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CROP WATER STRESS INDEX FOR PREDICTING YIELD LOSS IN COMMON BEAN

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1 ABSTRACT

The crop water stress index (CWSI), an index derived from canopy temperature, has been widely studied as a physiological indicator of plant water status to optimize irrigation in common beans. However, it is not clear how this index could contribute to yield prediction as a decision support tool in irrigation management. This paper aimed to use the CWSI for predicting yielding loss in common bean (*Phaseolus vulgaris* L.) subjected to water stress under drip irrigation. A rain shelter experiment was conducted using a completely randomized design with five replications. The indeterminate growth cultivar TAA Dama was subjected to three irrigation treatments: 100% of the field capacity (FC), 75 and 50% FC from 20 days after sowing (DAS) until the end of the crop cycle. Grain yield was reduced by 42% under 50% FC treatment. Furthermore, stomatal conductance was reduced at this treatment, whereas the CWSI and canopy temperature increased as irrigation levels decreased. The relationship between grain yield and CWSI (R^2=0.76, RSME=2.35g) suggests that canopy temperature data could be used to forecast grain yield losses. In conclusion, farmers can have a low-cost, effective technique for making water management decisions in common bean.

Keywords: *Phaseolus vulgaris*, water deficit, canopy temperature

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ÍNDICE DE ESTRESSE HÍDRICO DA CULTURA (CWSI) PARA PREVISÃO DA PERDA DE RENDIMENTO EM FEIJÃO COMUM

2 RESUMO

O índice de estresse hídrico da cultura (CWSI), índice derivado da temperatura do dossel, tem sido amplamente estudado como um indicador fisiológico do estado da água das plantas para otimizar a irrigação em feijão comum. No entanto, não está esclarecido como o índice poderia contribuir para a previsão do rendimento como instrumento de apoio à decisão na gestão da irrigação. O presente estudo objetivou utilizar o *CWSI* para prever queda de rendimento em feijão comum (*Phaseolus vulgaris* L.) submetido a estresse hídrico sob irrigação por gotejamento. Foi realizado um experimento em estufa utilizando um desenho completamente aleatório com cinco réplicas. A cultivar de crescimento indeterminado TAA Dama foi

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submetida a três tratamentos de irrigação: 100% da capacidade do campo (CC), 75 e 50% FC desde 20 dias após a semeadura até ao fim do ciclo de cultivo. O rendimento do grão foi reduzido em 42% sob o tratamento de 50% CC. Além disso, a condutância estomática foi reduzida sob este tratamento, enquanto que o CWSI e a temperatura do dossel aumentaram à medida que os níveis de irrigação diminuíram. A relação entre o rendimento de grãos e o *CWSI* (R^2=0,76, RSME=2,35g) sugere que os dados da temperatura do dossel podem ser utilizados para prever as perdas de produção de grãos. Em conclusão, os agricultores podem ter uma técnica de baixo custo e eficaz para tomar decisões de gestão da água em feijão comum visando garantir a produtividade.

Keywords: *Phaseolus vulgaris*, déficit hídrico, temperatura do dossel

3 INTRODUCTION

Phaseolus vulgaris is an important legume cultivated around the world. Currently, Brazil is the largest producer of this crop and the predicted yield for the 2020/2021 harvest is around 3.1 million tons (CONAB, 2021). In this country, 93% of common beans are cultivated under rainfed conditions in vulnerable areas to drought stress (HEINEMANN et al., 2016). There is evidence that water shortages reduce grain yield by up to 80% (CALVACHE et al., 1997).

The lack of information about drought tolerance in common beans favors inadequate water management (MATHOBO et al., 2017). For example, irrigation deficit strategies could be used to save water in water-scarce regions. Thus, it is essential to develop rapid tools to assess crop water status. In this way, the use of thermal data to determine water stress has been well studied (FUCHS, 1990). Water stress causes stomatal closure reducing the transpiration cooling ability (JACKSON et al., 1981), allows indirectly detect changes in plant water availability through a non-destructive technique.

Limitations in the use of canopy temperature are related to the efficient use of information. However, in recent years, indexes such as the crop water stress index (CWSI) have normalized the data using meteorological parameters (RU et al., 2020). For example, baselines can be used in different climates and soil types. In addition, this index has good correlations with gas exchange traits, pigments, yield and leaf water potential (SOURESHJANI et al., 2019; ANDA et al., 2020; COSTA et al., 2020).

Grain yield in common beans is limited by water availability (GALVÃO et al., 2019). However, depending on the water stress level, the yield response could vary (BAI; PURCELL, 2018). Therefore, it is interesting to observe if the CWSI responds to the variations under mild water stress and high frequency irrigation.

