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Water deficit on the growth and yield of irrigated soybean in the Brazilian Cerrado region[1]

Déficit hídrico no crescimento e produtividade de soja irrigada na região do Cerrado brasileiro

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HIGHLIGHTS:

When necessary, it is possible to reduce the irrigation depth by up to 60% without major reductions in soybean yield.
There was no significant decrease in soybean yield from 80 to 100% available water in the soil (AW) and from 60 to 80% AW.
The highest grain yield per cubic meter of water applied was obtained in winter, for the water deficit between 20 and 40%.

ABSTRACT: The increase in disputes over water use in the Brazilian Cerrado has demanded improvements in irrigation management and increase in water use productivity. In this context, deficit irrigation is an interesting management strategy, as it enables water savings without significant losses of yield. The present study aimed to evaluate the phenology and yield of a soybean cultivar subjected to different soil moisture contents. The experimental design used was randomized blocks with five treatments and four replicates. In each treatment, an irrigation strategy was applied based on the available water in the soil (AW). The T1 treatment was performed by applying from 80 to 100% AW; in T2 treatment, the allowed variation was from 60 to 80% AW; in T3 treatment, it was from 40 to 60% AW; in T4, from 20 to 40% AW; and in T5, from 0 to 20% AW. It was verified that, in winter and summer, even without the need to reduce water withdrawal, it is recommended to apply from 60 to 80% of the available water in the soil for soybean crop, without decreasing yield. In situations of water restriction, it is possible to have yield of around 55 and 70% in winter and summer, respectively, for the condition from 20 to 40% of the available water in the soil.

Key words: *Glycine max* L., water stress, irrigation management, evapotranspiration

RESUMO: O aumento das disputas pelo uso de água no Cerrado brasileiro, tem demandado melhorias no manejo de irrigação e aumento da produtividade de uso da água. Neste contexto, a irrigação com déficit se apresenta como uma estratégia de manejo interessante, possibilitando economia de água sem prejuízos significativos à produtividade. O presente estudo teve como objetivo avaliar a fenologia e produtividade de uma cultivar de soja submetida a diferentes condições de déficit hídrico no solo. O delineamento experimental utilizado foi em blocos casualizados com cinco tratamentos e quatro repetições. Em cada tratamento, uma estratégia de irrigação foi aplicada com base na água disponível no solo (AD). O tratamento T1 foi realizado aplicando 80 a 100% AD; no tratamento T2, a variação permitida foi de 60 a 80% AD; no tratamento T3, foi de 40 a 60% AD; em T4, de 20 a 40% AD; e em T5, de 0 a 20% AD. Verificou-se que tanto no inverno quanto no verão, mesmo sem a necessidade de redução da retirada de água, é recomendável aplicar 60 a 80% da água disponível no solo para a cultura da soja, sem diminuir a produtividade. Em situações de restrição hídrica, é possível ter produtividade em torno de 55 e 70% no inverno e no verão, respectivamente, para a condição de 20 a 40% da água disponível no solo.

Palavras-chave: *Glycine max* L., estresse hídrico, manejo de irrigação, evapotranspiração

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Introduction

With a cultivated area of approximately 37 million hectares, typically under rainfed conditions, and a national average yield (Y) of 3,330 kg ha^{-1} and total production of 120.9 million tons, in the 2019/2020 season, Brazil is the largest soybean producer in the world (CONAB, 2020). More than half of the area cultivated with soybean in Brazil, in the 2018/19 season, was concentrated in the Cerrado biome (AGROSATÉLITE, 2020).

Although only 11% of Brazilian soybean plantations use irrigation (Silva et al., 2019), factors such as the long periods of variability in rainfall, which bring uncertainty regarding the best sowing time, as well as production, and the fall in yield (Montoya et al., 2017; Battisti & Sentelhas 2019; Wang et al., 2020), ranging from 46% to 74% (Sentelhas et al., 2015; Battisti et al., 2018), have increased the area of irrigated soybean, as in the Brazilian Cerrado. This region, which concentrates about 80% of all center pivots (Althoff & Rodrigues, 2019) and holds 64% of the irrigated area in Brazil (BRASIL, 2014), has faced serious water scarcity problems in some of its main hydrographic basins.

If not well planned, the growth of irrigation in the Cerrado may lead to an increase in conflicts over water use. Any strategy that aims to improve irrigation efficiency should prioritize the adjustment of management, and should consider improvements in the values of irrigation water use efficiency (WUEi) and water use productivity (WP) (Montoya et al., 2017; Gajić et al., 2018; Jha et al., 2018).

With a view to increasing WP, it is essential to understand, especially for the new soybean varieties, to which extent soil water deficit influences the characteristics of the plant and its yield. Other points to be considered are the factors that can influence soybean growth, phenology and consequently its yield, which will also influence WUEi. (Anda et al., 2020; Liu & Dai, 2020; Mesquita et al., 2020).

