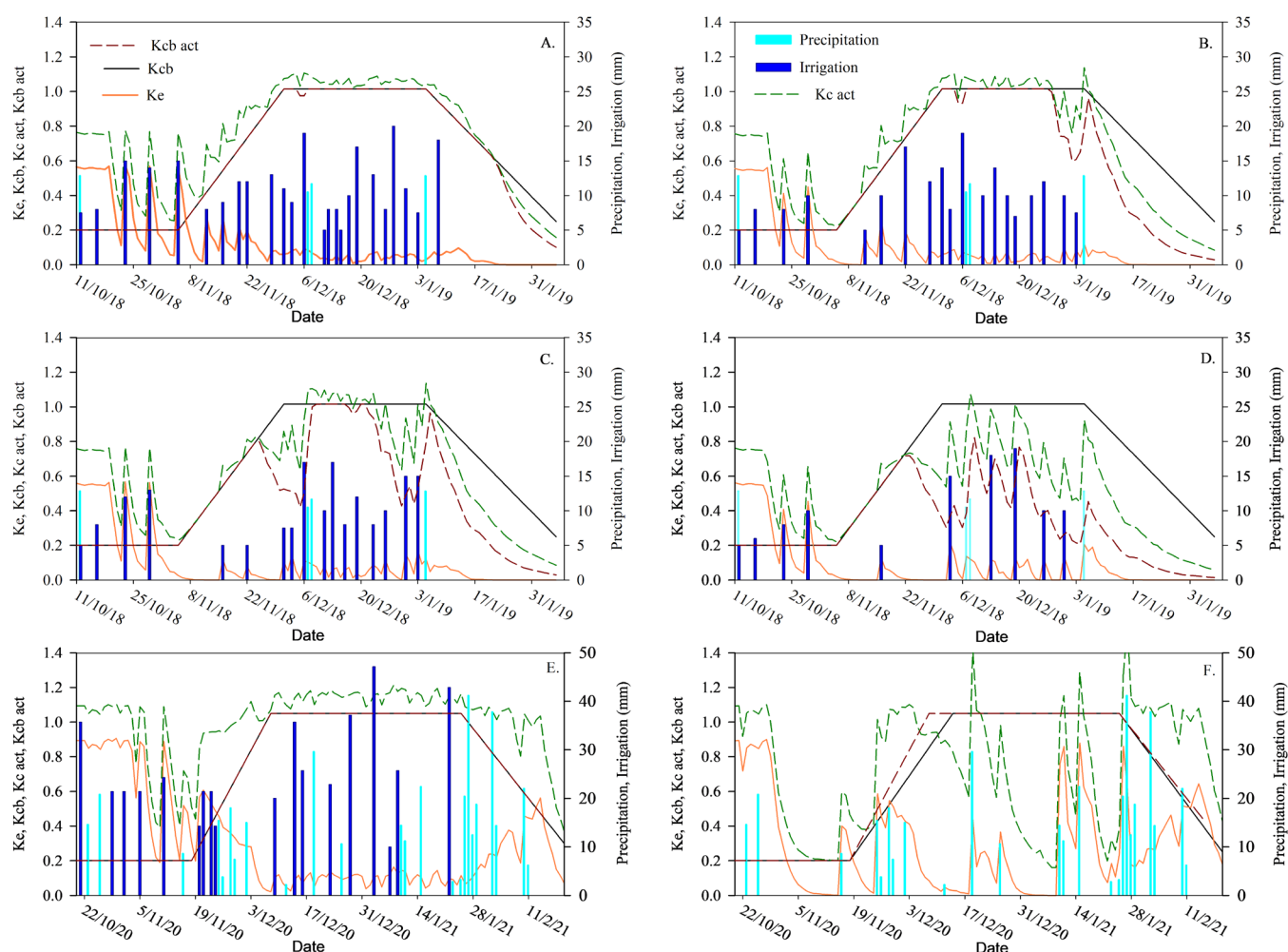


Figure 4. Daily variation in the basal crop coefficient (K_{cb} , —), actual basal crop coefficient ($K_{cb\ act}$, ---), the evaporation coefficient (K_e , —) and the actual crop coefficient ($K_{c\ act}$, ---) for the treatments in Study I, maintaining the total available water (TAW) percentage for model calibration at (A) 80% TAW and for validation at (B) 70% TAW, (C) 60% TAW and (D) 50% TAW, in the 2018/19 growing season; (E) Irrigated, (F) Rainfed, during the 2020/21 growing season, Irrigation (mm) and precipitation events are also depicted (mm)