It was hypothesized that it is possible to predict grain yield penalty with reasonable accuracy through the index derived from canopy temperature. Therefore, the main objective of this study was to determine the relationship between the average CWSI and the grain yield of common beans subjected to different irrigation levels.

4 MATERIALS AND METHODS

The experiment was conducted at a greenhouse under rain shelter conditions at the São Paulo University, Piracicaba, southwestern Brazil, which is considered a humid subtropical zone, Cw, according to the Koppen climate classification. The greenhouse structure (130 m^2) consisted of a ceiling height of 5.5 m, a transparent plastic cover (diffuser film), and a black screen on the sides that intercepted 50% of the incident radiation.

The common bean TAA Dama cultivar was subjected to three irrigation treatments: L100, L75, and L50. The experimental design was distributed completely at random, with five replications. Each experimental unit consisted of a box with a volume of 0.33 m^3 and dimensions of 1.04 x 0.41 x 0.76 m (length, width and depth) filled with soil classified as red-yellow latosol with a sandy-loam texture. Before the beginning of the trial, soil analysis was done and fertilization was conducted according to Van Raij (1997) recommendations for São Paulo State. In addition, non-deformed soil samples were obtained for hydro-physical characterization. The physical water-retention characteristics of the soil are given in Table 1.

Table 1. Physical and hydrological characteristics of the soil used in the experiment.

Layer	θ_{fc}	θ_{wp}	AWC	Ds	Sp	Texture		
						Sand	Silt	Clay
m	$cm^3\ cm^{-3}$		mm	$g\ cm^{-3}$	%		%	
0.00-0.20	0.224	0.161	22.10	1.61	40.10	72.29	8.00	19.71
0.20-0.40	0.226	0.163	19.62	1.58	41.20	72.03	8.04	19.93
0.40-0.60	0.229	0.166	18.49	1.54	42.70	72.03	7.69	20.28

θFC: moisture at field capacity (corresponding to a matric potential (ψm) of -4.85 kPa for drip irrigation); θWP: moisture at the wilting point (corresponding to a matric potential (ψm) of −1500 kPa); AWC: available water capacity; Ds: soil bulk density; Sp: total soil porosity.

The experiment started on March 4, 2020 and was completed in June, 2020. In each plot, 15 common bean seeds were sowed and thinning was done 12 days after emergence (DAE), maintaining 10 plants per plot during the entire growing cycle. Weeding was conducted manually and agro-chemicals were applied when necessary to control pests (leaf miners and white fly) and diseases (anthracnose).

A small drip line (1 m) with six emitters and a total flow rate of 3.6 L h^{-1} was installed in each plot. Plots were managed individually through a control panel installed in a support greenhouse. Irrigation was conducted based on the soil water matric potential. Thus, tensiometers were installed at three depths (0.15, 0,30 and 0.50 m) in the reference treatment (L100) to monitor the soil tension at three layers: 0.0-0.2, 0.2-0.4 and 0.4-0.6 m, totalizing 15 tensiometers in the whole experiment.

Soil tension was acquired every other day. The water replacement amount for the three soil layers was estimated from the matric potential using the van Genuchten soil water retention curve (VAN GENUCHTEN, 1980). The reference treatment (L100) corresponded to the water depth necessary to return the three soil layers to field capacity. All other treatments were a fraction of the water applied in the reference treatment. Irrigation withholding treatments started at 20 days after sowing (DAS).

Air temperature, relative humidity and solar radiation flux were acquired inside the greenhouse with the sensors: HMP45C, barometer CS 106 and the pyranometer LI200X, respectively (Campbell Scientific, Logan, Utah, USA). A CR1000 data-logger integrated the micrometeorological data every 15 minutes. Air temperature was used for CWSI calculation and all other micrometeorological variables to calculate the reference evapotranspiration (ET_o) using the Penman-Monteith method (ALLEN et al., 1998). Micrometeorological data are shown in Table 2.

Table 2. Climatic data inside the greenhouse during the common bean crop cycle.

Month	Temperature		Relative humidity (%)	Solar radiation (MJ m^{-2} day^{-1})	ET$_o$
	Minimum	Maximum			
March	34.8	18.2	69.3	13.0	4.5
April	32.0	14.9	69.5	10.2	3.5
May	28.9	11.0	70.1	6.7	2.3
June	29.7	17.8	73.0	5.2	1.9

Stomatal conductance was measured at 61 DAS with a portable infrared gas analyzer (IRGA) (LiCOR-Inc, Lincoln, Nebraska, USA) at a flux density of 1000 µmol m^{-2} s^{-1} on a cloudless day in a leaf fully exposed to the sun located in the middle third of the plants. During the crop cycle, the canopy temperature was measured with a portable infrared sensor, TIV 6500 (Vonder, Curitiba, Brazil) three times under the same conditions. All these measurements were done with three technical repetitions per plot.

