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Estimation of soybean crop water deficit sensitivity index

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ABSTRACT: Brazil is the world's largest soybean exporter. Over half of the cultivated area is in the Brazilian Savanna (Cerrado) region, where soybean is typically grown under rainfed conditions. However, soybeans have been cultivated in irrigated systems, further increasing water demand in the region, which already faces water problems. Therefore, it is crucial to generate technical information to support the management of water resources in irrigated soybean crops. This study aimed to estimate the water deficit sensitivity index of soybean crops. Two field experiments were carried out in randomized blocks with four treatments and four replicates from May to Aug 2019 and 2021. Three treatments with irrigation suspension were applied in three different phenological stages: vegetative, reproductive, and seed filling, and a fully irrigated control plot to meet the total plant demand. The results showed 40 % and 34 % reductions in soybean seed yield when water deficit was applied in stages R1-R5 and R5-R7, respectively, compared to the control treatment. There was a linear correlation with r^2 values equal to 0.98, 0.97, and 0.99 for the relationships between seed yield and applied irrigation, seed yield and actual evapotranspiration (ET_a), and ET_a and irrigation, respectively. The yield response factors were equal to 0.12, 0.36, and 0.57 for the stages V2-R1, R1-R5, and R5-R7, respectively. The yield response factor for the soybean cycle was equal to 1.16.

Keywords: deficit irrigation, irrigation management, evapotranspiration, crop water production functions

Introduction

Due to the increased demand for food, several countries, including Brazil, are working to ensure food security. The country stands out as a producer and exporter of various agricultural commodities. In 2019, Brazil and the United States supplied 64 % of the European soybean demands (FAO, 2021). Brazil is the world's largest soybean exporter, with an output of 78.7 million tons of soybean, generating a revenue of US$ 53.2 billion in 2023 (SECEX, 2023).

Most soybean production in Brazil comes from rainfed areas (Silva et al., 2019); however, more and more crops have been planted in irrigated systems, mainly due to water scarcity at certain times during essential stages of crop development in the summer, when most precipitation occurs in the region. In the winter, when rainfall is practically non-existent, irrigation is used for soybean seed production, usually in the Cerrado biome (Agrosatélite Geotecnologia Aplicada, 2018), which concentrates roughly 80 % of all center pivots in the country (Althoff and Rodrigues, 2019).

The growth of irrigated soybean cultivation indicates the need to improve the criteria for irrigation management of soybean crops, considering the current scenario of water use and the emerging conflicts over this resource. One way to improve irrigation management is to use deficit irrigation (Zou et al., 2021; Jahromi et al., 2023; Xu et al., 2023).

The water deficit irrigation technique requires knowledge about the index of crop response to water deficit in its different growth stages to be more effective in irrigation management and agricultural modeling in water scarcity scenarios. A previous experiment with water deficit at different phenological stages of the corn crop found adequate indices to provide a reference for the calibration of one agricultural model (Ma et al., 2023). However, the index of crop response to water deficit can differ widely depending on the growth stage and the water deficit severity (Badr et al., 2022). The study mentioned focused on determining the crop response index for water deficit of other crops in different locations; thus, studies are needed on the crop response index for water deficit in different soybean growth stages in Brazil. This study found fundamental technical coefficients to identify the impact of water deficit in soybean phenological stages in irrigated crops or rainfed agriculture. Therefore, this study aimed to determine seed yield, actual evapotranspiration, and water-yield relationship and to determine soybean water stress index.

Materials and Methods

Characteristics of the study area and climatic data

Two experiments were conducted from May to Aug 2019 and 2021 in the central plateau region of the Cerrado biome (15°35′55.1″ S, 47°42′27.4″ W, 979 m). The physical and chemical characteristics of the soil at the experimental site are presented in Table 1.

In both experiments, data on climate, from sowing to harvest, were acquired from the weather station located approximately 2 km away from the experimental site. We collected data on air temperature, solar radiation,

Table 1 – Soil physical and chemical properties in the experimental site.

