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Water use efficiency and canopy temperature response of soybean subjected to deficit irrigation

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Abstract. Deficit irrigation is a key strategy for improving water use efficiency (WUE) under irrigated conditions. However, there is a lack of information regarding the optimal water replacement that have minimal negative effects on soybean productivity. The objective of this study was to determine the water replacement levels associated with insignificant grain yield (GY) losses in soybean crops. A rain shelter experiment was conducted using a randomized complete block design with six replicates. Eight irrigation replacement levels, L120, L100, L90, L80, L70, L60, L50, and L40, were applied, where L100 was the reference treatment that kept soil moisture content along the soil profile under field capacity conditions and all other replacement levels were a fraction of this reference level. Grain yield ranged from 2.2 Mg ha^{-1} in L40 to 4.4 Mg ha^{-1} in L100, with a significant GY reduction in irrigation levels below 70%. The average crop water stress index (CWSI) ranged between 0.26 at L120 and 0.66 at L40 irrigation levels. WUE varied significantly only for the extreme irrigation levels studied, with the greatest value at the L40 irrigation level (1.2 kg m^{-3}) and the lowest value at the L120 irrigation level (0.65 kg m^{-3}), whereas for the intermediate irrigation levels from 50 to 100%, the WUE was equal to approximately 1.1 kg m^{-3}. The relationship between CWSI and GY ($R^2 = 0.85$) suggested that the maximum GY occurred at a CWSI of 0.34. In addition, the relationship between CWSI and WUE ($R^2 = 0.73$) showed that as evapotranspiration decreased, crop temperature increased. In conclusion, the implementation of a continuous water deficit in soybeans is feasible for farmers in water-scarce areas, but the minimum value of area productivity must be considered, even though WUE increases under more intensive values of water deficit.

Keywords: *Glycine max* L., water deficit strategies, canopy temperature, morphological responses.

HIGHLIGHTS

- Water replacement levels below 70% of required irrigation depth causes significant grain yield losses;
- Water replacement level of 40% of required irrigation depth improving water use efficiency;
- Long-term irrigation deficit reduces biomass of pods, leaves and stalks;
- CWSI showed significant quadratic relations with grain yield and water use efficiency.

1. INTRODUCTION

Currently, Brazil is the world's leading producer of soybeans (*Glycine max* L.), with a cropped area of roughly 38 million hectares and an average yield of 3517 kg ha^{-1} (Conab, 2023). This crop is one of the main commodities in the world, is of great importance in human and animal nutrition, and plays an important role in the bioenergy industry (Vale et al., 2019). However, soybean-cropped areas in Brazil are under rainfed conditions (90%) (Battisti et al., 2018), most of which are susceptible to drought stress, and hence yield gaps (Battisti and Sentelhas, 2019).

Water stress during the soybean growing cycle causes yield reductions between 46 and 74% (Sentelhas et al., 2015; Battisti et al., 2018). Furthermore, these negative effects may increase in the future because of water scarcity for agricultural activities related to climate change (Singh et al., 2014; Kang et al., 2021). Consequently, new irrigated areas for soybean production are being developed in this country (Fernandes et al., 2022). However, irrigated areas require technologies that contribute to the rational use of water in agriculture (Blum, 2009; Quiloango-Chimarro et al., 2022). Among these technologies, deficit irrigation appears to be the primary strategy to promote water saving, which can be quantified through water use efficiency (WUE) (Geerts and Raes, 2009; Kang et al., 2021). For example, a meta-analysis in China showed that deficit irrigation strategies in wheat and maize increased WUE by 9.25% and 6.38%, respectively, and water saving varied between 100 and 200 mm per growing cycle (Li et al., 2022). In soybean, a recent study showed that differences between full (80% of required irrigation depth) and deficit irrigation (60% of required irrigation depth) were only 2.9% in grain yield (GY) (Kocar et al., 2022). This finding highlights the benefits of deficit irrigation in soybean; however, further research is needed to determine the specific deficit irrigation levels that improve WUE with incipient GY reductions.

The effects of water stress can be evaluated using several methods in both plants and soil (Petrie et al., 2019). An important cost-effective indicator of crop water status in real time is canopy temperature (Bian et al., 2019; Costa et al., 2020). This method of assessing the water deficit in plants is based on the principle that the reduction in temperature is proportional to the rate of plant transpiration due to the evaporative cooling process (Zia et al., 2013; Costa et al., 2018; Khorsandi et al., 2018). Temperature data acquisition has advanced over the last 50 years (Craparo et al., 2017; Kirnak et al., 2019). Currently, thermal cameras are increasingly being integrated or adapted to be used in satellites, drones, and even smartphones (Bian et al., 2019; Petrie et al., 2019). Temperature data obtained through thermography has shown promising correlations with physiological and productivity-related parameters (Yang et al., 2019; Anda et al., 2020). Additionally, canopy temperature allows the computation of indices such as the crop water stress index (CWSI), which is the most commonly used index to quantify plant spatial and temporal variability of drought stress and to schedule precision irrigation on large irrigated fields (Khorsand et al., 2021).

The Crop Water Stress Index serves to simplify the interpretation of a plant's water status (Biju et al., 2018), providing a value ranging from 0 (indicating non-stressed conditions) to 1 (representing maximum stress conditions). These facilities and the robustness of thermography would allow farmers to make better decisions regarding irrigation. Temperature-derived indices are important for reliably estimating decreases in soybean GY (Gajić et al., 2018; Anda et al., 2020). For example, Anda et al. (2019) found that for each 0.1 increase in CWSI above 0.2, GY decreased by 434.1 g m^{-2}. However, the same authors highlighted that the relationship between the CWSI and GY should be studied for each specific climatic condition to ensure accurate and relevant results.

It was hypothesized that deficit irrigation would improve WUE in soybeans without significant yield losses. Thus, the objectives were to determine the water replacement level where soybean has no significant GY losses, to identify water stress through the canopy temperature response patterns, to verify the relationships between CWSI and GY, and between CWSI and WUE.

