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Relationship between physiology and production of maize under different water replacements in the Brazilian semi-arid[1]

Relação entre fisiologia e produção de milho sob diferentes reposições hídricas no semiárido brasileiro

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HIGHLIGHTS:

Water deficit in the soil reduces leaf gas exchange and maize grain yield.
Replacements of 100% and 175% of ETo increase the leaf gas exchange and maize grain yield.
Grain yield can be estimated from physiological variables obtained during flowering.

ABSTRACT: Water restriction causes physiological disorders and reduces maize yield in semi-arid regions. The objective of this study was to correlate instantaneous physiological variables with the grain yield of maize using different replacement percentages of water lost through evapotranspiration and to fit a multiple regression model to estimate grain yield in the dry season in the Brazilian semi-arid region. The experiment was installed in a randomized block design, with six percentages of reference evapotranspiration (ETo) repositioning (50, 75, 100, 125, 150, and 175%). The AG 7088 hybrid had a higher CO_2 assimilation rate, stomatal conductance, transpiration, and instantaneous water use efficiency, and reduced leaf temperature and vapor pressure deficit under full irrigation (100% of ETo, 458 mm), with yields of 5.75 t ha^{-1}, reaching 6.8 t ha^{-1} (572 mm) and 7.65 t ha^{-1} (801 mm) with replacements of 125 and 175% of ETo, respectively. Measurements of leaf gas exchange, vapor pressure deficit, and leaf temperature can be performed at phenological stage R1 to estimate grain yield with greater robustness when combined with water rates applied during the crop cycle.

Key words: *Zea mays* L., irrigation depths, gas exchange, grain yield estimation

RESUMO: A restrição hídrica provoca desordens fisiológicas e reduz o rendimento do milho no semiárido. Objetivou-se relacionar variáveis fisiológicas instantâneas com rendimento de grãos de milho sob percentagens de reposição da água perdida por evapotranspiração e ajustar um modelo de regressão múltipla para estimativa do rendimento de grãos no período de estiagem no semiárido brasileiro. O experimento foi montado no delineamento de blocos casualizados, com seis percentagens de reposição da evapotranspiração de referência - ETo (50, 75, 100, 125, 150 e 175%). O híbrido AG 7088 teve maior taxa de assimilação de CO_2, condutância estomática, transpiração, eficiência instantânea do uso da água e redução da temperatura foliar e do déficit de pressão de vapor sob irrigação plena (100% da ETo, 458 mm), com produção de 5,75 t ha^{-1}, podendo chegar a 6,8 (572 mm) e 7,65 t ha^{-1} (801 mm) com reposições de 125 e 175% da ETo, respectivamente. Mensurações de trocas gasosas foliares, déficit de pressão de vapor e temperatura foliar podem ser realizadas no estádio fenológico R1 para estimar o rendimento de grãos com maior robustez quando combinados com lâminas de água aplicadas durante o ciclo da cultura.

Palavras-chave: *Zea mays* L., lâminas de irrigação, trocas gasosas, estimativa de rendimento de grãos

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Introduction

Water scarcity affects approximately 52% of the global population inhabiting arid and semi-arid regions and has increased the pressure to reduce water resources used for irrigation, while maintaining high crop yields to meet food demand (Gheysari et al., 2017). The poor temporal and spatial distribution of rainfall, coupled with global climate change, has stimulated the scientific community to develop strategies to maximize agricultural production (Lu et al., 2017).

The Northeast region of Brazil is characterized by a semi-arid climate, with seasonal water limitation due to low rainfall levels, and prone to the occurrence of water deficit, which limits agricultural production, especially during the dry season (Cirilo et al., 2017).

Maize is grown in several locations worldwide. The relevance of its cultivation is justified by its high production potential (Li & Sun, 2016) owing to its high capacity for the uptake and assimilation of CO_2 inherent to the physiological metabolism of C_4 plants (Dantas Júnior et al., 2011). The grain yield of maize is reduced under water stress (Chilundo et al., 2017), especially in the period between flowering and pollination, thereby indicating physiological disorders in plants.

Despite the significant contribution of C_4 plants to food security, studies on the responses of leaf gas exchange to water stress are still required to better understand the topic. Evidence indicates that some C_4 plants, such as maize, are sensitive to water deficit, with an abrupt reduction in water vapor conductance and CO_2 assimilation rate as leaf water potential is reduced (Ghannoum, 2009).

Leaf gas exchange is used as a specific indicator of the water status of plants, enabling the instantaneous diagnosis of physiological disorders caused by water stress, which may result in significant production reductions. However, although there are fitted models to predict maize grain yield as a function of the water applied during the cycle, little is known about the use of instantaneous physiological variables for this purpose.

The objective of this study was to correlate instantaneous physiological variables to the grain yield of maize hybrid AG 7088 under different percentages of replacement of water lost through evapotranspiration (ETo) and to fit a multiple regression model to estimate grain yield in the dry season in the Brazilian semi-arid region.