Layer	OM	pH	BD	FC	WP	TAW
m	%		Mg m^{-3}	----------- m^3 m^{-3} -----------		
0-0.2	2.7	5.6	1.10	0.35	0.21	0.14
0.20-0.40	2.6	5.6	1.08	0.35	0.20	0.15

OM = organic material; BD = bulk density; FC = soil moisture at field capacity; WP = soil moisture at wilting point; TAW = soil moisture at total available water.

precipitation, and reference evapotranspiration (ET_o), which was calculated using the Penman Monteith equation (Allen et al., 1998).

Irrigation system

Irrigation was applied in each experimental plot through a subsurface drip irrigation system, composed of one lateral drip line buried at 0.28 m and emitters spaced 0.9 m between lines and 0.4 m apart, with initial pressure of 196 kPa and a flow rate of 2 L h^{-1}. Irrigation valves were installed at the beginning of each experimental site to turn the irrigation system on and off. The irrigation system was supplied with water from a dam located approximately 3 km away from the experimental site. The water was conducted through an open canal, and a 1.49 kW pump distributed it to the irrigation system.

Crop management

Sowing was carried out at 0.5 m spacing between rows and 18 plants per linear meter, aiming to reach a density of 360,000 plants per ha. Fertilization was performed based on the soil chemical analysis and following the recommendations of Sousa and Lobato (2004). Sowing was carried out in May 2019 and 2021, while harvest was carried out in Aug 2019 and Sept 2021.

Experimental treatments

Three treatments with irrigation suspension were applied in three different phenological stages: Vegetative (V2-R1) = irrigation suspension from the second-node stage until the beginning of flowering; Reproductive (R1-R5) = irrigation suspension from the beginning of the flowering stage until the beginning of seed filling; Seed filling (R5-R7) = irrigation suspension from the seed filling stage until the beginning of physiological maturation. One plot was irrigated to meet the total plant demand (full irrigation (control)). Thus, there were four treatments, with four replicates in each experimental site. The experimental design was randomized blocks.

Irrigation management and soil moisture measurement

Eighteen soil samples were collected at 0-0.20 and 0.20-0.40 m layers to evaluate the soil water retention curve and apparent density. The retention curve was constructed using the methodology of the tension table (Leamer and Shaw, 1941; Oliveira, 1968) for the points of 1, 3, 6, 10, 33, and 60 kPa and the pressure plate apparatus of Richards (Richards, 1947) for 800, 1500 kPa. For the apparent density, the volumetric ring method was used (Teixeira et al., 2017). The soil water depletion factor (p) equal to 0.5 was used to control the irrigation timing, as this limit does not cause a significant reduction in soybean yield (Allen et al., 1998). Soil moisture was measured by the gravimetric method in soil samples collected from the 0-0.20 m and 0.2-0.40 m layers, within a maximum interval of seven days between one sampling and another; thus, one sample was taken before irrigation and another 24 h after irrigation. Irrigation depth was calculated using the equation Eq. (1).

$$I = 10\ (\theta_{FC} - \theta_{actual})\ Z \quad (1)$$

where: I is the applied irrigation in mm; θ_{FC} is the soil moisture at field capacity in m^3 m^{-3}; θ_{actual} is the actual soil moisture in each treatment in m^3 m^{-3} and Z is the depth of the crop root system in cm.

Actual evapotranspiration

The actual evapotranspiration (ET_a) for each growth stage evaluated in all treatments was estimated using the soil water balance approach using the collected values of soil moisture using Eq. (2).

$$ET_a = P + I + CR - D - R + \Delta S \quad (2)$$

where: P is total precipitation of period evaluated in mm, I is irrigation depth in mm, CR is capillary rise in mm, D is deep percolation in mm, R is surface runoff in mm, ΔS is soil water storage variation in the plant rooting depth in mm (Allen et al., 1998). Deep percolation was considered zero because irrigation was applied only in the layer corresponding to the root system of the crop (0.0-0.40 m). Surface runoff was ignored because the irrigation system used was subsurface drip. The capillary rise of the water table was ignored because the study site had no drainage and salinity problems.

