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Winter wheat irrigation parameters in the Brazilian Cerrado

Jorge Cesar dos Anjos Antonini[1], Artur Gustavo Muller[1], Alexsandra Duarte de Oliveira[1*], Fabiana Piontekowski Ribeiro[1], Jorge Henrique Chagas[2], Angelo Aparecido Barbosa Sussel[1], Juaci Vitoria Malaquias[1], Marcos Vinícius Araújo dos Santos[1], Julio Cesar Albrecht[1]

[1]Embrapa Cerrados, BR 020, km 18, CEP. 08223 – 73310 – 970, Planaltina, DF – Brasil
[2]Embrapa Wheat, Rodovia BR-285, Km 294 Caixa Postal: 3081 CEP: 99050-970 - Passo Fundo, RS, Brazil

***Corresponding Author: alexsandra.duarte@embrapa.br**

Abstract

Wheat is the second most produced cereal in the world. The gap between production and consumption in Brazil shows that wheat production must be increased to meet the domestic demand. In this context, the objective of this study was to determine the crop coefficient of wheat and the ideal moment for irrigation, based on the soil water depletion rate (f). The study was carried out in the tropics, on an Oxisoil (Typic Haplustox), in an experimental field of Embrapa Cerrados in Planaltina, Federal District of Brazil. The experimental design consisted of randomized blocks with three replications. The treatments were differentiated by the soil water depletion index (f) of 0.2, 0.4, 0.6, and 0.8. In other words, irrigation was initiated when 20, 40, 60 and 80% of the available soil water capacity (AWC) at a soil depth of 0.4 m was consumed by the crop. Wheat yield and yield components were evaluated. The phenological development was monitored based on Zadok's scale, in days after emergence, and the management parameters crop coefficient (Kc) and irrigation timing were determined. The results indicated a soil water depletion index of 0.4 as the best indicator for beginning wheat irrigation. Under this condition, Kc can be estimated daily as a function of days after emergence (DAE) by the quadratic polynomial regression or curve fitting method, adjusted as follows: $Kc = -0.000298 \times DAE^2 + 0.036695 \times DAE + 0.332486$. Alternatively, the means of Kc of each phenological crop phase can be used: Kc = 0.45 (establishment); 0.81 (tillering); 1.21 (booting); 1.43 (flowering); 1.27 (grain formation); and 0.89 (maturation). Thus, there is a limit of consumption of soil available water, at which wheat still achieves the full yield potential, with a rational use of water which varies according to the development phase.

Keywords: soil water management, crop coefficient, evapotranspiration.

Introduction

With a production of 789.5 million tons of grains in the 2022/23 growing season, wheat is the second most produced cereal in the world, behind only rice (Li et al., 2022; USDA, 2023). In the same growing season, 10.55 million tons were produced in Brazil, whereas total consumption was 12.39 million tons (CONAB, 2023). Brazil is the world's second-largest importer of wheat (*Triticum aestivum* L) (Cracknell, 2016), due to the high production costs and relatively low yields, compared with other wheat-producing countries (Brum and Müller, 2008).
Around 90% of all wheat in Brazil is grown in the southern region, although an area of around 1.5 million hectares in the Brazilian Cerrado, specifically, in Central Brazil, is available for irrigated cultivation of high-quality wheat for industrial baking (Pasinato, 2018; Oliveira et al., 2021).
Due to the strong climatic seasonality of the Cerrado region (6 dry and 6 rainy months), winter wheat can only be cultivated if irrigated. In the last 10 years, the mean wheat yield in this region (4,466 kg ha^{-1}), was higher than in the South (2,716 kg ha^{-1}), under rainfed cultivation (CONAB, 2023). The high levels of wheat yield and quality clearly show the economic viability of irrigated wheat in Central Brazil (Flumignan et al. 2013; Guedes et al., 2021; Soares et al., 2023). Studies indicated that irrigated wheat is a high-yielding crop and an interesting option for fall and winter crop rotations in the Midwest, owing to the environmental characteristics of the region (Silva et al., 2020). From this point of view, the prospect of expansion of irrigated wheat in tropical regions of Brazil requires updated studies on water use and irrigation management (Ferrarini et al. 2016).
The lack of basic information on the crop water demand in tropical environments is one of the causes of the inefficiency of agricultural water use (Barrow, 2016). Suitable irrigation practices must be established that define how to use the available water resources most efficiently to optimize yields for farmers. A successful irrigation management depends on the correct timing and dosage of water application. In this case, the physico-hydrical properties of soil, plant physiology and local climatic conditions must be known (Brito et al., 2015). Particularly, knowledge about the available water capacity (AWC) is fundamental to define the appropriate irrigation time. This property corresponds to the difference