CWSI calculation was done following the methodology proposed by Jackson et al. (1981), as showed in Equation 1.

$$CWSI = \frac{(T_c - T_{air}) - T_{wet}}{T_{dry} - T_{wet}} \quad (01)$$

Where: T_c is the leaf canopy temperature; T_{air} is the air temperature; T_{wet} is the non-water stressed baseline; and T_{dry} is the water stress baseline.

To calculate the baselines, the maximum and the minimum canopy temperature observed in the trial were adopted as T_{dry} and T_{wet}, respectively (COSTA et al., 2020).

The harvest occurred at physiological maturity and all aerial biomass was dried at 65 °C in an oven with forced air circulation for three days, and then the grains of each plot were weighted to determine the grain yield per plot.

5 RESULTS AND DISCUSION

The irrigation accumulated for the treatments L100, L75, and L50 were 450.6, 356.6, and 294.0 mm, respectively, which is consistent with the minimum water requirements for common bean (MATHOBO et al., 2017). Water savings in L75 and L50 were 23 and 36%, respectively.

Grain yield potential was 23.1 g plant^{-1}, and the reductions in L75 and L50 were by 32 and 42%, respectively (Table 3). These results were similar to those of previous studies in common bean under mild and moderate water stress, where yield losses ranged from 35 to 45% (CALVACHE et al., 1997; GALVÃO et al., 2019). Therefore, water availability at field capacity led to increased physiological mechanisms expressing the potential grain yield, whereas insufficient water replacement levels can disrupt the metabolic processes of stressed plants, reducing the grain yield components.

Table 3. Grain yield, canopy temperature, average CWSI and stomatal conductance (gs) of common bean subjected to water stress.

Treatment	**Grain yield ($g\ plant^{-1}$)**	**Canopy temperature (°C)**	**Average CWSI**	**gs ($mol\ m^{-2}\ s^{-1}$)**
L100	23.1±1.7a	23.3±0.3c	0.2±0.08c	0.22±0.01a
L75	15.7±1.6b	24.5±0.2b	0.5±0.06b	0.20±0.03a
L50	13.4±0.9b	26.5±0.2a	0.9±0.04a	0.10±0.03b
F value	12.1**	48.5**	37.5**	8.5**
CV (%)	16	2	23	26

Mean values ± SE (n=5). Letters explain the differences between treatments through the LSD test.

The average canopy temperature varied significantly between treatments, ranging from 23.3 °C in L100 to 26.5 °C in L50 (Table 3). According to Bai and Purcell (2018), canopy temperature is a reliable tool to assess water stress even under mild drought stress conditions. This was confirmed since, despite the high frequency of drip irrigation, the thermal responses of the crop indicate the water status of the plants. In addition, the canopy temperature of plants under L50 was on average 2.5 °C higher than the air temperature, which, according to Fuchs (1990), may cause irremediable damage to the photosynthetic apparatus.

Average CWSI showed similar responses to canopy temperature and ranged between 0.2 in L100 and 0.9 in L50 (Table 3). Costa et al. (2018) in *Coffea arabica* subjected to different levels of irrigation concluded that CWSI increases as the irrigation level decreases. CWSI is the most popular index for assessing water stress in plants with information derived from canopy temperature because it isolates certain environmental factors. For example, in arid regions, canopy temperature can be influenced by air temperature, resulting in erroneous water stress detections (RU et al., 2020).

Stomatal conductance (gs) was significantly affected by stress treatment L50, reduced by 55% compared to L100 (Table 3). Mathobo et al. (2017) and Androcioli et al. (2020) also reported that stomatal conductance was less under water stress than in well-watered conditions. On the other hand, plants under stress after irrigation tend to increase stomatal conductance (SOURESHJANI et al., 2019). Therefore, high frequency irrigation may have influenced the response of plants under L70 that maintain gs values similar to those of plants under L100.

The relationship between grain yield and CWSI showed a linear relationship (R^2=0.76) (Figure 1A). Previous work also showed a strong relationship between grain yield and CWSI in soybean subjected to water stress (ANDA et al., 2020). Therefore, yield forecasting based on CWSI measurements is important to farmers in situations of water scarce or under deficit irrigation strategies. The correlation between measured and estimated grain yield with the model defined for CWSI presented a RMSE of 2.35 g $plot^{-1}$ (Figure 2). Further research is needed to explore other methods to perform CWSI with the purpose of increasing accuracy in predicting grain yield.