Soil water deficit

The soil water deficit (SWD) in the three treatments with irrigation suspension was calculated through Eq. (3) following the methodology proposed by Berliner and Oosterhuis (1987):

$$SWD = \left[-1\frac{\theta_{actual} - \theta_{PWP}}{\theta_{FC} - \theta_{PWP}}\right] \times 100 \quad (3)$$

where: θ_{FC} = soil moisture at field capacity, m^3 m^{-3}; θ_{actual} = actual soil moisture in each treatment, m^3 m^{-3}; θ_{PWP} = soil moisture at permanent wilting point (1,500 kPa), m^3 m^{-3}.

Yield response factor and production functions

The water deficit sensitivity indices of soybean crops were estimated using the approach of Jensen (1968) Eq. (4) for the water deficit applied in the different phenological stages and the approach of Doorenbos and Kassam (1979) Eq. (5), considering the total soybean cycle. The response factors of the equation by Jensen (1968) were calculated by parameterizing the equations using the generalized reduced gradient method (Lasdon et al., 1974). The yield response factor of Doorenbos and Kassam (1979) was defined as the curve intersection generated between treatments with water deficit (V2-R1, R1-R5, and R5-R7).

$$\left(\frac{Y_a}{Y_m}\right) = \left(\frac{ET_{aI}}{Y_{mI}}\right)^{\lambda_I} \left(\frac{ET_{aII}}{Y_{mII}}\right)^{\lambda_{II}} \left(\frac{ET_{aIII}}{Y_{mIII}}\right)^{\lambda_{III}} \quad (4)$$

$$\left(1 - \frac{Y_a}{Y_m}\right) = K_y \left(1 - \frac{ET_a}{ET_m}\right) \quad (5)$$

where: I, II, III = index referring to the crop development stage (V2-R1, R1-R5, and R5-R7); λ = stress sensitivity index as a function of Jensen soil moisture deficit for development stages; K_y = cycle yield response factor of Doorenbos and Kassam; $ET_{a\ I,\ II,\ III}$ = Total actual evapotranspiration at crop development stage I, II, or III, mm; $ET_{m\ I,\ II,\ III}$ = Total maximum actual evapotranspiration at crop development stage I, II, or III, mm; ET_a = Actual evapotranspiration occurred in the crop cycle, mm; ET_m = Maximum actual evapotranspiration occurred in the crop cycle, mm; Y_a = actual crop yield obtained at the end of the cycle in the treatment subjected to water deficit, kg ha^{-1}; Y_m = Maximum crop yield obtained at the end of the cycle in the treatment without water deficit, kg ha^{-1}.

Seed yield measurement

A site was randomly chosen in each of the four replicates, and all plants within two linear meters were harvested to evaluate seed yield. The pods of each plant were peeled, and the grains were packed adequately in identified paper bags and sent to the seed analysis laboratory, where the seeds were weighed on an analytical scale. The yield in each treatment was determined after the correction of grain moisture to 13 %.

Statistical analysis

The yield obtained in the treatments of each year was subjected to the analysis of variance (ANOVA) and the means were compared by Tukey test ($p < 0.05$). The regression analysis assessed the relationship between yield, Et_a, and applied irrigation.

Results

The soybean phenological stages and their respective durations are presented in Table 2. The phenological stages had similar durations; that is, no difference was found for the phenological stages between the experiments of both years.

During the phenological stages VC-V2, V2-R1, R1-R5, and R5-R7, there was no precipitation in 2019 (Figure 1). In 2021, there was precipitation of 7.8 mm in the VC-V2 stage and 0.5 mm in the seed-filling stage. In 2019, ET_0 ranged from 2.7 to 5.6 mm d^{-1}, mean air temperature ranged from 16.9 to 23.7 °C, and solar radiation ranged from 10.7 to 21.1 MJ m^{-2} d^{-1} (Figure 1). In the 2021 experiment, ET_0 values ranged from 2.4 to 6.3 mm d^{-1}, mean air temperature ranged from 16.1 to 27.2 °C, and solar radiation ranged from 11.1 to 22.6 MJ m^{-2} d^{-1} (Figure 1).