For different soybean cultivars, greater yield and profit was obtained by applying 75% of the required irrigation depth (IR) in stages R1 to R8 (Montoya et al., 2017) and 65% of the IR during the entire cycle (Gajić et al., 2018), 64% of maximum yield when applying 50% of the IR (Nunes et al., 2016), and 92% of maximum yield when applying 75% of the IR (Aydinsakir, 2018).

In this context, the present study aimed to evaluate the growth and yield of a new soybean variety, subjected to different soil water deficit conditions.

Material and Methods

To evaluate the yield and biometric characteristics of soybean plants, considering different irrigation strategies, two experiments were installed (winter and summer of 2019), with the soybean cultivar BRS 7581RR (indeterminate growth type), at the Reference Unit in Water Management (URMA). The winter experiment was only carried out because this is the only season with water restriction in the Cerrado. With altitude of 979 m, the URMA is installed at the Center for Agricultural Research of the Cerrados (Embrapa Cerrados), located in the Central Plateau region of the Cerrado Biome (15° 35' 55.1" S, 47° 42' 27.4" W). The climate of the region is classified as Aw (Köppen, 1948), with average air temperature of 22 °C and average total rainfall equal to 1,500 mm year^{-1}, concentrated between October and March (Malaquias et al., 2010).

The experiments were set up in a randomized block design, with four replicates and five treatments, totaling 20 experimental plots, corresponding to an area 9 m wide and 20 m long. The useful plot had dimensions of 4 m width by 2 m length. The plots were separated by a 9 m border; the blocks were separated by a 2.5 m border.

In each treatment, an irrigation strategy was applied based on the available water in the soil (AW). The T1 treatment was performed by applying 80 to 100% AW; in the T2 treatment, the allowed variation of water deficit was 60 to 80% AW; in the T3 treatment, it was 40 to 60% AW; in T4, from 20 to 40% AW; and in T5, from 0 to 20% AW. The soil of the area is classified as Oxisol, with 37, 51 and 12% of sand, clay and silt, respectively, in the 0-0.2 m layer, and 32, 52 and 16% of sand, clay and silt, respectively, in the 0.2-0.4 m layer. For the layers 0-0.2 and 0.2-0.4 m, the soil moisture contents at field capacity were equal to 0.35 and 0.34 m^3 m^{-3} and at permanent wilting point were equal to 0.23 and 0.22 m^3 m^{-3}, respectively. The chemical attributes of the soil are presented in Table 1.

Based on the results of the chemical analysis of the soil in the experimental area, basal fertilization for the soybean crop was performed with the application of 22.5 kg of N ha^{-1}, 112.5 kg of P_2O_5 ha^{-1} and 112.5 kg of K_2O ha^{-1}, as recommended by Sousa & Lobato (2004). Sowing was performed on May 6 (winter) and September 9 (summer) 2019 with the cultivar BRS 7581RR, using 18 plants per linear meter and 0.5 m spacing between rows, aiming at a population of 360,000 plants ha^{-1}.

After sowing, irrigation depths were applied to keep the soil moist and thus ensure germination and seedling emergence. The conventional sprinkling system was used up to 10 days after sowing (DAS). At 12 DAS, the plants received the first water depth of the micro-sprinkler system. From 13 DAS, monitoring was initiated for the application of each strategy, which ended at 90 DAS in the winter experiment and at 107 DAS in the summer experiment.

During the experiments, the necessary phytosanitary treatments were carried out with applications of herbicide, fungicide and insecticide.

Irrigation was performed by means of a micro-sprinkler irrigation system, model HADAR 7110. The system consisted

Table 1. Chemical attributes of the experimental area

Layer (m)	pH	OM	BS	Al	Ca	H+Al	Mg	CEC $pH_{7.0}$	SB	Cu	K	Mn	P	Zn
		%		cmolc dm^{-3}						mg dm^{-3}				
0-0.2	5.6	2.7	46	0.04	2.7	4.7	1.0	8.8	3.5	0.35	0.40	9.6	11.9	0.2
0.2-0.4	5.6	2.6	41	0.04	2.5	5.1	0.8	8.7	3.2	0.35	0.23	8.3	9.1	0.0

pH of water; OM - Organic matter; BS - Base saturation; CEC - $pH_{7.0}$: Cation exchange capacity at pH 7.0; SB - Sum of basis; OM - Walkley-Black method; Ca/Cu/Mg/Mn/Zn - Atomic absorption method; Al/H+Al - Titrimetry method; K - Flame photometer method; and P - Mehlich-1 method of 16-mm-diameter tubes connected to a 32-mm-diameter mainline, both made of polyethylene. The micro-sprinklers were spaced by 3.0 m between rows and 5.0 m apart from one another. The operating pressure was 196 kPa with flow rate of 87 L h^{-1} and precipitation intensity of 5.3 mm h^{-1}, wetted diameter of 8.5 m. The Christiansen's uniformity coefficient (CUC) obtained in the plots showed an average value of 90%, and the efficiency of water application measured in the irrigation system was equal to 85%. Irrigation management was carried out according to the deficit range of each treatment, always maintaining soil moisture between the upper and lower limits of the treatment.