2. MATERIAL AND METHODS

2.1. Site characterization

The study site is located at University of São Paulo, Piracicaba-SP, in southwestern Brazil, which is considered a humid subtropical zone, Cw, according to the Koppen climate classification. The experiment was conducted under rain shelter conditions. The structure of the cover measured 5.2 meters in ceiling height and was composed of a transparent plastic cover (diffuser film) and lateral black screens, which were designed to intercept 30% of incoming radiation. The experimental area extended over 164 m^2 and was divided into 96 plots, each of which was a fiber cement box with a volume of 0.1 m^3 and had dimensions of 0.60 meters in length, 0.45 meters in width, and 0.40 meters in depth. The soil within each box was classified as red-yellow latosol with a sandy-loam texture. The plots were arranged in four rows, with 0.80 meters between rows and 0.50 meters between plots within each row.

2.2. Plant materials, experimental preparation and treatment application

Glycine max L. semi-determined habit cultivar TMG 7062 was sowed on December 16, 2019. Before initiating the sowing, a chemical analysis of the soil was conducted, and the fertilization recommendations provided by the São Paulo State Agricultural Company (IAC Nutrition Bulletin) were carefully followed. Consequently, 300 grams of monoammonium phosphate and potassium chloride were applied to the soil via fertigation. Approximately eight days after seeding (DAS), the plants were thinned to maintain a distance of twelve plants per meter (six plants per plot). Throughout the growing cycle, manual weed management was practiced, and appropriate agrochemicals were applied to address any pest or disease.

The experiment was based on a randomized block design and six replications per treatment. Soybean plants were subjected to eight irrigation replacements (L120, L100, L90, L80, L70, L60, L50, and L40), resulting in an experiment with 96 useful plots. The reference treatment (L100) was based on the water depth necessary to keep the soil profile at field capacity (Fc) every other day, whereas all other treatments were a fraction of this treatment.

The irrigation system consisted of a 500 L water reservoir, polyethylene piping, water pump, ring filter, and four watering manifolds with eight outlets each. Two emitters with a flow rate of 8 L h^{-1} were installed in each plot. For a homogeneous distribution of water on the plot, a two-way splitter was installed on each emitter. The irrigation system was managed through an *Arduino* mega microcontroller. Furthermore, the Arduino platform controlled two relays for activation of the irrigation pump and the reservoir output solenoid.

Before the beginning of the experiment, the irrigation system was evaluated to verify the emitters' flow rate. Christiansen's uniformity coefficient (CU), Distribution Uniformity (DU) and the total system flow rate were used. The performance of the irrigation system was considered excellent, as evidenced by the CU and DU values of 95.5% and 86.1%, respectively, and the total system flow rate of 1.5 m^3 h^{-1}.

Irrigation management was based on the soil water matric potential. For this purpose, tensiometers were installed at 0.15, 0.25 and 0.35 m in all repetitions of the reference treatment (L100). The matric potential was measured daily with a digital portable punction tensimeter calibrated against a mercury vacuum gauge. A spreadsheet developed in Microsoft Excel® was used for irrigation amount calculations.

Irrigation for the L100 level was computed by adding the water necessary to increase the soil water to the field capacity for all three soil layers. The amount of soil water in each layer before irrigation was estimated from the matric potential by using the van Genuchten soil water retention equation (van Genuchten, 1980), according to Equation 1:

$$\theta\ (\Psi_m) = \theta_r + \frac{(\theta_s - \theta_r)}{(1 + (\alpha \times \Psi_m)^n)^m} \qquad (1)$$

where θ (ψm) is the soil volumetric water content (cm^3 cm^{-3}), θ_r is the soil residual volumetric water content ($cm^3\,cm^{-3}$), θ_s is the volumetric water content of the saturated soil ($cm^3\,cm^{-3}$), m and n are the regression parameters of equation (dimensionless), α is the parameter with dimension equal to the inverse of the tension (kPa^{-1}) and ψ_m is the function of the matric potential (kPa).

The physical water retention characteristics of the soil and parameters for the van Genuchten model are listed in Table 1. The criterion established to start irrigation allowed us to maintain the soil matric potential at -25 kPa prior to the initiation of irrigation throughout the entire growing cycle. This soil-based irrigation scheduling method ensures that the soybean crop achieves its potential grain yield (GY) (França et al., 2024). Before irrigation level treatments were implemented, plants were given 100% irrigation (L100) until the seedling stands were well established.

The total irrigation amount varied from 1125 mm in L120 to 375 mm in L40 (Table 2). The potential water demand (L100) in this trial (938 mm) was higher than the usual range for this crop, which commonly varies between 400 and 840 mm under field conditions (Candogan et al., 2013; Silva et al., 2017). The total number of irrigation events was 41 for all treatments.

Table 1. Physical water-retention characteristics of the soil and parameters for the van Genuchten model.

Layer m	θs $cm^3\ cm^{-3}$	θr $cm^3\ cm^{-3}$	α kPa^{-1}	m	n	θfc $cm^3\ cm^{-3}$	θwp $cm^3\ cm^{-3}$	AWC mm
0-0.20	0.095	0.422	1.346	0.1802	2.7275	0.225	0.102	24.6
0.20-0.30	0.085	0.412	1.571	0.1649	2.5001	0.226	0.098	12.8
0.30-0.40	0.123	0.375	1.128	0.2758	1.5638	0.242	0.133	10.9

Empiric parameters (α, m and n), soil residual and saturation water content (θr, θs) of the van Genuchten model, moisture at field capacity (θfc), moisture at the wilting point (θwp) and available water capacity (AWC).

Table 2. Irrigation water accumulated and number of irrigations during the soybean growing cycle.

Treatments	L40	L50	L60	L70	L80	L90	L100	L120
Accumulated irrigation ($mm\ cycle^{-1}$)	375.1	468.9	562.7	656.5	750.3	844.1	937.9	1125.5
Number of irrigation events	41	41	41	41	41	41	41	41

2.3. Micrometeorological monitoring, canopy temperature and crop water stress index measurements

Micrometeorological data were measured inside the greenhouse in the center of the experimental area. Measurements of air temperature, relative humidity and solar radiation flux density were recorded with a Vaissala sensor HMP45C, Vaissala barometer CS 106, and a pyranometer sensor LI200X, respectively (Campbell Scientific, Logan, Utah, USA). Micrometeorological data were integrated every 15 minutes (average values) through a CR1000 data-logger (Campbell Scientific, Logan, Utah, USA).