The variation in SWD for all treatments over the two years of the experiment is shown in Figure 2. In 2019, SWD ranged from 21 % to 41 %, with an average value of 30 % in the control treatment. In the V2-R1 treatment, SWD ranged from 39 % to 100 %, with an average value of 85 % during the V2-R1 stage. In the R1-R5 treatment, SWD ranged from 40 % to 100 %, averaging 84 % during the R1-R5 stage. In the R5-R7 treatment, SWD ranged from 31 % to 100 %, with an average value of 92 % during the R5-R7 stage. Regarding soil water deficit, the worst situation occurred in the R5-R7 treatment, which remained for 32 days with SWD values above 80 %. In 2021, in the control treatment, SWD ranged from 21 % to 48 %, with an average value of 37 %. In the V2-R1 treatment, SWD ranged from 26 % to 100 %, averaging 82 % during the V2-R1 stage. In the R1-R5 treatment, SWD ranged from 23 % to 100 %, averaging 87 % during the R1-R5 stage. In the R5-R7 treatment, SWD ranged from 27 % to 100 %, with an average value of 96 % during the R5-R7 stage.

The volume of irrigation water applied in the experimental treatments and the actual evapotranspiration (ET_a) are shown in Figure 3. ET_a ranged from 115 mm to 168 mm in 2019 and 112 mm

Table 2 – Phenological stages and duration.

		Phenological stages and duration				
Years	Seeding date	Vegetative (VC-V2)	Vegetative and flowering (V2-R1)	Pod formation (R1-R5)	Seed filling/Maturation (R5-R7)	Total
		days				
2019	06/05/2019	15	20	30	32	97
2021	26/05/2021	13	23	30	29	95

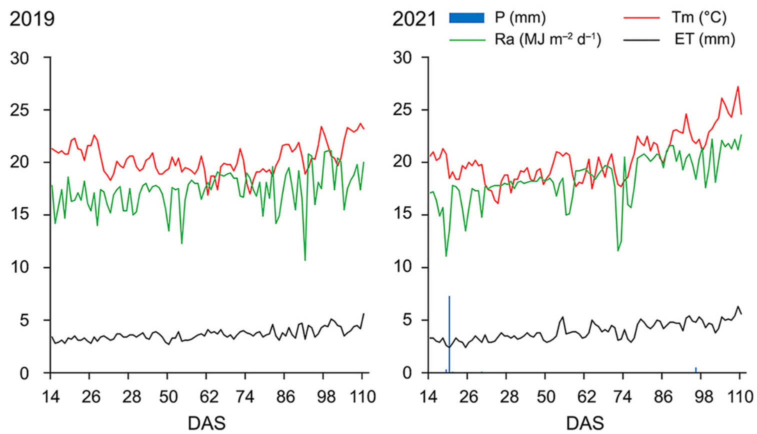

Figure 1 – Tm = Mean air temperature; Ra = solar radiation; P = precipitation; and ET = reference evapotranspiration in the 2019 and 2021 experiments. DAS = Days after sowing.