between soil moisture at field capacity (FC) and the permanent wilting point (PWP), measured at the effective depth of the plant root system, where 80% of the roots are concentrated. However, as soil moisture decreases from the FC level, at a certain limit, crop yields begin to be affected. This limit depends on the crop and edaphoclimatic conditions and has been conceptualized as soil water depletion index (f). This índex represents the fraction of AWC the plant can consume without difficulty in extraction. Thus, f represents the limiting threshold of AWC depletion, which indicates the time to initiate irrigation (Bernardo et al., 2019).

Under controlled irrigation conditions, the AWC depletion limit can be determined by monitoring the soil water balance daily. This balance represents the difference between the water that enters a cultivated area, through effective rainfall and irrigation, and the water that leaves the area by crop evapotranspiration (ETc). For irrigation management, ETc can be estimated as the product of reference evapotranspiration (ETo) and crop coefficient (Kc). Reference evapotranspiration (ETo) can be estimated by several indirect methods of which the Penman-Monteith is the standard method for estimating ETo daily (Allen et al., 1998). This is an acknowledged, universal approach to determine the crop water demand and schedule irrigation applications (Rosa et al. 2012; Taylor et al. 2015). Despite the expansion of irrigated wheat in Brazil, basic knowledge on wheat evapotranspiration and irrigation demand in the tropical producing regions of Brazil is scarce, resulting in inefficient irrigation managements (Pereira et al., 2023).

In an irrigated system in the Cerrado region, assuming a depletion coefficient of 0.5, Silva et al., (2020) found that the mean ETc in wheat cultivars varied from 3.87 to 4.10 mmd^{-1} and, accordingly, the maximum Kc was 1.33 in the flowering phase. Also in the Cerrado, at a depletion coefficient of 0.55, Pereira et al., (2023) found ETc values between 2.45 and 4.51 mmd^{-1}, while Kc peaked in the middle of the cycle, with 1.28. In a greenhouse study, Soares et al., (2023) observed that the cultivars recommended for the Cerrado have high water requirements, which causes yield losses, as water depletion in the soil increases. This reinforces the appropriateness and importance of studies on the timing of irrigation based on soil water depletion.

Previous studies (Moreira et al., 2004) established the irrigation timing and Kc values for wheat in the Cerrado region, based on soil water tension. These studies used old cultivars, no longer recommended for cultivation. The modern genotypes on the other hand, developed in regional breeding programs, have a much higher yield ceiling and grain quality. Therefore, we hypothesized that the actual water demand of the highest yielding wheat cultivars is greater, requiring adjustments of these parameters. In this context, the objective of this study was to estimate the irrigation timing and Kc of wheat cv. BRS 394, based on soil water depletion (f).