Table 6. Crop coefficients (K_c) for the irrigation strategies in the two experiments

Crop year	Irrigation strategy	Crop development stage				
		Initial	Growth	Mid-season	End season	Harvest
2018/19	80% TAW	0.56	0.56 - 1.06	1.06	1.06 - 0.16	0.16
	70% TAW	0.49	0.49 - 1.02	1.02	1.02 - 0.08	0.08
	60% TAW	0.52	0.52 - 0.95	0.95	0.95 - 0.08	0.08
	50% TAW	0.49	0.49 - 0.73	0.73	0.73 - 0.06	0.06
2020/21	Irrigated	0.89	0.89 - 1.15	1.15	1.15 - 0.31	0.31
	Rainfed	0.58	0.58 - 0.61	0.61	0.61 - 0.43	0.43

Table 7. Water balance components calculated using the SIMDualKc model for the different irrigation strategies during the 2018/19 and 2020/21 studies

Irrigation strategy	P (mm)	I	DP	RO	NBWUR (%)	ΔASW (mm)	$ET_{c\ act}$ (mm)	$T_{c\ act}$	E_s	$E_s/ET_{c\ act}$ (%)
2018/19										
80% TAW	85	283	0	3	3	-45	412	342	69	16.8
70% TAW	85	197	0	6	7	-84	362	312	50	13.8
60% TAW	85	175	0	5	6	-83	340	289	52	15.1
50% TAW	85	106	0	5	1.9	-91	279	233	46	16.4
2020/21										
Irrigated	417	324	49	56	14.0	34	596	418	175	29.5
Rainfed	417	0	0	44	11.0	-36	395	244	151	38.2

P - Precipitation; I - Irrigation; DP - Deep percolation; RO - Runoff; $(DP+RO)/(P+I)$ NBWUR - Non-beneficial water use ratio; ΔASW - Variation in available water in the soil; $ET_{c\ act}$ - Actual or real crop evapotranspiration; $T_{c\ act}$ - Actual or real crop transpiration; E_s - Soil evaporation; $E_s/ET_{c\ act}$ - Soil evaporation rate

Rosa et al. (2012). There was a significant difference in $ET_{c\text{act}}$ (32%) between the treatment maintained without stress (80% of TAW) and the treatment with the highest induced stress (50% TAW), with a lower value in the latter. The reduction in $ET_{c\text{act}}$ affected growth parameters such as IAF (Figure 2) and crop yield. Soil evaporation (E_s) was low throughout the crop cycle in Study I, and remained below 20% of the $E_s/ET_{c\text{act}}$ ratio, i.e. less than 20% of the total water entering the experimental area was lost through E_s . This rate of loss was directly related to the soil wetting events and less favorable weather conditions for evaporation during the 2018/19 growing season. In Study II, the E_s was higher than in Study I due to the larger number of soil wetting events (rain + irrigation). Practices that improve precipitation and irrigation water use tend to increase Tc and reduce losses such as E_s , DP and RO, according to Jovanovic et al. (2020).