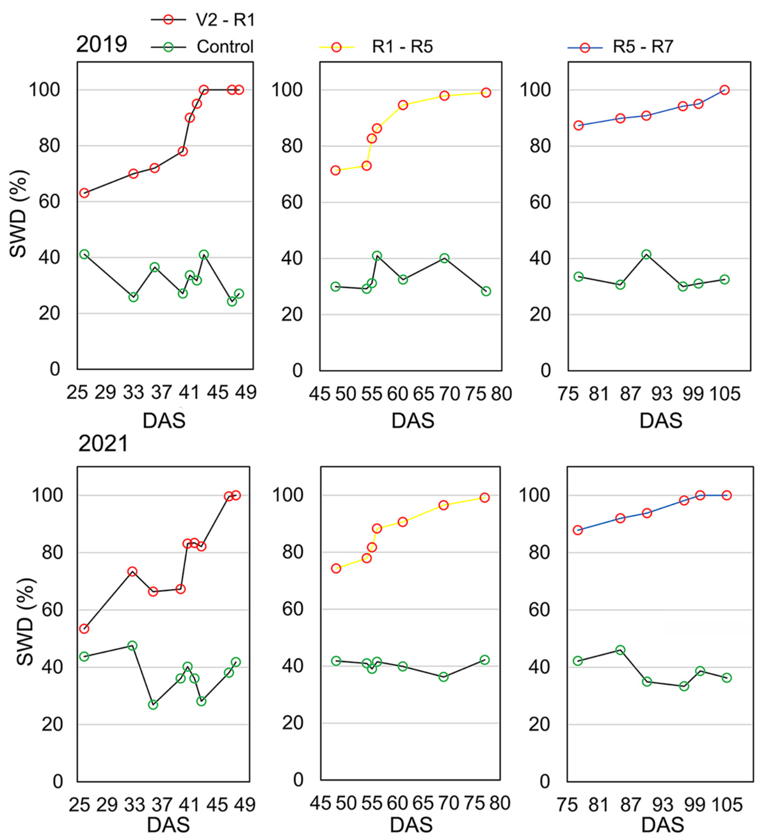

Figure 2 – Soil Water Deficit (SWD) in the soil profile of 0-0.40 m in different experimental treatments in two years, according to gravimetric soil moisture. V2-R1 = water deficit applied from the second-node stage until the beginning of flowering; R1-R5 = water deficit applied from the beginning of flowering until the beginning of grain filling; R5-R7 = water deficit applied from the beginning of grain filling until the beginning of physiological maturation. Control = without water deficit. DAS = Days after sowing.

to 173 mm in 2021. Compared to the control treatment, the V2-R1, R1-R5, and R5-R7 treatments had reductions in ET_a of 19 %, 31 %, and 25 % in 2019 and 27 %, 35 %, and 30 % in 2021, respectively. The average value (2019-2021) of ET_a was equal to 170 mm in the control treatment, and the V2-R1, R1-R5, and R5-R7 treatments had 23 %, 33 %, and 28 % lower values than the control.

The irrigation applied in the treatments V2-R1, R1-R5, and R5-R7 was 15 %, 27 %, and 21 % lower than in the control treatment (148 mm) in 2019. In 2021, the

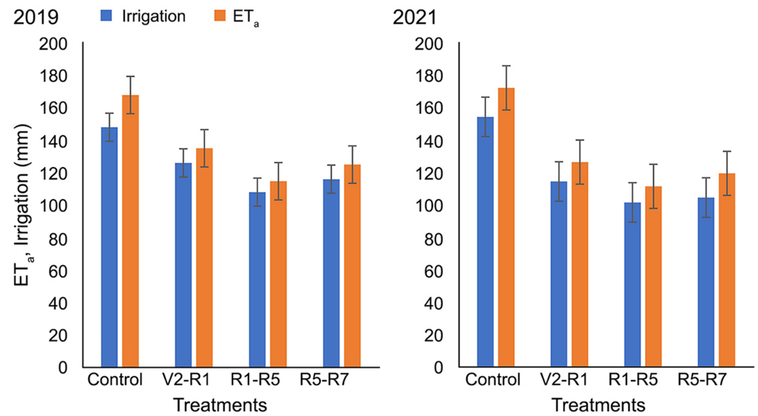

Figure 3 – Irrigation depth, actual evapotranspiration (ET_a) in different experimental treatments in two years. V2-R1 = water deficit applied from the second-node stage until the beginning of flowering; R1-R5 = water deficit applied from the beginning of flowering until the beginning of grain filling; R5-R7 = water deficit applied from the beginning of grain filling until the beginning of physiological maturation. Control = without water deficit.

applied irrigation was 25 %, 34 %, and 32 % lower in the treatments V2-R1, R1-R5, and R5-R7, respectively, compared to the control treatment (173 mm).