Infrared thermal images were taken with a FLIR One Pro thermal camera (FLIR Systems, Portland, USA) with a resolution of 160 × 120 pixels and emissivity values of 0.95. These images were acquired above the leaf canopy at a height of 1.5 m, on leaves fully exposed to the sun and with a similar insertion angle in relation to the vertical plane (Figure 1). Thermal evaluations were done three times during the growing cycle on cloudless days around noon (vegetative stage, 30 DAS; flowering, 62 DAS; and ripening, 90 DAS). Images of each plot were processed and analyzed in the software FLIR Tools, in which a representative part of the canopy was selected to calculate the average canopy temperature.

Using infrared thermal data and micrometeorological data, the CWSI was computed according to the methodology of Jackson et al. (1988), as in Equation 2:

$$CWSI = \frac{(T_c - T_{air}) - T_{wet}}{T_{dry} - T_{wet}} \qquad (2)$$

T_{air} is the temperature of the air, T_c is the temperature of the canopy, T_{wet} is the non-water stressed baseline (temperature of the canopy transpiring at the potential rate), and T_{dry} is the water stressed baseline (temperature of the non-transpiring canopy). The difference between T_c and T_{air} is the canopy temperature depression (CTD).

The lower and upper temperature baselines were determined by the minimum and maximum difference between T_c and T_{air}, respectively. For CWSI calculation, (T_c - T_{air}) above 7 °C and below -10 °C were eliminated following the methodology proposed by Meron et al. (2013).

2.4. Morphological evaluations and water use efficiency

The height of the plants was evaluated in four periods during the growing cycle (20, 40, 60 and 80 DAS). Plants were harvested at physiological maturity (March 29, 2020) and divided into vegetative and reproductive components, then dried at 65° C in an oven with forced air circulation for 72 hours, and finally weighted on a precision scale. The biomass of stalks, branches, leaves, pods, and seeds resulted in the biological yield of the crop. The harvest index was calculated as the ratio of GY to biological yield, as in Equation 3:

$$HI = \frac{\text{Grain yield (kg)}}{\text{Biological yield (kg)}} \times 100 \qquad (3)$$

Soybean grain yield was normalized for 13% seed water concentration. Grain yield was scaled to Mg ha^{-1} considering a useful area of 0.27 m^2 per plot. Water use

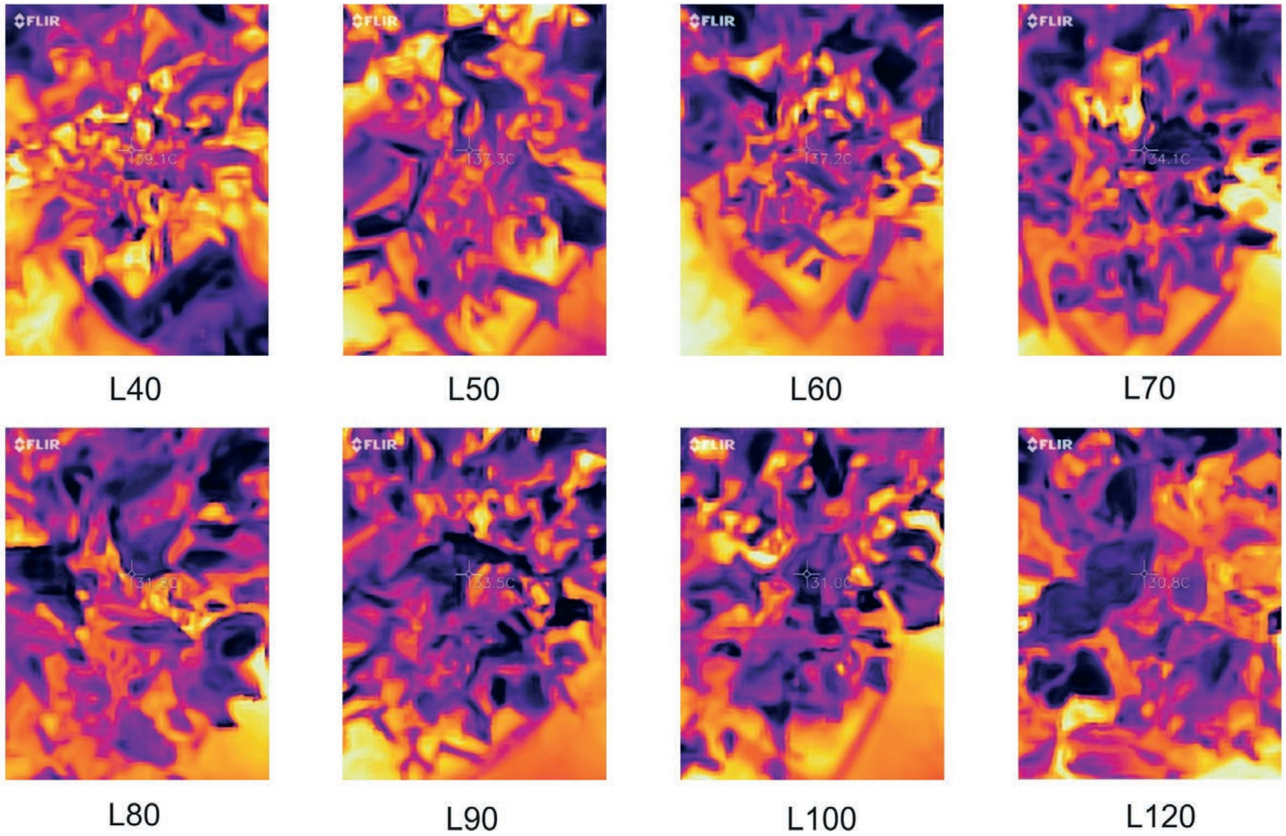

Figure 1. Infrared images from the eight water replacement levels. The darker colors in the thermal images represent cooler temperatures, while the lighter colors represent warmer temperatures.

efficiency (kg m^{-3}) was calculated as the ratio of GY to the amount of total water input, as in Equation 4:

$$\mathrm{WUE} = \frac{\text{Grain yield (kg)}}{\text{Water consumption } (\mathrm{m}^3)} \tag{4}$$

2.5. Statistical analysis

All the statistical analyses were performed with the R software (R Project for Statistical Computing, version 4.1.2). Exploratory data analysis was conducted to detect outliers using box-plot graphs. Analyses of variance (ANOVA) were performed after testing the homogeneity of variances and normality of the residuals by the Levene and Shapiro-Wilks tests, respectively. Variables with a significant *F* value at 5% probability were subjected to regression analysis and the post-hoc Tukey test at 5% probability. In addition, Pearson's linear correlation coefficient was performed to evaluate the relationship between the following variables: biomass of leaves, pods, stems and branches, 100-seed weight, CTD, canopy temperature, HI, irrigation amount, WUE, GY and CWSI. This coefficient and its significance level were mainly determined to illustrate how canopy temperature influences the morphological and yield variables.