The irrigation depth applied in each treatment was calculated based on the actual soil moisture content in each treatment, using the equation:

$$LA = \frac{10\left(\theta_{UL} - \theta_{actual[T1,T2,T3,T4\ or\ T5]}\right)}{Ef} Z \quad (1)$$

where:

LA - irrigation depth applied, mm;

θ_{UL} - soil moisture at the upper limit of treatment, $m^3\ m^{-3}$;

θ_{actual} - actual soil moisture in each treatment (TI, T2, T3, T4 or T5), $m^3\ m^{-3}$;

Z - depth of the crop root system, cm; and,

Ef - Efficiency of irrigation system (Ef = 0.85).

Irrigation was applied in order to maintain the soil moisture within the water deficit range established for each treatment. Soil moisture was calculated using the gravimetric method. Soil samples weighing an average of 0.2 kg were collected daily in the 0-0.2 and 0.2-0.4 m layers in each treatment, in two replicates, weighed and subsequently dried in an oven at 105 °C for 24 hours. After drying, the soil samples were weighed again. After obtaining the wet and dry weights of the soil, the actual soil moisture was obtained and the irrigation depth to be applied in each treatment was calculated.

The climatic data necessary for irrigation management were obtained from the weather station of Embrapa Cerrados, located approximately 2 km away from the experiment. Temperature, air relative humidity, wind speed, solar radiation and precipitation data were used. Reference evapotranspiration (ETo) was calculated by the FAO-Penman Monteith equation (Allen et al., 1998). Due to its variability, precipitation was measured using two rain gauges installed in the experimental area (Figure 1). Effective precipitation was determined using the soil water balance (Irrigation + precipitation - actual evapotranspiration ± soil water storage, which is, I + P - ETa ± ARM).

In winter, the temperature ranged from 8.0 to 18.5 °C, for minimum, and 22.5 to 32.0 °C for maximum. In summer, the variation was from 13.5 to 21.0 °C and from 26.2 to 37.0 °C for the minimum and maximum temperatures, respectively (Figure 1A). During the winter experiment, no precipitation events were observed, except at 9, 10 and 11 DAS, totaling 9.5 mm throughout the experiment. In the summer, the greatest values of rainfall was between 71 and 105 DAS, when the crop was in the middle and final development phase. In total, it rained 418 mm in the summer (Figure 1B).

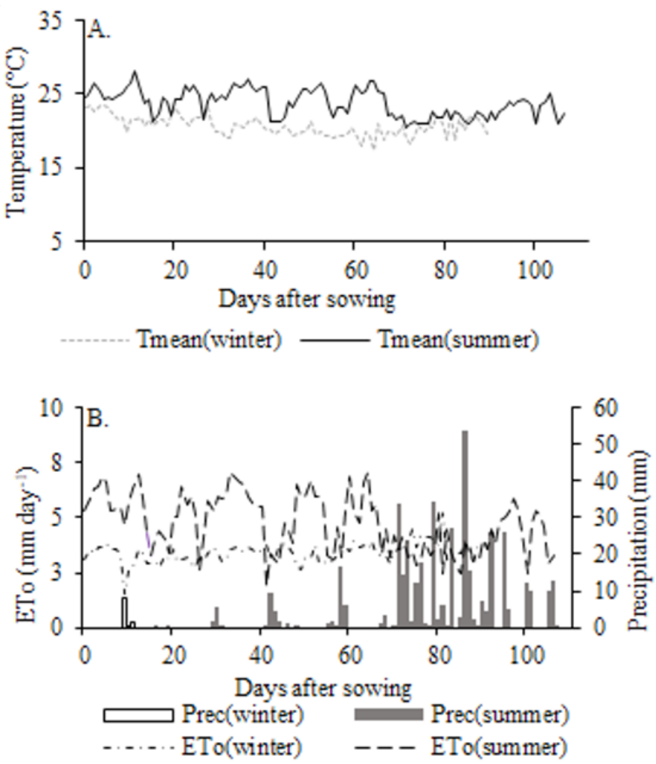


Figure 1. Mean air temperature (Tmean) (A) and reference evapotranspiration (ETo) and daily precipitation (B) in winter and summer experiments

Actual evapotranspiration of the soybean crop was calculated based on the variation of soil moisture in the 0-0.2 and 0.2-0.4 m layers, estimated by the gravimetric method (ETa_{GRA}), and the depth of the root system, by means of the equations:

$$ETa_{0-40cm} = \left\{\left[\left(\theta_{1i0\text{-}20cm} - \theta_{2i0\text{-}20cm}\right) Di\right] + \left[\left(\theta_{1i\ 20\text{-}40cm} - \theta_{2i\ 20\text{-}40cm}\right) Di\right]\right\}, \text{ for } 0 \le Z \le 40 \quad (2)$$

where:

θ_{1i} - volumetric moisture on day i, $m^3\ m^{-3}$;

θ_{2i} - volumetric moisture on day i-1, $m^3\ m^{-3}$; and,

Di - layer thickness, cm (20 cm). For Z ≤ 20, B = 0.