Overall, there was variation in the soybean seed yield between treatments for the 2019 and 2021 seasons (Table 3). The control treatment obtained higher seed yield in 2019 (3,153 kg ha^{-1}) and 2021 (3,252 kg ha^{-1}). Among the treatments with water deficit, V2-R1 showed the highest seed yield, with differences of 28 % (2019) and 15 % (2021) from the control treatment. The R1-R5 treatment had the lowest seed yield, with reductions of 37 % (2019) and 45 % (2021), respectively, compared to the control treatment. The R5-R7 treatment showed 35 % and 32 % lower seed yield than the control in 2019 and 2021, respectively. The average value (2019-2021) of seed yield was 3,203 kg ha^{-1} in the control treatment, and the treatments V2-R1, R1-R5, and R5-R7 had 22 %, 40 % and 34 % lower values compared to the control, respectively.

The relationships between seed yield, actual evapotranspiration, and applied irrigation during the soybean cycle in the 2019 and 2021 experiments are shown in Figure 4. In the 2019 and 2021 experiments, a linear relationship was found between seed yield and applied irrigation, with r^2 of 0.96 and 0.97, respectively. The same pattern was found for the relationship between seed yield and ET_a, with r^2 of 0.93 (2019) and 0.98 (2021). For the average of the years 2019 and 2021, there was a linear correlation with r^2 values of 0.98, 0.97, and 0.99 for the relationship between seed yield and applied irrigation, seed yield and ET_a, and ET_a and irrigation, respectively.

The crop yield response factors using the approach of Jensen (1968) are shown in Figure 5A. The values of the yield response factor in stages V2-R1, R1-R5, and R5-R7 were equal to 0.10, 0.30, and 0.56 in 2019 and to 0.19, 0.28, and 0.59 in 2021.

The water deficit sensitivity indices of soybean crops using the approach of Doorenbos and Kassam (1979) are shown in Figure 5B. The Ky value was equal to 1.12 in 2019 and 1.18 in 2021.

Table 3 – Average seed yield of soybean in the different treatments, with and without water deficit, in 2019 and 2021 experiments.

Treatments	Seed yield	
	2019	2021
	------------------------ kg ha^{-1} ------------------------	
Control	3,153 a	3,252 a
V2-R1	2,678 b	2,330 b
R1-R5	1,986 c	1,800 d
R5-R7	2,143 c	2,100 c

Averages followed by the same letter in the columns did not differ by the Tukey test ($p < 0.05$). Control = control treatment (without water deficit); V2-R1 = water deficit applied at the V2-R1 stage; R1-R5 = water deficit applied at the R1-R5 stage; R5-R7 = water deficit applied at the R5-R7 stage.

Discussion

In general, the worst situation for SWD occurred in the R5-R7 treatment in both years, which remained for approximately 30 days with SWD values above 80 %, while SWD 50 % is the maximum allowed in irrigation management not to compromise crop yield. The magnitude of yield loss depends on the duration and severity of water stress as well as on the phenological stage in which the crop is affected (Sah et al., 2020).

ET_a showed a reduction in all treatments due to the stomatal closure in response to the low water content in the soil, reducing CO_2 entry with consequent reduction of photosynthesis (Bailey-Serres et al., 2019), resulting in lower crop evapotranspiration. The greatest ET_a reductions were observed in treatments R1-R5 and R5-R7; that is, irrigation suppression for 30 d in R1-R5 and R5-R7 may have been severe in these stages and; as a response, the plant may have reduced its water use to the maximum to ensure final yield. Other studies have reported similar results for soybeans in experiments conducted in pots under water deficit at different stages of development (Cui et al., 2021; Wei et al., 2018).