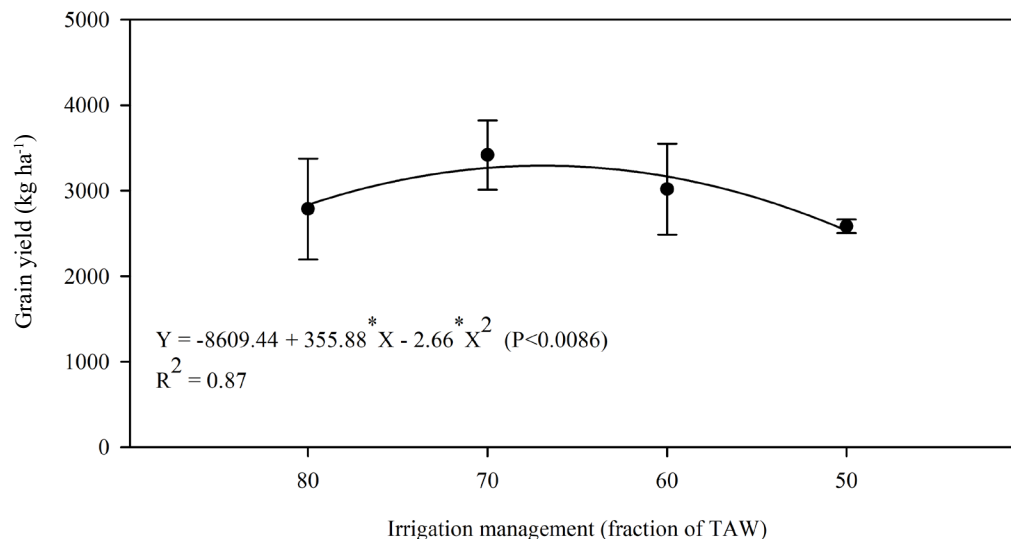
Figure 5 shows the sunflower grain yield for the different irrigation treatments used in Study I. The highest yields were found in the treatment maintained at 70% TAW followed by that maintained at 60%, with the crop maintained at 50% TAW having the lowest yield. Table 8 shows that grain yield was the highest in the treatment maintained at 70% of TAW, in Study I, suggesting that the strategy of partially reducing water recharge could be a viable irrigation management strategy, especially in water-scarce areas. Although in Study II, the difference in $ET_{c\text{act}}$ between irrigated and rainfed sunflowers was similar to the difference between the treatments of 80 to 50% of TAW in Study I, the yield loss in Study I was higher

(40%). Compared to studies in the literature, both WP and WP_i were higher in both experiments. Howell et al. (2015) found a mean of 0.52 kg m^{-3} in well-watered sunflowers in Texas.

Soothar et al. (2021) reported that a soil moisture of 70% allows crop yields to be maintained in relation to water use efficiency under conditions of water scarcity. In the current study, as irrigation increased grain yield increases to the level equal to 70% of TAW, and grain yield decreases when the available soil water is increased to 80% of TAW. The water stresses alter plant growth patterns and reduce productivity as the intensity of the stress increases. But managing irrigation with a mild water deficit to the crop allows farmers with water restrictions to maintain crop yields without over-irrigating above the crop's water needs.

CONCLUSIONS

1. The single and basal crop coefficients of sunflower were calibrated for the mid-season and the end season. Estimation errors obtained by the study were small, with root mean square error values ranging from 3.25 to 8.75 mm.
2. Grain yield and water use efficiency were high in the irrigation strategies adopted, ranging from 2065 to 3420 kg ha^{-1} and 0.44 to 2.59 kg m^{-3} , respectively.
3. The best water supply strategy observed was the one in which the soil available water was maintained at 70% of total available water.



* - Significant at $p \leq 0.01$ by F test. Vertical bars indicate standard deviation

Figure 5. Sunflower grain yield in function of fraction of total available water (TWA) in Study I

Table 8. Grain yield, water input components, water productivity and irrigation water productivity

Growing season	Irrigation strategy	Ya (kg ha^{-1})	TWU (m^3)	WP (kg m^{-3})	WPI (kg m^{-3})
2018/19	80% TAW	2790	3230	0.86	0.99
	70% TAW	3420	1980	1.73	1.74
	60% TAW	3018	1770	1.71	1.72
	50% TAW	2585	1000	2.59	2.44
2020/21	Irrigated	3425a	7750	0.44	1.06
	Rainfed	2065b	3810	0.54	
	CV (%)	18.30			
	Mean	2745			

Averages followed by the same letter do not differ at 5% significance by the Scott-Knott test; CV: Coefficient of variation; Ya - Crop yield; TWU - Total water used; WP - Water productivity; WPI - Productivity of irrigated water

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