Eighteen soil samples were collected at the layers of 0-0.2 and 0.2-0.4 m to evaluate soil texture, soil water retention curve and apparent density. Texture was estimated using the procedure defined by Teixeira et al. (2017). The retention curve was constructed using the methodology of the tension table (Leamer & Shaw, 1941; Oliveira, 1968) for the points of 1, 3, 6, 10, 33, 60 kPa and Richards' pressure plate apparatus (Richards, 1947) for 800, 1500 kPa. For the apparent density, the volumetric ring method was used (Teixeira et al., 2017).

Leaf area index (LAI) was calculated by the ratio between the mean leaf area per plant (LA) and the planting density (PD). To estimate LA, eight plants were collected in each treatment every 10 days. After collection, the plants were placed in plastic bags and taken to the Plant Biology Laboratory of Embrapa Cerrados, where their leaves were separated and leaf area was calculated using an electronic planimeter (LI-3100C).

On the day of LA collection, Canopeo software (Patrignani & Ochsner, 2015) was used to measure the percentage of soil cover by vegetation (SC). For this, a smartphone, without zoom, was used to take four photographs per treatment of an area with a dimension of 1.0 x 1.0 m, always in the same place. To standardize the process of obtaining the photographs, a support for the smartphone was built (Figure 2). The photos were always taken between 15 and 17 hours.

Soybean root system depth and stem height were evaluated weekly. For this, four plants were randomly collected in the area of each experimental unit and evaluated for maximum root length and stem height.

Harvests were carried out on August 9 and December 25, 2019, for the winter and summer experiments, respectively. Crop yield was obtained through the weight of grains harvested along 2.0 m for each replicate. Plants were manually collected and inserted into a mechanized threshing machine. Then, the grains were weighed and put into the grain moisture meter, to correct the yield for commercial moisture, adopted as 13% in this study.

Treatment effects were evaluated by analysis of variance (ANOVA) and the Tukey test at $p \leq 0.05$. The values of stem height, root system depth, maximum cover percentage and maximum leaf area index were fitted as a function of irrigation depths and total ETa, through regression analysis. For the quality of the models generated from the relationship between irrigation depths and total ETa with yield, in addition to R^2, the standard error of the estimate (SEE) was used.

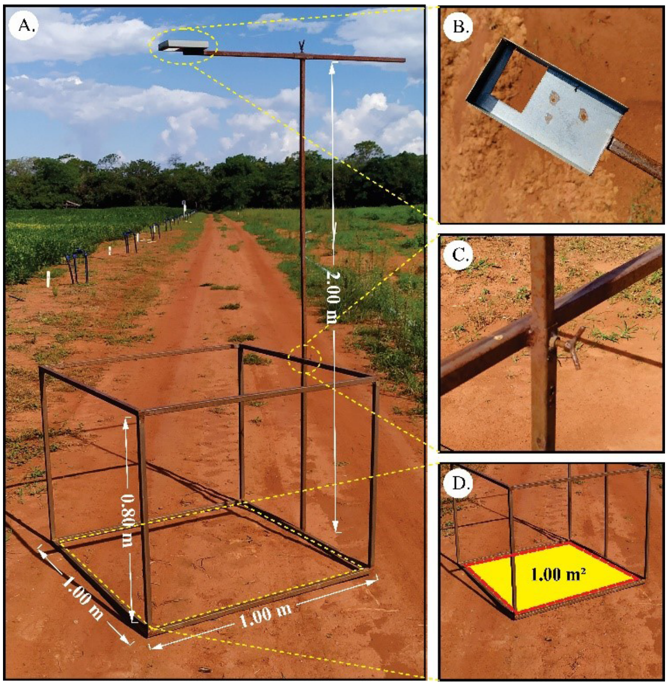


Figure 2. Lifting station (A) showing where to place the smartphone (B), the height adjustment of the photo (C) and the area used to determine the percentage of soil cover by vegetation (D)

Results and Discussion

In winter, the total irrigation depth applied was lower in all treatments, when compared to summer. In the summer, since the amount of rainfall was higher during part of the reproductive phase, the effective precipitation was added to the applied irrigation depth. The total ETa was also greater in the summer than in the winter (Table 2).