3. RESULTS AND DISCUSSION

3.1. Micrometeorological data, canopy temperature and crop water stress index (CWSI)

The climatic data collected during the experimental period are presented in Figure 2. The average temperature during the growing cycle was found to be within the optimal range for soybean growth, fluctuating between 21.1 and 31 °C (Setiyono et al., 2007). The maximum temperature varied between 25.6 and 46.1 °C, while the minimum temperature ranged between 15.9 and 24.4 °C (Figure 2A). Throughout the growing cycle, the average relative humidity varied between 73.4 and 100%, while the solar radiation fluctuated between 2.8 and 22.3 MJ m^{-2} day^{-1}, with an average value of 13.7 MJ m^{-2} day^{-1} (Figure 2B).

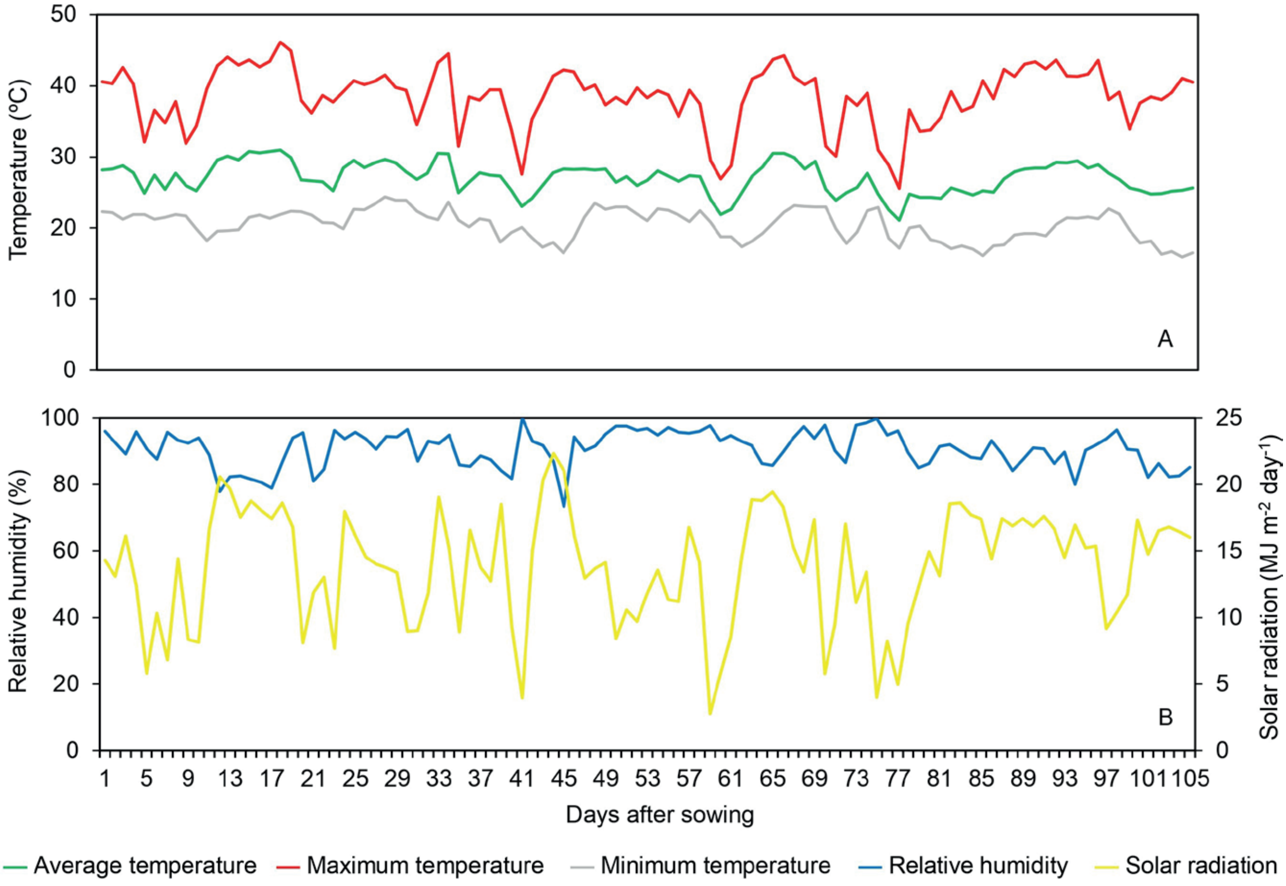

Figure 2. Maximum, minimum, and average air temperature (**A**), relative humidity and solar radiation (**B**) in the experimental area during the soybean growing cycle. 0 days after sowing (DAS): December 16, 2019 and 105 DAS: March 29, 2020.

Irrigation treatments showed a significant response in canopy temperature (T_c) and canopy temperature depression (CTD) (Table 3). The T_c was 32.9 °C for the reference treatment (L100), which was comparable to the T_c for treatments L120, L90, and L80. In contrast, the T_c of treatments L60, L50, and L40 differed from the reference irrigation treatment by an average of 4.9 °C (Figure 3A). The observed increase in canopy temperature can be attributed to the stomatal closure that contributes to a diminished capacity for transpiration cooling (Banerjee et al., 2020). Stomatal closure is a critical adaptive mechanism for plants under water stress and affects various physiological processes, including photosynthesis, transpiration, and leaf water status (Flexas and Medrano, 2002; Quiloango-Chimarro et al., 2022; Zahra et al., 2023). These changes in crop physiology also influence soybean growth and development, as discussed below.