Results and discussion

Water depletion index and yield components

The data of yield and yield-related components at four water depletion index (f) are shown in Table 2. At the 5% probability level, the yields were statistically not significantly different at (f) 0.2; 0.4, and 06. However, the yield was significantly lower at (f) 0.8, compared to (f) 0.2 and 0.4. This yield pattern in response to the variation of (f) highlights that the soil moisture level at irrigation application influenced wheat production significantly. At a depletion of 40% or lower in the soil AWC (f = 0.4), the wheat crop became water-stressed due to the increased difficulty with water and nutrient uptake. Water stress hampers photosynthesis and the translocation of nutrients assimilated by leaves, decreasing grain yield, as similarly described by Amer et al. (2016). Regardless of the plant developmental stage, drought is one of the stress types that reduces crop yields most drastically (Pereira et al., 2019). According to Soares et al. (2023), the water requirement of wheat cv. BRS 394 to express the maximum productive potential (growth and production) in Cerrado soil is high (5 kPa, water tension in the soil equivalent to field capacity), in disagreement with our study, where yields were unaffected at (f) = 0.4.

Different (f) levels did not affect the grain quality either since hectoliter weight (HW) and 1000-seed weight (1000SW) data did not differ significantly in response to the different levels. Indirectly, HW expresses the grain quality. The higher the HW value, the higher the semolina yield. In Brazil, wheat is classified into three types for market purposes, based on the minimum HW value. Type 1 has the highest commercial value and a minimum reference value of 78 kg h L^{-1} (Corrêa et al., 2006). The grain quality for industrial processing is defined by 1000SW, where a value of 35 to 45 g is desirable (Guarienti, 1996).

The number of spikelets per square meter (NSM) did not differ significantly at any (f) level, while the number of spikelets per head (NSH) was affected by the varying (f) values. A NSH value of 12.6 was found for (f) = 0.8, significantly lower than in the other treatments. A similar pattern was observed for crop yield, suggesting that the performance of the number of spikelets per head is a parameter that affects yield, as already stated by Vahamidis et al. (2019) and Moreira and Cardoso (2009) in studies on water stress effects on the reproductive phase of wheat.

Principal component analysis showed a total variance of 61% in the first two principal components, (Figure 3). The PCA weights for yield, HW, and 1000SW were 0.66, 0.75, and 0.66, respectively, while number of grains per spikelet (NGS) had a PCA weight of 0.97.

Kc determination and dynamics

The experimental data to estimate ETc and Kc were obtained in the treatment at (f) = 0.4. Statistically, wheat yield remained at the maximum level, and no relevant water restriction for wheat was observed in this treatment (Table 2).

Regression analysis involving Kc values as a function of number of days after emergence (DAE) resulted in a better fit of the quadratic polynomial equation, according to the results of determination coefficient (R^2 = 0.77) (Figure 4). In the initial phase, the Kc amplitude was relatively small. However, as the crop cycle advanced, the values tended to increase, reaching a maximum value (1.45) at 60 DAE, and then decreasing until the end of the crop cycle. Values were highest between 50 and 72 DAE, at wheat flowering. This behavior was already expected, because the leaf area index reaches its maximum in this phase, which intensifies transpiration and, consequently, results in higher crop water consumption. Similar Kc dynamics for the entire wheat cycle, in several different regions and climate conditions, were also described by Laaboudi et al. (2015).

Table 1. Soil physical-hydraulic properties in the experimental area. BD = bulk density; FC = field capacity; PWP = permanent wilting point; and AWC = available water capacity.

Soil Depth (cm)	Sand (%)	Clay (%)	Silt (%)	BD (g cm^{-3})	FC (cm³ cm-³)	PWP (cm³ cm-³)	AWC (mm)
0 – 20	33	52	16	1.08	0.32	0.19	26.00
20 – 40	32	54	14	1.06	0.31	0.19	24.40