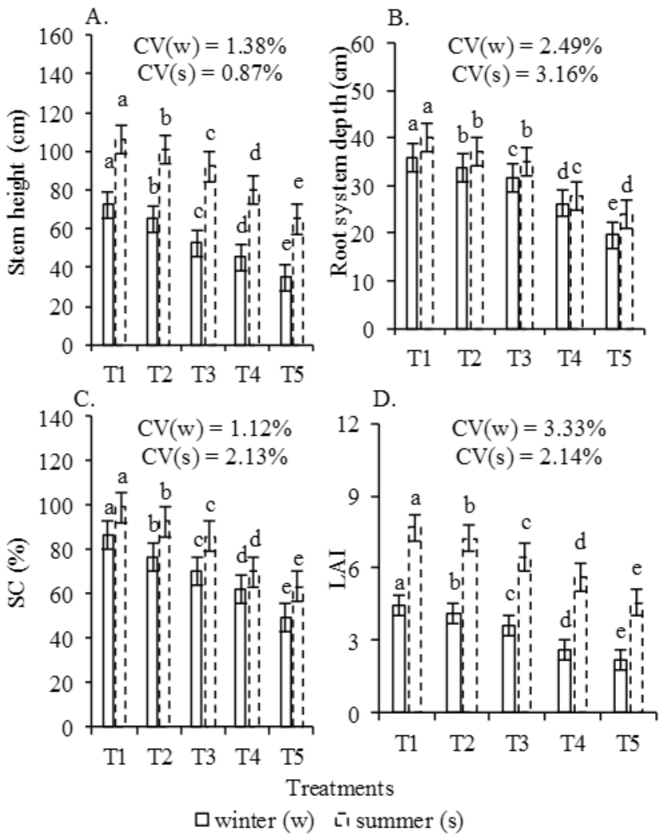
Table 2. Total values of irrigation depth and actual evapotranspiration (ETa) of soybean for the treatments in winter and summer experiments

Treatment	Depth (I + Pe)		ETa	
	(mm)			
	winter	summer	winter	summer
80-100% AW	287	521	278	467
60-80% AW	261	426	235	448
40-60% AW	245	394	224	412
20-40% AW	226	325	204	370
0-20% AW	199	307	187	339

I - Irrigation; Pe - Effective precipitation

Figure 3 shows the means of maximum stem height (H) (Figure 3A), maximum root system depth (Z) (Figure 3B), maximum percentage of soil cover - SC (Figure 3C) and maximum leaf area index (Figure 3D) for soybean crop, determined during the winter and summer experiments.

Figure 3A shows that the maximum stem height values were statistically different between the treatments for the winter and summer experiments. In winter, the maximum stem height in the T1 treatment was 38 cm greater than in T2, equivalent to a difference of 52%. In summer, the behavior was similar, also with reduction between T1 and T5, with difference of 39% between them. Such difference, less pronounced for the summer experiment, can be attributed to precipitation events



T1 - Water deficit from 0 to 20% of the available water in the soil (AW); T2 - 20-40% AW; T3 - 40-60% AW; T4-60-80% AW; T5 - 80-100% AW. Means followed by different letters in columns differ statistically by Tukey test at $p \leq 0.05$ for the winter and summer experiments, separately. Vertical bars represent standard error (n = 20)

Figure 3. Means of maximum stem height (A), maximum root system depth (B), maximum percentage of soil cover - SC (C) and maximum leaf area index - LAI (D) for soybean crop as a function of the treatments, during the winter and summer experiments

that occurred mainly after 70 days after sowing (DAS). When the variation of the maximum stem height was compared between the two experiments, it was possible to observe that, in the summer experiment, the maximum stem height was about 32, 36 and 46% higher in T1, T2 in T5. For T3 and T4, the increase was 42%.

For the maximum root system depth, significant statistical differences were also observed in winter and summer experiments (Figure 3B). In the winter experiment, the maximum root system depth values for the T1 treatment were 6, 11, 28 and 44% higher than those observed in T2, T3, T4 and T5, respectively; in the summer experiment, the mean maximum root system depth values observed in T1 were about 8, 13, 30 and 40% higher than those observed in T2, T3, T4 and T5, respectively. Between the winter and summer experiments, the differences between the treatments T1, T2, T3, T4 and T5 were 10, 8, 8, 7 and 17%, respectively.

For the maximum percentage of soil cover (SC) (Figure 3C), statistical difference was also observed between treatments, indicating the effect of water deficit on the SC. The SC observed in the T1 treatment was 10, 19, 28 and 43% higher in winter and 6, 13, 29 and 36% higher in summer, compared to the treatments T2, T3, T4 and T5, respectively. Among the experiments, the values obtained in the summer were 13, 17, 19, 11 and 22% higher for the treatments T1, T2, T3, T4 and T5, respectively.