Figure 1. Relationship between A) average crop water stress index and grain yield and B) average crop water stress index and stomatal conductance.

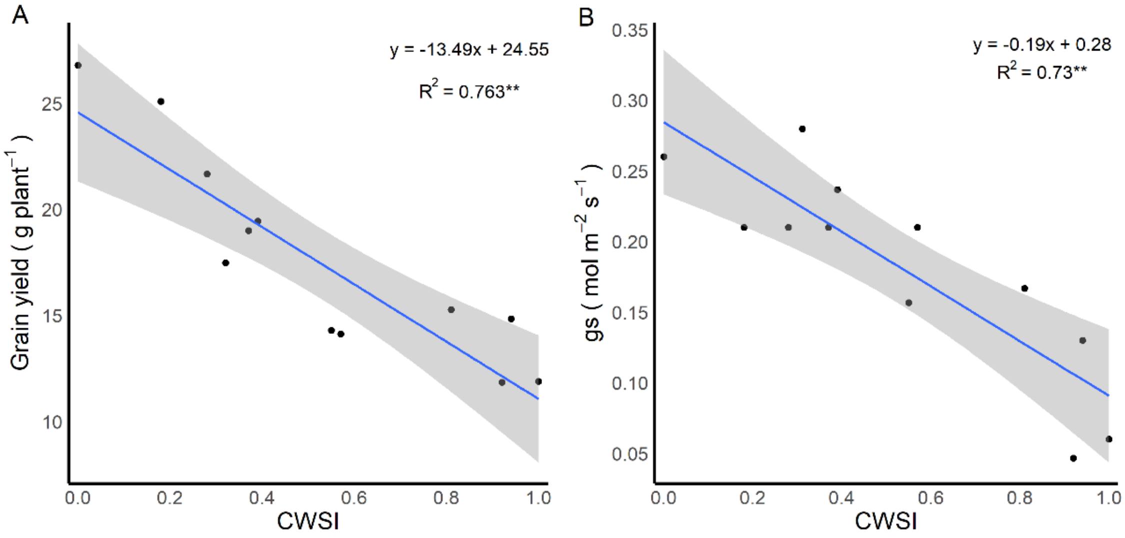
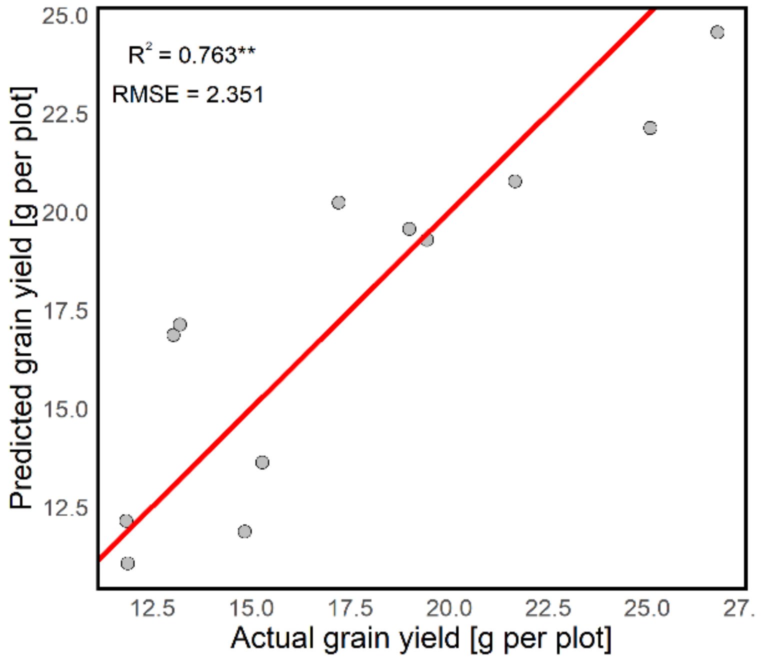


Figure 2. Actual and predicted common bean yield derived from canopy temperature.



The relationship between stomatal conductance and CWSI showed a linear relationship (R^2=0.73) (Figure 1B). It is in accordance with theory, which indicates that low canopy temperature shows high stomatal conductance. Moreover, other water stress indicators such as leaf water potential showed good correlations with CWSI (COSTA et al., 2020), suggesting that CWSI is a robust tool to determine plant water status.

6 CONCLUSIONS

Canopy temperature and the crop water stress index increased as irrigation levels decreased. Changes in canopy temperature were significant even under mild drought stress.

The crop water stress index was closely related to the stomatal conductance (R^2=0.73).

Grain yield losses due to drought stress can be predicted using the crop water stress index (R^2=0.76), which allows farmers to manage water resources according to the situation for each region.

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