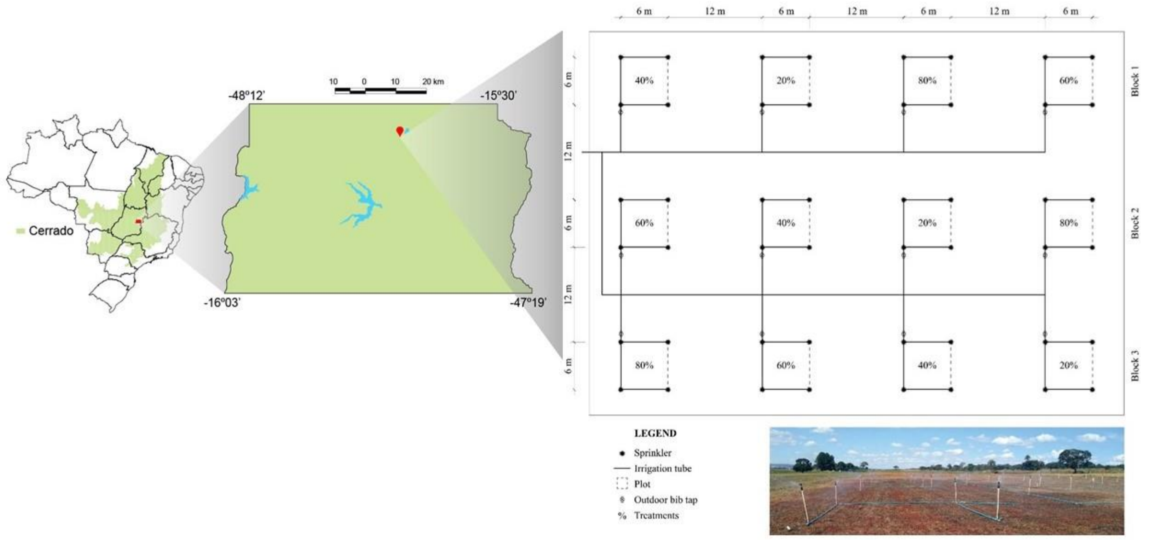

Fig. 1. Location of the study area and experimental design.

Table 2. Analysis of variance and separation of the mean values of yield (Y), hectoliter weight (HW), 1000-seed weight (1000SW), number of spikes per square meter (NSM), number of spikelets per head (NSH), and number of grains per spikelet (NGS) of wheat, according to the soil water depletion index (f), at the time of irrigation application and the growing season (GS).

Source of variation		Y	HW	1000SW	NSM	NSH	NGS
		(kg ha^{-1})	(g hl^{-1})	(g)			
Soil water depletion index (f)	0.2	5387.77a	80.43a	35.93a	487.33a	14.87a	1.98a
	0.4	5365.08a	79.48a	36.82a	478.50a	14.15a	2.30a
	0.6	4994.86ab	81.98a	36.88a	428.67a	13.97a	2.08a
	0.8	4416.04b	81.73a	38.13a	433.00a	12.63b	1.97a
Growing season (GS)	GS	5348.92a	80.24a	36.25b	500.75a	13.30a	2.06a
	GS	4732.95b	81.58a	37.63a	413.00b	14.51b	2.11a
F test	F	3.98*	2.74ns	1.98ns	1.28ns	8.41*	1.43ns
	CY	7.33*	3.58ns	4.62*	10.70*	14.14*	0.15ns
	CYxf	1.02ns	2.73ns	1.91ns	0.66ns	0.78ns	0.77ns
CV%		11.05	2.13	4.27	14.38	5.66	15.07

* Significant by the F test at the level of significance of 5%; ns = non-significant. Mean values followed by the same letter in a column did not differ statistically from each other by Tukey's test at 5% significance.