Among the variables, the maximum leaf area index - LAI (Figure 3D) was the one with the highest variation between treatments and also between winter and summer experiments. In the winter experiment, the LAI values in the treatments T2, T3, T4 and T5 were on average 7, 18, 40 and 50% lower than the LAI values observed in T1, respectively, while in the summer, the differences were 6, 16, 26 and 40%, respectively. Considering the behavior of LAI in the two experiments, it was observed that its values in the summer experiment were on average 42, 43, 44, 53 and 52% higher for the treatments T1, T2, T3, T4 and T5, respectively. For all conditions evaluated, the means between treatments differed statistically by Tukey test ($p \leq 0.05$).

These differences were due to the lower availability of water in the soil, originating from the lower irrigation depths. With the increase in the restriction, it was possible to observe a smaller increase in the growth variables H, Z, SC and LAI compared to the treatments. Through Figure 3 it was possible to observe that this behavior occurred in both summer and winter.

In Table 3, the variables maximum stem height, maximum root system depth, maximum percentage of soil cover, and maximum leaf area index were associated with the total water depth in the soil and with the total actual evapotranspiration of soybean crop through regression.

The behaviors of H, Z, SC and LAI were similar in the winter and the summer experiments. For all variables R^2 ranged from 82 to 99%, demonstrating the high relationship between the variables studied when subjected to different irrigation depths (Table 3). Based on Table 3, it can be observed that for each mm increased in water deficit there was a reduction in H of 0.44 cm in the winter and 0.23 cm in the summer. Similar behavior was observed with ETa, for which each mm of reduction in water deficit resulted in a reduction in H of 0.42 cm in winter and 0.30 cm in summer. Gava et al. (2016) observed that the deficit of 25% of soil water reduced stem height by 21%, while for the deficit of 50% the reduction was 36%. In this study, for the soil water deficit ranging from 20 to 40%, the stem height reduction was 11% in winter and 5% in summer. For the 40 to 60% AW deficit, the stem height reduction was 28% in winter and 14% in summer.

For Z, each mm of increase in water deficit resulted in reductions of 0.20 and 0.10 cm in the soybean root system depth in winter and summer, respectively. For ETa, each mm of reduction in water deficit led to reductions in Z of 0.20 cm in winter and 0.10 cm in summer (Table 3). Unlike studies that apply the water deficit in the soil between the field capacity and the percentage of available water, this study kept the deficit monitored within a range, making the surface always moist, even though the moisture was very low. During the experiment, only the T1 treatment received water replacement up to field capacity. It was observed that the roots were concentrated in the region close to the available moisture, and did not deepen, as observed in studies of water deficits in which, after reaching the deficit related to the treatment, the soil returns to the field capacity.

The SC also decreased for each mm of increase in water deficit, with reductions of 0.40% in winter and 0.20% in summer. The reduction of each mm of ETa also caused decreases in SC on the order of 0.40 and 0.30% in winter and summer, respectively. For each mm of increase in water deficit, there were reductions of 0.027 cm^2 in leaf area during the

Table 3. Maximum stem height (H), maximum root system depth (Z), maximum soil cover percentage (SC) and maximum leaf area index (LAI) as a function of total soil water depth and accumulated actual evapotranspiration (ETa) for the winter and summer experiments

	Variables	Winter			Summer		
		Equation Y = a ± bx	CV (%)	R^2	Equation Y = a ± bx	CV (%)	R^2
Total water depth (mm)	H (cm)	54.264-0.4449*x	22.10	98	0.4405-0.2319*x	16.6	93
	Z (cm)	16.608-0.1889*x	19.70	93	3.4807-0.0943*x	18.1	96
	SC (%)	34.455-0.4263*x	18.50	98	2.2619-0.2153*x	16.8	95
	LAI	3.3507-0.0277*x	22.20	95	0.4482-0.0174*x	17.6	91
Total ETa (mm)	H (cm)	39.548-0.4162*x	22.10	92	37.427-0.3103*x	16.6	98
	Z (cm)	8.8705-0.1701*x	19.70	82	17.503-0.1237*x	18.1	98
	SC (%)	19.638-0.3956*x	18.50	91	34.649-0.2833*x	16.8	97
	LAI	2.3687-0.0257*x	22.20	87	3.2267-0.0232*x	17.6	96

* - Significant at $p \leq 0.05$ by t-test

winter experiment and 0.017 cm^2 in summer. The reduction of each mm of ETa also reduced soybean leaf area by 0.025 cm^2 in winter and 0.023 cm^2 in summer (Table 3). Such behavior was also observed by Montoya et al. (2017), who observed a reduction in soybean leaf area with the decrease in soil water content. Nunes et al. (2016), studying two soybean cultivars subjected to different water deficits, observed reductions in leaf area on the order of 80 and 52%, respectively, when subjected to a deficit of 75%. In this study, for the deficit from 60 to 80%, the decrease in leaf area was of 41% in winter and 27% in summer.