In the present study, the variation of the CTD was about ± 2.6 °C. Under irrigation treatments L120, L100, L90, and L80, the CTD was negative, whereas under the irrigation treatments L60, L50, and L40, the CTD was positive (Figure 3B). The variation of CTD and T_c was similar, but with the increase in water supply, CTD decreased while T_c increased. CTD has been used to assess plant water status (Zia et al., 2013; Biju et al., 2018) and has been preferred in high air temperatures and low relative humidity for irrigation management (Amani et al., 1996). In addition, Singh et al. (2021) suggested that CTD and water deficit are unrelated until the soil water availability changes significantly.

Average CWSI values ranged between 0.26 in L120 and 0.66 in L40 (Figure 4). Overall, CWSI increased as irrigation levels decreased. CWSI varied between 0.18-0.25 in L120, 0.21-0.24 in L100, 0.22-0.31 in L90, 0.23-0.36 in L80, 0.33-0.50 in L70, 0.38-0.68 in L60, 0.50-0.58 in L50, and 0.61-0.71 in L40. Similar CWSI responses due to water stress have been reported in soybean. For example, in a recent study by Morales-Santos and Nolz (2023), CWSI values ranging between 0.13 and 0.23 were reported for drip-irrigated soybean. These

Table 3. Analysis of variance (ANOVA) to compare the means of the studied variables.

Source of variation	Variables	Sum of squares	Mean square	F
Water replacement levels	Canopy temperature (T_c) and canopy temperature depression (CTD)	212.87	30.41	18.23*
	CWSI end of the vegetative stage ($CWSI_A$)	0.90	0.13	10.28*
	CWSI flowering ($CWSI_B$)	1.55	0.22	17.76*
	CWSI ripening ($CWSI_C$)	1.03	0.15	41.33*
	Average CWSI ($CWSI_D$)	1.19	0.17	17.96*
	Plant height at 20 days after sowing (DAS)	6.52	0.93	0.31^{ns}
	Plant height at 40 DAS	75.97	10.85	1.53^{ns}
	Plant height at 60 DAS	752.70	107.53	6.48*
	Plant height at 80 DAS	2134.50	304.93	14.82*
	Dry weight of leaves	18239	2605.59	5.04*
	Dry weight of pods	15451	2350.15	10.48*
	Dry weight of stems and branches	23961	3424	15.94*
	Grain yield (GY)	33.72	4.82	7.99*
	Harvest index (HI)	144.72	20.68	1.40^{ns}
	Water use efficiency (WUE)	1.08	0.15	3.41*

^{ns}not significant; *significant at a probability level of 5%.

values closely aligned with the CWSI values obtained in the present study under the reference treatment (L100), despite the different environmental conditions (subhumid and humid subtropical). This consistency highlights the robustness of CWSI as a standard metric for irrigation scheduling, effectively isolating independent environmental factors (DeJonge et al., 2015; Kullberg et al., 2017).

3.2. Morphological responses to water deficit

Figure 5 shows the plant height response to deficit irrigation, measured four times during the growing cycle. Irrigation treatments had no effect on plant height in the first and second periods (Table 3), with average of 0.35 and 0.42 m, respectively (Figure 5A and 5B). In the third period, plant height was lower under irrigation treatments L40 and L50, with a difference of ~0.10 m compared with the L120 treatment (Figure 5C). In the fourth period, plant height was lower under the irrigation treatments L40, L50, and L60, and the greatest difference was found between L40 and L120 (~0.20 m) (Figure 5D). The final plant height under well-watered conditions was on average 0.88 m. According to Dong et al. (2019), plant height inhibition in soybeans under drought stress is more pronounced when plants are subjected to severe and long-duration stress. For example, Rosadi et al. (2005) showed that soybeans under 40% of required irrigation depth maintained plant height until the fourth week of stress, and at the end of the growing cycle, plant height was reduced by 0.26 m. Therefore, plant height is an indicator of soybean growth and development when employing water-deficit strategies.

Aerial biomass accumulation diminished as water stress increased (Figure 6). The decline in total dry matter under L40 compared with that under L100 was 48%. The biomass of leaves, pods, and stalks showed similar decreases under irrigation deficits. Thus, there was a huge difference in the biomass weight of these components in L40, L50, and L60 compared to the reference treatment (L100). When comparing the L100 and L40 treatments, there was a reduction in the biomass of the leaves, pods, and stalks by 29%, 52%, and 43%, respectively. Similar decreases in pod and leaf biomass have been observed in short-term drought stress trials (Rosales-Serna et al., 2004). However, short periods of water stress have no effect or even increase the stalk biomass (Wijewardana et al., 2018). According to Ohashi et al. (2009), drought stress at specific phenological stages induces greater partitioning of assimilates to vegetative parts (stalks) rather than reproductive parts. Thus, it is interesting to note that long-duration water deficits led to losses in all biomass components.

Grain yield decreased as the irrigation deficit increased (Table 4). Compared to the reference treatment (L100), significant reductions in GY ranged from 11% in L70 to 50% in L40. These results are comparable with those reported by Irmak et al. (2014) in which each 25.4 mm increase in water amount improved soybean yield by 0.3 Mg ha^{-1}. For example, in our study, the differences in the water amount and GY between L100 and