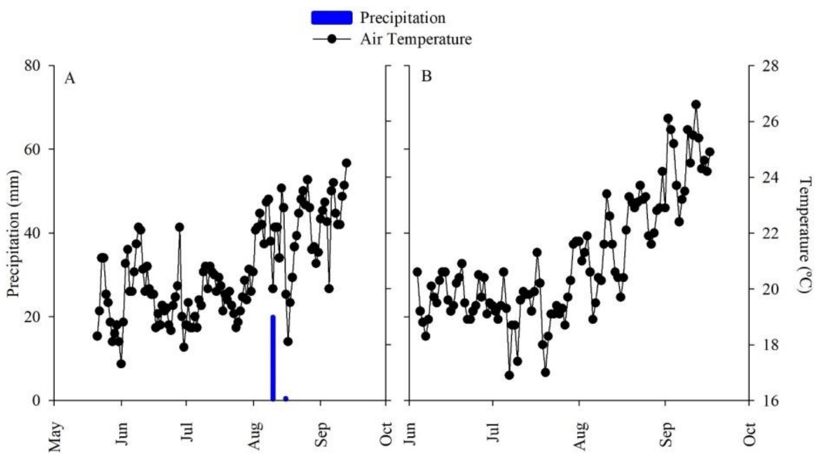

Fig. 2. Precipitation (mm) and air temperature (◦C) in 2018 (A) and 2019 (B).

Table 3. Variations in the wheat crop coefficient, according to the phenological stage, in the soil and climatic conditions of the Distrito Federal

Phenological stage	Duration (days)	Crop coefficient (Kc)		
		Initial	Final	Mean
Establishment	8	0.33	0.57	0.45
Tillering	15	0.61	1.00	0.81
Booting	25	1.02	1.40	1.21
Flowering	20	1.41	1.45	1.43
Grain formation	30	1.45	1.09	1.27
Maturation	15	1.07	0.70	0.89
Total cycle	113	-	-	1.16

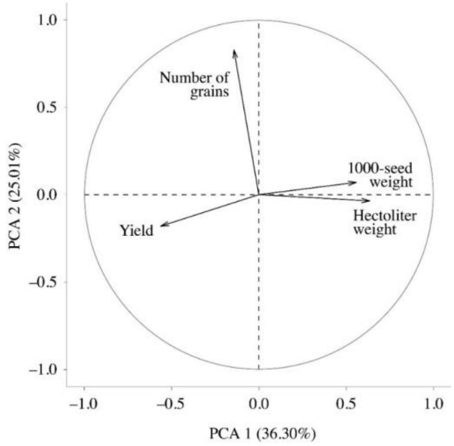

Fig. 3. Principal component analysis for yield variables of wheat cv. BRS 394 in an experiment installed in a no-tillage system in 2018 and 2019.

Table 4. Variations in wheat parameters, according to the soil water depletion index f) in the crop cycle (CC), irrigation application (IA), cumulative evapotranspiration (ETa), number of irrigation applications (NIA), mean water level applied by irrigation (MWD), and water-use efficiency (WUE).

(f)	CC (day)	IA (day)	ETa (mm)	NIA	MWD (mm)	WUE (kg ha^{-1} mm^{-1})
0.2	103	95	497.51	36	13.82	10.83
0.4	101	93	456.06	19	24.00	11.76
0.6	100	92	447.08	14	31.93	11.17
0.8	96	88	331.28	9	36.81	13.33

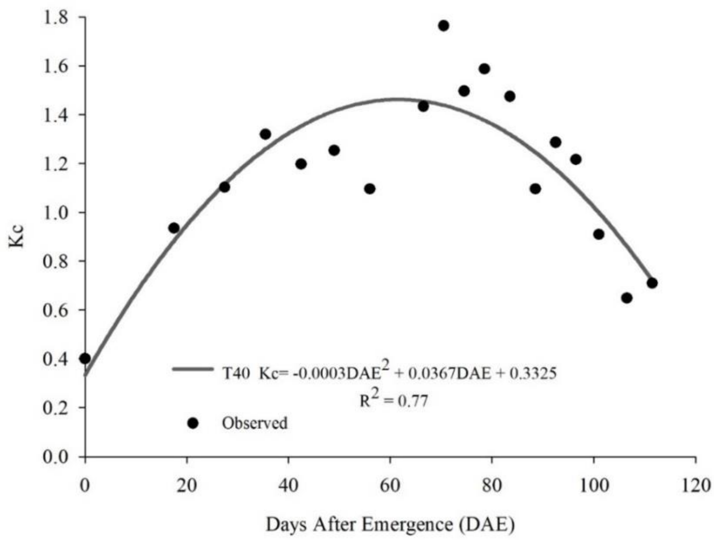

Fig.4. Relationship between crop coefficient (Kc) and number of days after emergence (DAE) of wheat cv. BRS 364 under the edaphoclimatic conditions of the Federal District in 2018 and 2019.