Figure 4 shows the variation in soybean crop yield (Y) as a function of the increase in soil water deficit (T1 to T5). A statistically significant difference in the values of yield between treatments was observed in both experiments, with CV = 7.64% in winter and 1.79% in summer. Among the treatments, despite the statistical difference in ETa, total irrigation depth and crop phenology, the yield between treatments T1 and T2 did not show statistical difference by the Tukey test ($P \leq 0.05$), for the winter and summer experiments. In the winter experiment, no statistical differences were observed between treatments T2 and T3 and between T4 and T5. The possible explanation for the absence of difference between T1 and T2 in the summer experiment is the occurrence of several rain events during the reproductive period of the crop, which increased the soil's field capacity during much of the final phase of the experiment. Equality in the winter experiment may have arisen from the cultivar's response to water deficit.

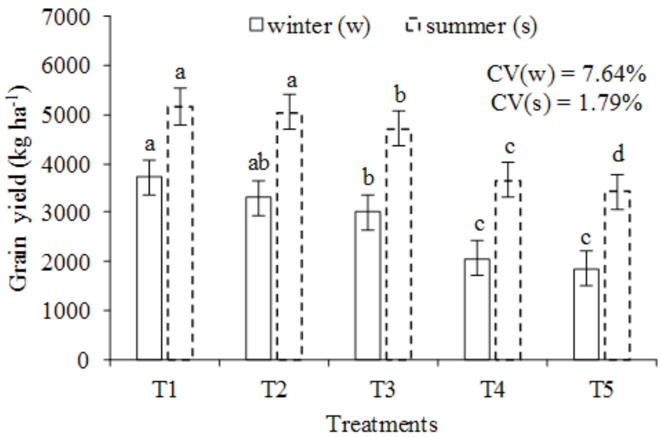
Also in Figure 4, in the winter experiment, it was observed that the reduction in the yield of the T1 treatment when compared to T3, T4 and T5 was equal to 20, 45 and 50%, respectively. In the summer, the differences were 10, 29 and 34%, respectively. This finding makes it possible to infer that, when necessary, it is possible to apply a water deficit in the soil ranging from 40 to 60% and have a yield reduction of 20 and 10% in winter and summer, respectively.

In a comparison of T1 with T3, there were reductions in the total irrigation depth on the order of 42 mm in winter and 78 mm in summer, and reductions in soybean yield of 710 kg ha^{-1} in the winter experiment and 460 kg ha^{-1} in the summer experiment. Considering an irrigated area of 100 ha, with the increase in the deficit from T1 to T3, water volumes equivalent to 42,000 m^3 in the 90 days of cultivation in winter and 78,000 m^3 in the 107 days of cultivation in summer were no longer applied, for yield reductions of 20 and 10%, respectively. Under this condition, it is possible to note, among other factors, the importance of the planting date for water saving and crop yield.

In summer, in situations of extreme water crisis, it is possible to keep the soybean water deficit between 80 and 100% (T5) in the vegetative phase and achieve yield of 3,400 kg ha^{-1}, close to the national average of 3,330 kg ha^{-1} (CONAB, 2020), returning to applying the necessary water depth. In view of this observation, the stage of development in which the crop is found to be at the moment when the water deficit occurs must be taken into account. Studies indicate that soybean is more sensitive to water deficit in the production formation stage, mainly from stage R1 to R8 (Nunes et al., 2016; Montoya et al., 2017; Gajić et al., 2018). In this study, the main precipitation events were observed in part of the reproductive phase (71 and 105 DAS), which allows stating that the plants only received a deficit up to 71 DAS, and that the rain directly influenced yield.

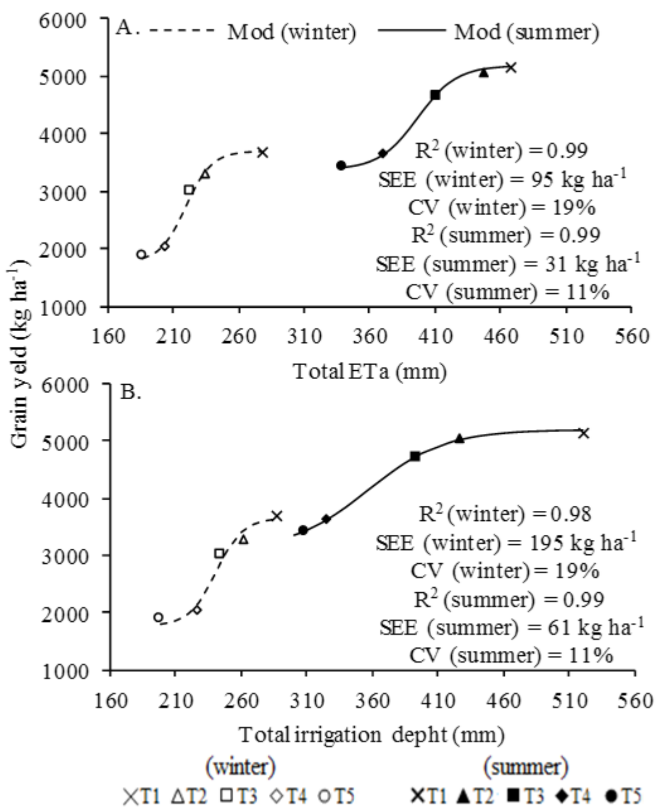
In Figure 5, models were fitted between soybean yield for the winter and summer experiments, as a function of total ETa (Figure 5A) and total irrigation depth applied (Figure 5B), for all treatments.