The average value (2019-2021) of irrigation was equal to 160 mm in the control treatment, while treatments

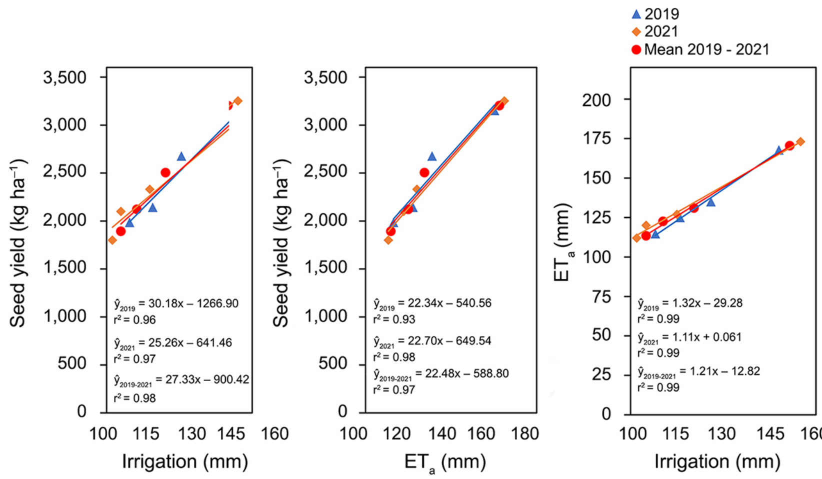

Figure 4 – Relationships between soybean seed yield, irrigation, and actual evapotranspiration (ET_a) for all treatments in the years 2019 and 2021.

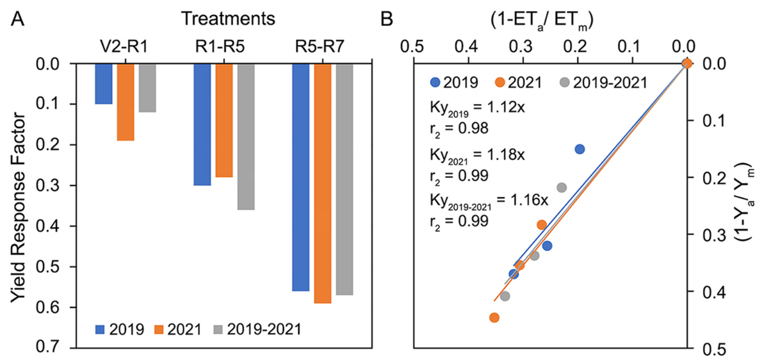

Figure 5 – Yield Response Factor using the approaches of Jensen (1968) (A) and Doorenbos and Kassam (1979) (B) for soybean under water stress at different stages of development in the years 2019 and 2021. V2-R1 = water deficit applied from the second-node stage until the beginning of flowering; R1-R5 = water deficit applied from the beginning of flowering until the beginning of grain filling; R5-R7 = water deficit applied from the beginning of grain filling until the beginning of physiological maturation. Control = without water deficit.

V2-R1, R1-R5, and R5-R7 showed 20 %, 30 %, and 26 % lower values compared to the control, respectively. These values express the effects of the number of days in which the irrigation system was not activated in each treatment, with a consequent reduction in the total amount of water supplied to the plant.

Reductions were more significant in seed production in R1-R5 and R5-R7 when compared to the control treatment. In these treatments, when water deficit was applied, the plants were in the pod formation and seed filling stages, respectively. In these growth stages, the plant uses a high volume of water; thus, prolonged drought stress adversely impacts its yield (Du et al., 2020). Another factor that reduced seed yield was the irrigation suppression time, which led to more significant water deficit in these stages, resulting in greater impact on the physiological functions of the crop (Felisberto et al., 2023). In addition, under water stress conditions, plants close their stomata to avoid water loss (Balfagón et al., 2020; Jumrani and Bhatia, 2019; Zandalinas et al., 2020), which reduces the efficiency of the plant photosynthetic apparatus in turn, decreasing seed production. Other authors have observed a sibstantial yield reduction when water deficit was applied in these stages (Wijewardana et al., 2018; Cohen et al., 2021). Therefore, stage V2-R1 demonstrated an impact of water deficit; nevertheless, seed yield reached 80 % of the value obtained in the control treatment.