The initial, final, and mean Kc values for the entire wheat cycle as well as for each phenological phase are listed in Table 3. The mean Kc value for the total cycle was 1.16, very close to the value of 1.15 indicated by the Food and Agriculture Organization (FAO) (Allen et al., 1998). The Kc values in the phenological stages of establishment, tillering, booting, flowering, grain formation, and maturation were 0.45; 0.81; 1.21; 1.43; 1.27; and 0.89, respectively. The highest mean value (1.43) was found in the flowering phase. For this phase, Vieira et al. (2016) found a value of 1.01, Laaboudi et al. (2015) 1.35, and Pereira et al., (2023), in the Cerrado region, found Kc values from 0.88 to 1.36 during the crop cycle. The differences between these values and the results of our study can mainly be explained by the differences between the climatic conditions of the study sites, as pointed out by Allen et al. (1998) and Pereira et al. (2022).

Table 4 shows that, as (f) increases, the growth cycle and cumulative evapotranspiration decrease. Thus, we can conclude that the plant adjusts to the soil water conditions, which accelerates physiological and biochemical processes and affects the regulation of stomata opening and chlorophyll biosynthesis, corroborating findings of Aurangzaib et al. (2021) and Campos et al. (2021). Water use efficiency (WUE) indicates the crop responsiveness to water stress in relation to the potential yield (Zhang et al., 2010). In this study, WUE increased as ETa decreased, as similarly observed by Brito et al. (2013) and Soares et al. (2021) in studies on sweet corn in the United States and sweet corn in the state of Paraíba, Brazil, respectively. The reduction in the number of irrigation applications and increase in water level delivered per operation was related to the underlying criterion of defining irrigation according to the (f) level, with a water level equal to that required to reestablish field capacity in the soil profile exploited by the effective root system of the crop.

The contribution of this study on the water depletion rate and Kc of wheat allows a reduction in irrigation frequency and water levels, according to the evapotranspiration demand. This can make an expansion of this crop into non-traditional cultivation areas possible and contribute to a more rational use of water input, which is an important factor in the context of climate change and increased food demand.

Materials and Methods

Research site

The study was conducted in an experimental area of Embrapa Cerrados, in Planaltina, Distrito Federal, Brazil (15° 35' 30" S, 47° 42' 30" W; at 1030 m asl) (Figure 1). According to the Köppen-Geiger climate classification system, the dominant climate in the study area is Aw, i.e., tropical with dry winters and mean temperatures above 18 °C in the coldest month. Mean annual precipitation is 1394 mm, of which 87% falls between October and April. The mean annual temperature is 20.7 ºC. Rainfall and air temperature, for the study period of 2018 and 2019, are listed in Figure 2. The soil was classified as Oxisol (Typic Haplustox) (Soil Survey Staff, 2014), with physical-hydraulic properties specified in Table 1 and chemical properties described by Teixeira et al., 2017.

Experimental design and management

The experiment was installed in a no-tillage area, on 12 plots (6 × 6m), separated from each other by 12 m (Figure 1). The experiment was arranged in a randomized block design, with three replications. Wheat cv. BRS 394 was sown on May 21, 2018, and replicated on May 30, 2019, at a quantity to ensure a density of 315 viable plants per square meter. Each plot consisted of 28 plant rows spaced 0.175 m apart.