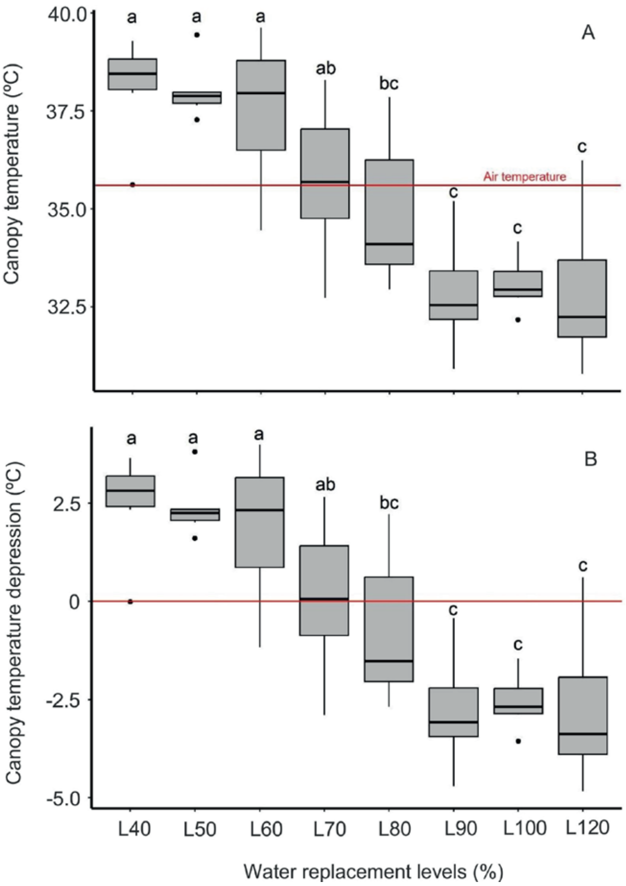

Figure 3. Boxplots of average canopy temperature derived variables. Canopy temperature (**A**), Canopy temperature depression (CTD) (**B**). Different lowercase letters indicate significant differences at 5% probability according to the Tukey test. The box represents the interquartile range (IQR) and whiskers represent the range of data. The median is depicted by a horizontal line within the box, and the outliers are illustrated by individual points outside the whiskers.

Table 4. Grain yield, harvest index and water use efficiency of soybean subjected to eight water replacement levels.

Water replacement levels	Grain yield (Mg ha^{-1})	Harvest index (%)	Water use efficiency (kg m^{-3})
L120	3.3±0.5abc	29.9±1.7	0.61±0.10b
L100	4.4±0.4a	36.5±1.4	0.88±0.13ab
L90	3.4±0.5ab	33.2±2.3	0.83±0.06ab
L80	3.5±0.4ab	33.3±2.2	0.97±0.10ab
L70	3.0±0.3bcd	33.0±1.4	0.96±0.10ab
L60	2.6±0.2bcd	31.8±1.8	0.94±0.11ab
L50	2.3±0.3cd	33.2±2.5	0.99±0.08ab
L40	2.2±0.2d	33.5±1.2	1.17±0.09a

Data are Mean ± SE (n = 6). Different lowercase letters indicate significant difference according to the Tukey's test.

L90 were 94 mm and 1 Mg ha^{-1}, respectively. In addition, non-significant decreases under excess irrigation (L120) reflect no damage effects in soybean, which is consistent with the study of Gava et al. (2016) in soybean subjected to 50% additional irrigation. Grain yield potential (L100) in this study (4.4 Mg ha^{-1}) was superior to the Brazilian average production (3.3 Mg ha^{-1}) (Conab, 2023), confirming the benefits of irrigation in soybean. Overall, the findings indicate that GY can be sustained under extended periods of water restriction (L80), resulting in a water saving of approximately 375 mm.

Irrigation treatments had no significant effect on the average harvest index (HI), which varied from 29.9 to 33.5% (Table 3). Similar results were found by Demirtaş et al. (2010) in soybean subjected to water stress under drip irrigation. In contrast, Gajić et al. (2018) and Frederick et al. (1991) reported that the HI tended to be higher under drought stress conditions. Thus, the response of HI to drought stress could be different due to genotype–environment interactions.

Significant differences in WUE were found between the irrigation treatments (Table 3). Water use efficiency ranged between 1.17 kg m^{-3} in L40 and 0.61 kg m^{-3} in L120. L40 (severe water stress) was 25% higher than L100 (reference treatment) with a water saving of 563 mm (Table 4). Gava et al. (2016) in soybean under irrigation treatments between 20 and 100% of required irrigation depth found higher values of WUE at 40-60% of water deficit (1.1 kg m^{-3}). On the other hand, lower WUE values were recorded in rainfed systems when compared with irrigated systems (Mekonnen et al., 2020), highlighting the importance of irrigation to increase the WUE of crop production. Overall, the results suggest that deficit strategies in irrigated soybean could be an option in water-scarce regions.

3.3. Correlations among studied traits

The correlation among traits is shown in Figure 7. Pearson correlation coefficients below 0.5 were marked by a "x mark" whereas positive correlations are in blue and negative correlations are in red. Grain yield was positively correlated with biomass of leaves, pods, and stalks, HI, and irrigation amount, but negatively with all derived canopy temperature variables (Canopy temperature, CTD, CWSI$_A$, CWSI$_B$, CWSI$_C$ and average CWSI$_D$). Average CWSI$_D$ was the only one closely related to GY and WUE (Pearson's R=-0.38** and 0.36*). Therefore, these relationships could be an indicator of the yield gap and allow for improved water management in irrigated soybean.