Under these conditions, for both experiments, soybean yield as a function of total ETa and total irrigation depth applied was described by a sigmoidal model with four parameters, according to Eq. 3.



T1 - Water deficit from 0 to 20% of the available water in the soil (AW); T2 - 20-40% AW; T3 - 40-60% AW; T4 - 60-80% AW and T5 - 80-100% AW. Means followed by different letters in columns differ statistically by Tukey test ($p \leq 0.05$) for the winter and summer experiments, separately. Vertical bars represent standard error (n = 20)

Figure 4. Means of soybean yield for the treatments in winter and summer experiments



T1 - Water deficit from 0 to 20% of the available water in the soil (AW); T2 - 20-40% AW; T3 - 40-60% AW; T4 - 60-80% AW; T5 - 80-100% AW; Mod - Model; SEE - Standard error of the estimate

Figure 5. Soybean yield during the winter and summer experiments, as a function of the total actual evapotranspiration (total ETa) (A) and the total irrigation depth applied (B) for the treatments

$$Y = Yo + \frac{\alpha}{1+e^{-\left(\frac{X-Xo}{b}\right)}} \quad (3)$$

where:

Yo - 1,760 and 5,182;
α - 1,956 and -1,793;
Xo - 220 and 396; and,
b - 10 and -15; for,
X - total actual evapotranspiration, for winter and summer experiments, respectively; and,
Yo - 1,787 and 3,102;
α - 1,878 and 2,083;
Xo - 241 and 357; and,
b - 10 and 29; for,
X - total irrigation depth applied, for winter and summer experiments.

For total ETa, in the winter and summer experiments, R^2 showed an average value of 99%. The model overestimated the soybean grain yield by 95 kg ha^{-1} for the winter and by 31 kg ha^{-1} for the summer, for each hectare.

For the total irrigation depth, the values of R^2 were on the order of 98 and 99% in the winter and summer experiments, respectively. In this case, the model overestimated soybean grain yield by 195 kg ha^{-1} for the winter and by 61 kg ha^{-1} for summer for each hectare.

Water use productivity (WP) values were higher in the treatments T1, T2 and T3, both in winter and summer.

In winter, WP values ranged from 1.0 (T4 and T5) to 1.4 kg m^3 (T2); in summer, WP ranged from 1.0 (T4 and T5) to 1.1 kg m^3 (T1, T2 and T3). Despite being subjected to a water deficit between 20 and 40%, soybean plants in the T2 treatment, in the winter experiment, showed the highest yield per m^3 of water applied. Considering an irrigated area of 100 ha (1 mm of water depth equals 1000 m^3 for 100 ha) and comparing the WP values in the T2 treatment with those of T1 (difference of 26 mm), there were savings of approximately 26,000 m^3 of water.

For Gajić et al. (2018), high soybean yield is obtained with actual evapotranspiration values above 380 mm, corroborating the results found in this study, where low yields were obtained in winter and high yields were obtained in summer. These authors also stated that in order to obtain high yields, the sum of precipitation (effective precipitation) with irrigation must be between 350 and 400 mm.

Zhang et al. (2018), to obtain high yields of soybean crop, found irrigation values ranging between 110 and 405 mm, for different soil types and climatic conditions, in the humid irrigated region of Mississippi, USA, and these results are consistent with those of the present study, especially in winter. In the summer, the maximum yield was obtained with an irrigation depth higher than 405 mm.

The differences in soybean yield and WP in relation to the growing season (winter or summer) were due to the characteristics of the climate, especially the number of light hours and temperature, considering that soybean is a photothermal crop (Liu & Dai, 2020).

Conclusions

1. In the summer, even with the presence of rain during part of the reproductive phase, the demand for water was greater than in the winter.

2. In both winter and summer, treatments with less water restriction were responsible for the greater growth and production of plants.

3. In both winter and summer, even without the need to reduce water withdrawal, it is recommended to apply 60 to 80% of the available water in the soil to the soybean crop, without decreasing yield.

4. In situations of water restriction, it is possible to have yield around 55% in the winter and 70% in the summer, when the available water in the soil varies from 20 to 40%.

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