A linear relationship was found between seed yield, applied irrigation, and evapotranspiration. In a previous experiment, ET_a exhibited a linear response to irrigation and yield of soybeans under subsurface drip irrigation (Sandhu and Irmak, 2022). Thus, the results presented indicate that, for every 1 mm increase in ET_a, seed yield increases by 30.2 kg ha^{-1} (2019) and 25.3 kg ha^{-1} (2021). A similar pattern was also found by Zhang et al. (2018); the authors explain that this linearity is because the production/biomass ratio is constant, decreasing or increasing linearly with the change in transpiration (T) or ET_a of the plant.

The highest values of the yield response factor were found in treatments R1-R5 and R5-R7, indicating that the crop is more sensitive to water stress in these stages. These phases, which includes flowering, pod formation, and grain filling are considered the most important for yield formation. A previous experiment observed that the highest values of Jensen (1968) were found for soybeans when water deficit was applied in the pod formation and grain filling stages (Fu et al., 2019).

Overall, using the means of ET_a and seed yield for the years 2019 and 2021, the values of the yield response factor were equal to 0.12, 0.36, and 0.57 for stages V2-R1, R1-R5, and R5-R7, respectively. When applying these values in Eq. (4) for each soybean growth stage, the estimated actual seed yield (Y_a) was equal to 2,504 kg ha^{-1}, 1,933 kg ha^{-1} and 2,104 kg ha^{-1} for treatments V2-R1, R1-R5, and R5-R7, respectively, that is, the production function of Jensen (1968) estimated the average Y_a of both years at 1.5 kg ha^{-1} more in the V2-R1 treatment, 40 kg ha^{-1} less in the R1-R5 treatment, and 17.3 kg ha^{-1} more in the R5-R7 treatment.

On average, K_y was equal to 1.16. The higher the K_y value, the more sensitive the plant is to water deficit. Therefore, according to this criterion, the soybean used in the present study is sensitive to water deficit. A previous experiment suggested a yield factor value for soybeans equal to 0.85, a value 27 % lower than that found in the present study (Steduto et al., 2012). These results showed that the K_y value was affected by climate and soil conditions, the irrigation method, and the volume of irrigation water applied (Aydinsakir et al., 2021), indicating the importance of conducting continuous studies considering the specificities of the region and new varieties under different irrigation systems. When applying the average K_y value (1.16) in Eq. (5), the estimated actual seed yield (Y_a) was equal to 2,455 kg ha^{-1}, 1,942 kg ha^{-1}, and 2,110 kg ha^{-1} for treatments V2-R1, R1-R5, and R5-R7, respectively, that is, the production function of Doorenbos and Kassam (1979) estimated the average Y_a of both years at 104 kg ha^{-1} more in the V2-R1 treatment, 22 kg ha^{-1} less in the R1-R5 treatment, and 55 kg ha^{-1} less in the R5-R7 treatment.

The results of the present study indicated that the soybean studied is more sensitive to water deficit in the development stages corresponding to flowering to pod formation (R1-R5) and seed filling (R5-R7). In the V2-R1 stage, the water deficit was impacted; however, seed yield reached 80 % of the value obtained in the control treatment. There is a linear correlation for the relationships between seed yield and applied irrigation, seed yield and ET_a, and ET_a and irrigation. The yield response factor for the soybean cycle was equal to 1.16; thus, the soybean used in the present study is sensitive to water deficit.

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Authors' Contributions

Conceptualization: Farias DBS, Rodrigues LN. **Data curation:** Farias DBS. **Formal analysis:** Rodrigues LN, Aleman CC, Cecon PR. **Investigation:** Farias DBS. **Methodology:** Farias DBS, Rodrigues LN. **Supervision:** Rodrigues LN. **Writing-original draft:** Farias DBS. **Writing-review & editing:** Rodrigues LN, Aleman CC, Cecon PR.

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