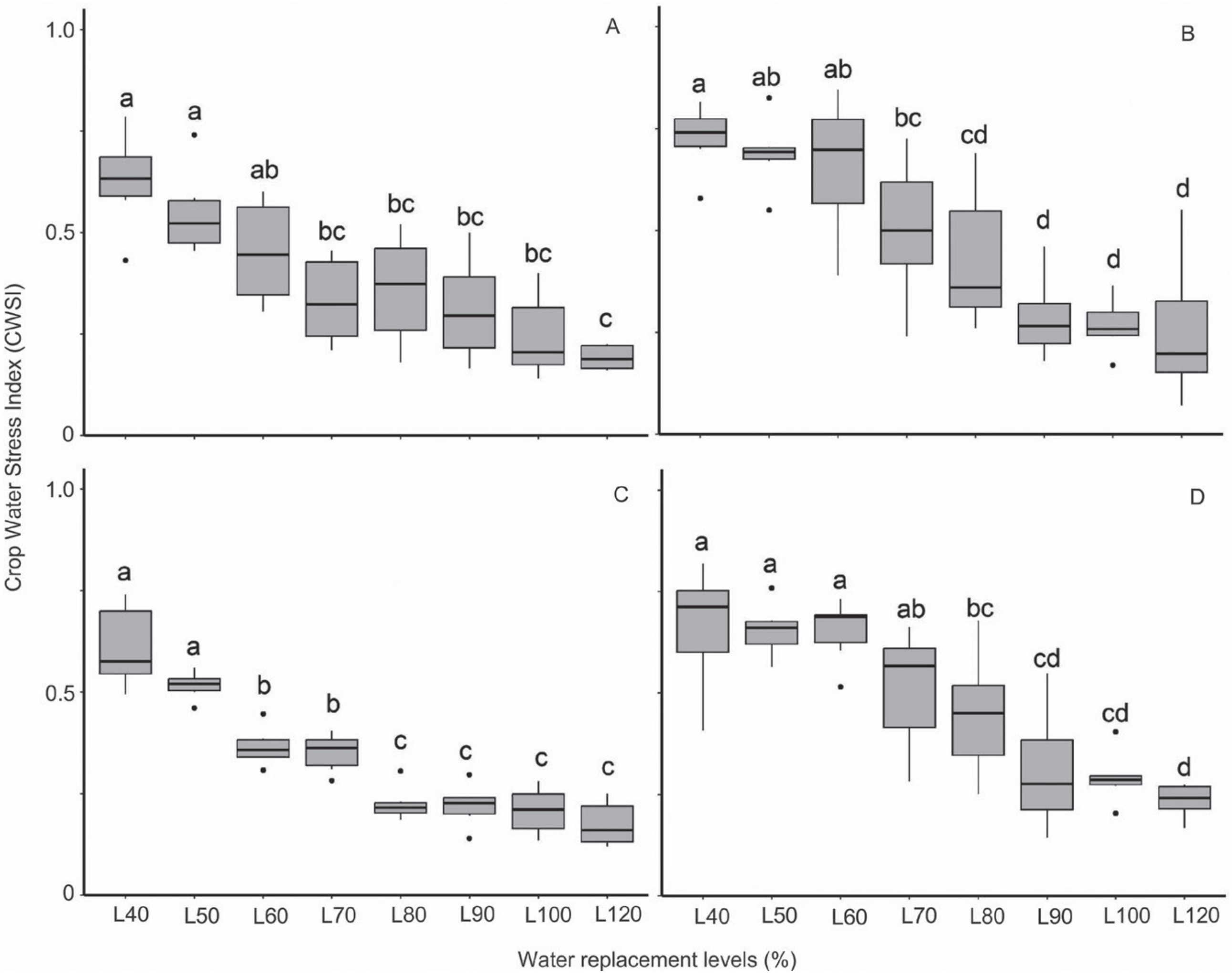

Figure 4. Crop water stress index (CWSI) throughout the growing cycle. (**A**), end of the vegetative stage; (**B**), flowering; (**C**), ripening and (**D**), average CWSI. Different lowercase letters indicate significant differences at 5% probability according to the Tukey test. The box represents the interquartile range (IQR) and whiskers represent the range of data. The median is depicted by a horizontal line within the box, and the outliers are illustrated by individual points outside the whiskers.

A second order polynomial was fitted to the average CWSI and GY (Figure 8A). A polynomial equation between CWSI-GY in soybean was also reported by Kocar et al. (2022) with a R^2=0.75. The maximum GY (4.67 Mg ha^{-1}) occurred at a CWSI of 0.34, which suggests that 80% of irrigation replacement can maintain soybean productivity similar to fully irrigated treatment (L100).

A second order polynomial was fitted to the average CWSI and WUE (Figure 8B) which is consistent with the equations found by Anda et al. (2020) and Candogan et al. (2013) in soybean deficit irrigation trials. Moreover, Dogan et al. (2007) concluded that irrigation deficit strategies in soybean improve WUE because less water is applied without great yield penalty. The maximum WUE (1.03 kg m^{-3}) occurred at a CWSI of 0.60. Overall, irrigation reduction can be conducted according to the conditions of each region.

Morales-Santos and Nolz (2023) assessed water stress indices based on canopy temperature for irrigated and rainfed soybeans in subhumid conditions, and their results indicated that the CWSI effectively reflected the different water conditions of the plant. Our findings suggest that the CWSI can serve as a basis for implementing a specific irrigation strategy in soybean cultivation. Algorithms based on Tc obtained through infrared sensors can be employed, especially in arid regions, to implement a deficit irrigation strategy that does not significantly compromise GY and enhance WUE. Fur-

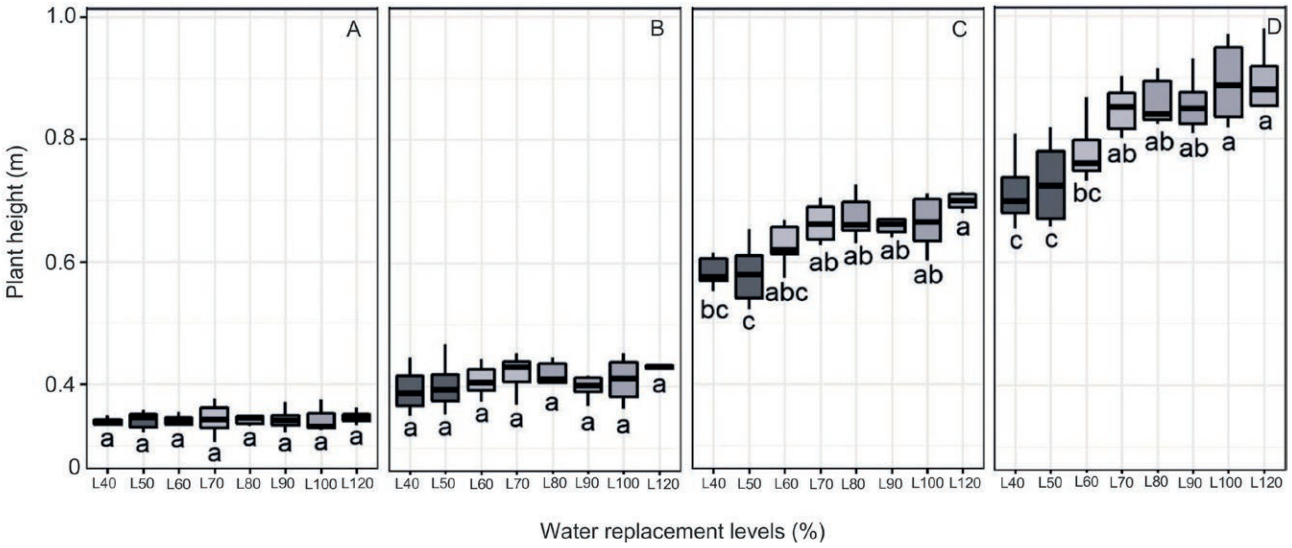

Figure 5. Growth dynamics of plant height at 20 days after sowing (DAS) (**A**), 40 DAS (**B**), 60 DAS (**C**) and 80 DAS (**D**). Different lowercase letters indicate significant differences at 5% probability according to the Tukey test. The box represents the interquartile range (IQR), whiskers represent the range of data, and the median is depicted by a horizontal line within the box.