Fertilization consisted of 400 kg ha^{-1} of 4-30-16 (N-P_2O_5-K_2O) fertilizer. Nitrogen was sidedresssed, at a rate of 120 kg ha^{-1}, 15 DAE, with urea as N source. Weeds were controlled with pendimethalin-based herbicides, applied at a rate of 4 L ha^{-1} of the commercial product before wheat germination. After emergence, metsulfuron-methyl based herbicide was applied at a rate of 10 L ha^{-1}. Armyworm (*Pseuddaletia sequax*) and aphid (*Rhopalosiphum padi*) incidence was controlled by two applications of chlorpyrifos insecticide at 1.5 L ha-1 during crop booting. To prevent fungal diseases, a fungicide based on trifloxystrobin and tebuconazole was applied at the booting stage at 0.8 L ha^{-1}.

Treatments (Irrigation regimes)

The treatments were designed according to the soil water depletion rate (f), namely 0.2; 0.4; 0;6; and 0;8. In other words, irrigation was initiated when AWC was reduced to 20, 40, 60 and 80%, respectively, due to crop evapotranspiration. In our study, AWC was considered at the effective depth of the root system, established as 0.4 m for wheat.

Irrigation management, monitoring and evaluations

A conventional irrigation system was used with four impact sprinklers per plot, at an operating pressure of 1.4 bar and a flow rate of 0.804 m³ h^{-1}. The estimated water application intensity was 9 mm h^{-1} and water distribution uniformity in the plot area 95%. After planting, all plots were irrigated with a water depth of 20 mm. Then, at an interval of two days, two more irrigations were applied with a water depth sufficient to raise soil moisture to FC at the effective depth of the root system. After plant germination, soil moisture was monitored daily with a CPN 503 Elite Hydroprobe® neutron probe. Aluminum access tubes were installed in the middle of the plots at a depth of 0.70 m, allowing soil moisture readings at depths of 0.10; 0.30; and 0.50 m, between 8:00 and 9:00 AM, local time. Irrigation was applied whenever moisture monitoring confirmed AWC depletion according to the established value for each treatment. Irrigations were scheduled to be completed later in the day at 5:00 PM so that the water was redistributed across the soil profile during the night.

The effects of different f treatments on yield and yield components were evaluated in order to identify the best timing for irrigation. In each plot, grain yield (Y), hectoliter weight (HW), and 1000-seed weight (1000SW) data were determined in five 6-m long rows. In addition, the number of spikelets per square meter (NSM), number of spikelets per head (NSH), and the number of grains per spikelet (NGS) were recorded by harvesting a 1.9-m long row. The ideal timing for irrigation was considered as the one when (f) corresponds statistically to the highest grain yield. Moreover, Kc was estimated based on this condition of f, according to Eq. 1 (Allen et al. 1998):

$$Kc = \frac{ETc}{ETo} \qquad (1)$$

The ETc was estimated from the soil water balance model (Eq. 2) (Reichardt and Timm, 2004), which was fed with soil moisture data recorded in a treatment in which the (f) variations did not affect yield statistically. Under this condition, we assumed that there was no water restriction for wheat development.

$$\mathrm{ETc} = \mathrm{R} + \mathrm{I} + \mathrm{Q} + \Delta\mathrm{A} \quad (2)$$

Where: R is precipitation; I irrigation depth; Q the water level that depends on the drainage and capillarity of the soil layer; and ΔA is water storage variation in the soil profile. As the water balance was estimated between irrigations and without rainfall, the capillary effect was assumed to be negligible since the soil profile was sufficiently deep. In this way, the water balance equation can be shortened as follows (Eq. 3):

$$\mathrm{ETc} = \Delta\mathrm{A} \quad (3)$$

The actual soil moisture values, as a function of depth (θ(Z)) and used to estimate water storage in the soil profile, were measured between irrigations, with the same equipment and at the same depths as described above. Initial storage (hzi) was estimated around 15 h after irrigation application whereas final storage (hzf) was estimated immediately before the next irrigation. Water storage was estimated by the trapezoidal rule (Libardi, 2005) (Eq. 4).