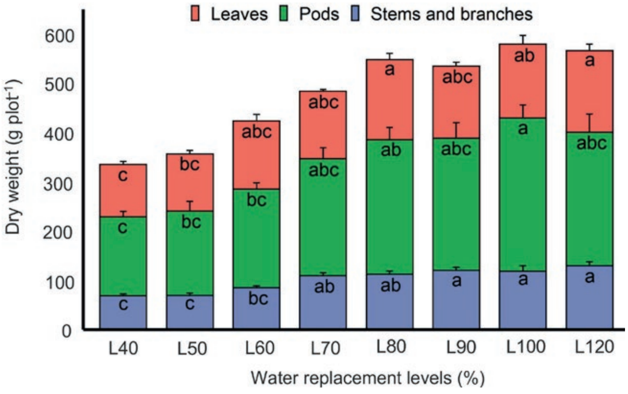

Figure 6. Average biomass allocation values of eight irrigation replacement levels. Different lowercase letters indicate significant differences at 5% probability according to the Tukey test. Bars indicate standard error of the mean.

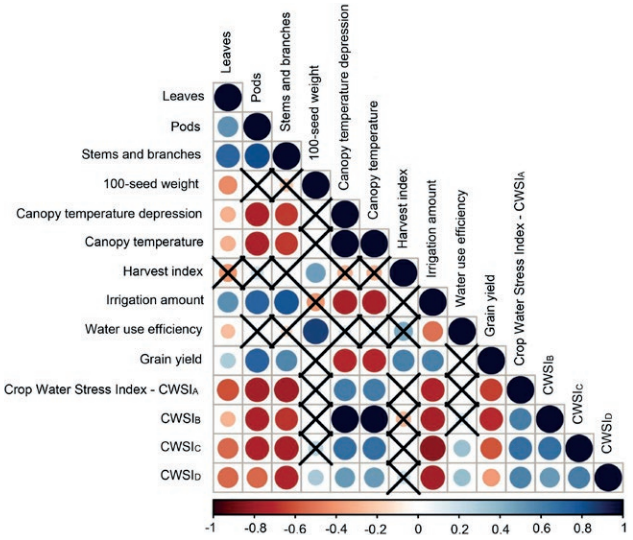

Figure 7. Relationships among studied traits. The Pearson correlation coefficients < 0.5 were marked by an “x”, whereas positive correlations are in blue and negative correlations are in red.

thermore, these relationships could be applied in humid regions, where climate change impacts agricultural production by increasing crop water consumption (Singh et al., 2021). Overall, deficit irrigation managed through the use of CWSI may become a viable strategy in different environments as mentioned by Jamshidi et al. (2021).

4. CONCLUSIONS

This study reveals that the implementation of long-duration deficit irrigation strategies can maintain water use efficiency (WUE) in soybean crops at a level comparable to that of the full irrigated treatment, even under a water replacement level of 40% of required irrigation depth, which also demonstrated the highest WUE. In contrast, under the water replacement level of 120% of required irrigation depth, WUE was lower than in the other deficit irrigation treatments (from L100 to L40). These results indicate that the adoption of deficit irriga-

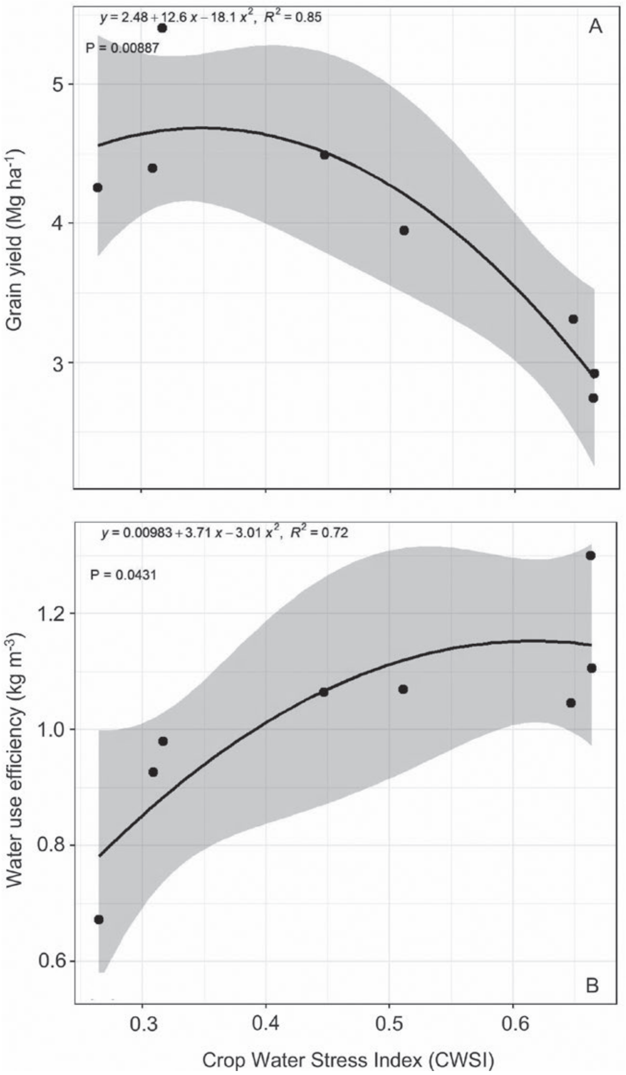

Figure 8. Relationships between (**A**) Crop water stress index (CWSI) and soybean productivity (GY) and (**B**) Crop water stress index (CWSI) and water use efficiency (WUE). The gray area indicates the 95% confidence interval.

tion strategies can lead to more sustainable and efficient water management practices in soybean production, especially in regions facing water scarcity.

The dynamics of the Crop Water Stress Index (CWSI) indicate that it can be utilized for irrigation scheduling owing to its good second-degree polynomial relationship with soybean yield and WUE. Based on the availability of water, farmers may employ distinct irrigation strategies to optimize yield or water-use efficiency, using average CWSI values as a threshold value to start irrigation.

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