$$\mathrm{hz} = [\theta(\mathrm{Z}10) + \theta(\mathrm{Z}30) + 0.5(\theta(\mathrm{Z}50))]\Delta\mathrm{Z} \quad (4)$$

Where: hz is water storage in the 0−50 cm soil layer; θ(Z10), θ(Z30), and 0.5(θ(Z50)) represent the volumetric water content in the 0−20, 20−40 and 40−50 cm soil layers, respectively; and ΔZ is the soil layer thickness, represented by the measurement points of θ, set at a soil depth of 20 cm. The variation in water storage between irrigation applications (ΔA) was determined by the difference between the water level stored in the control profile after irrigation application (hzi) and immediately before the next irrigation (hzf), according to the following equation (Eq. 5):

$$\Delta\mathrm{A} = \mathrm{hzi} - \mathrm{hzf} \quad (5)$$

Reference evapotranspiration (ETo) was estimated from data from the automatic meteorological station of Embrapa Cerrados. The weather station was installed at a distance of 500 m from the experiment, (elevation difference of 4.5 m). The ETo was estimated by the Penman-Monteith equation (Eq. 6) (Allen et al., 1998).

$$\mathrm{ETo} = \frac{0.408\Delta(\mathrm{Rn} - \mathrm{G}) + \gamma\frac{900}{\mathrm{T} + 273}\mathrm{U}_2(\mathrm{e_s} - \mathrm{e_a})}{\Delta + \gamma(1 + 0.34\mathrm{U}_2)} \quad (6)$$

Where: Rn is net irradiance; G the soil heat flux (G = 0, on a daily time basis); Δ the vapor pressure gradient; U2 the wind speed (mean daily value) at 2 m above the ground surface; e_s the saturation vapor pressure; e_a the actual vapor pressure; T the mean daily air temperature; and ɣ the psychrometric constant.

Water use efficiency (WUE) was computed as the ratio between yield (Y) and the actual cumulative evapotranspiration in the cycle (ETa) (Wang et al., 2016; 2023).

Statistical analysis

The yield and yield component data were first subjected to individual analysis of variance to determine the homogeneity of experimental error variance of the crops. Once the assumption of homogeneity of experimental error variance was met, indicated by the ratio of the highest by the lowest residual mean square of the individual analysis of variance of lower than seven (Gomes, 1991), combined analysis of variance of the experiments was performed.

After confirming the normality of data distribution by the Shapiro-Wilk test, the data were subjected to analysis of variance using the F test. In cases of statistically significant difference, the means were compared by Tukey's test at 5% probability, using the R statistical package, version 4.2.0. The Kc data were processed by regression analysis, using the model with the highest coefficient of determination (R^2). Yield and its components were subjected to principal component analysis (PCA).

Conclusions

The results of the two-year study on irrigation of winter wheat crop in the Brazilian Cerrado provided important information about the formation of yield and its components. The findings also allowed a proposal of a rational use of water for irrigation without affecting yield.

Irrigation for wheat cv. BRS 394 cultivation is indicated when (f) reaches 0.4. Under this condition, Kc can be estimated daily based on the DAE data and the following adjusted quadratic polynomial equation: $Kc = -0.000298 \times DAE^2 + 0.036695 \times DAE + 0.332486$. Alternatively, the following mean Kc values of each phenological stage of the crop can be used as well: Kc = 0.45 (establishment); 0.81 (tillering); 1.21 (booting); 1.43 (flowering); 1.27 (grain formation); and 0.89 (maturation). Thus, there is a limit of consumption of soil available water capacity, at which wheat still produces its full potential, with a rational use of water and consumption varying according to the developmental phase.

Declaration of Competing Interest

The authors report no conflicts of interest

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