Material and Methods

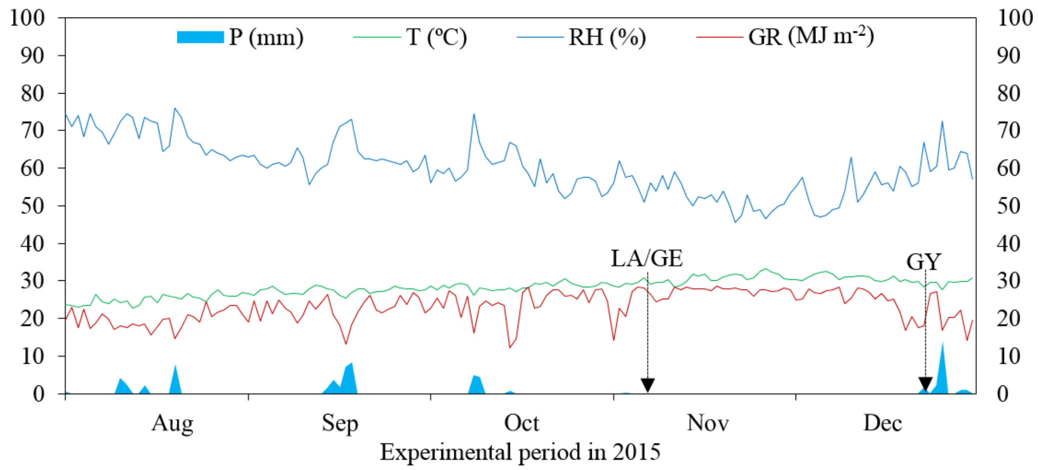
The experiment was conducted between August and December of 2015. The experimental area is located at Fazenda Tororó III, municipality of Pão de Açúcar, Alagoas (AL), Brazil, at the following coordinates: 09°45'20.7" S latitude, 37°25'12.3" W longitude, and an altitude of 18 m (Anjos et al., 2017). The local climate is classified as BSh, with a predominance of hypoxerophytic Caatinga, according to the Köppen classification (1948). The region has an average annual temperature of 27 °C and an average annual rainfall of 500 mm (Barros et al., 2012).

During the experimental period, climate monitoring was performed through the agroclimatic variables obtained at the automatic weather station of the National Institute of Meteorology-INMET (latitude: 09°44'56" S; longitude: 37°25'51" W; altitude: 15 m), located 1.6 km away from the experimental area; the daily averages are shown in Figure 1.

Prior to the installation of the experiment, 12 single soil samples were collected from the 0.00-0.30-m and 0.30-0.60-layers of the experimental area, and representative composite samples were obtained from each layer. Physical and chemical soil attributes were determined as described by Donagema et al. (2011) (Table 1).

The water used in the experiment came from the São Francisco River, collected three days before sowing at a location 113 m away from the experimental area, and the following chemical attributes were recorded: pH = 8.15, Ca = 0.44 $mmol_c$ L^{-1}, Mg = 0.16 $mmol_c$ L^{-1}, Na = 0.88 $mmol_c$ L^{-1}, K = 0.03 $mmol_c$ L^{-1}, Fe = 0.08 ppm, electrical conductivity = 0.16 dS m^{-1}, carbonates = 0.00 $mmol_c$ L^{-1}, bicarbonates = 0.32 $mmol_c$ L^{-1}, chlorides = 0.89 $mmol_c$ L^{-1}, sulfates = 0.35 $mmol_c$ L^{-1}, sodium adsorption ratio = 1.54 $(mmol\ L^{-1})^{0.5}$, class = C1-S1, overall classification = no restriction.

The total experimental area (480 m^2) was cultivated under a no-tillage system (NTS), desiccating the vegetation cover with the application of 1 L ha^{-1} (0.48 kg a.i. ha^{-1}) of glyphosate 15



P - Precipitation; T - Average air temperature; RH - Relative air humidity; GR - Global radiation

Figure 1. Meteorological variables recorded during the experimental period

Table 1. Physical and chemical attributes of the soil of the experimental area

Samples (m)	Attributes			
	Sand	Silt	Clay	Texture
		(%)		
0-0.30	60.58	26.50	12.92	SL[1]
0.30-0.60	52.65	42.61	4.74	SL[1]
	FC	PWP	Density	Porosity
	(cm³ cm⁻³)		(g cm⁻³)	(%)
0-0.30	0.23	0.04	1.39	48.13
0.30-0.60	0.26	0.06	1.41	47.78
	pH KCl (1:2.5)	OM (%)	P	K
			(ppm)	
0-0.30	6.54	1.07	31.00	76.00
0.30-0.60	5.95	0.93	13.00	43.00

[1] - Sandy loam; PWP - Permanent wilting point; FC - Field capacity; OM - Organic matter

days before sowing. Each experimental plot occupied an area of 20.0 m^2 (5.0 × 4.0 m), consisting of five irrigation lines each 5.0 m long, with 0.80-m spacing between the lines and 0.20-m spacing between the plants. At harvest, one row of each end of the plot (border) was disregarded, leaving a usable area of 12 m^2. Basal fertilization was performed according to Coelho (2006), based on the interpretation of soil analysis, applying 45 kg ha^{-1} of N, 138 kg ha^{-1} of P_2O_5, and 37 kg ha^{-1} of K_2O.

The AG 7088 hybrid maize, from Agroceres, was sown on August 25, 2015, by planting three seeds that were uniformly distributed. Ten days after sowing (DAS), thinning was carried out to leave one plant per hole, totaling a final stand of 62,500 plants ha^{-1}. Initially, the soil was irrigated to a field capacity of 14 mm. Subsequently, at 15 DAS, the soil was irrigated daily (12.5 mm), considering this time as sufficient for the establishment of seedlings in the field.

The experimental design used was randomized blocks with six treatments, corresponding to reference evapotranspiration (ETo) replacement percentages of 50, 75, 100, 125, 150, and 175%, with four replicates. The irrigation was suspended at 100 DAS. At the end of the experiment, the total applied quantity (including the quantity applied before sowing and subtracting the effective precipitation values) corresponded to $L_1 = 229$, $L_2 = 343$, $L_3 = 458$, $L_4 = 572$, $L_5 = 687$, and $L_6 = 801$ mm.

Irrigations corresponding to the ETo replacement treatments were implemented every two days, and were calculated by summing the ETo two days prior to the day of irrigation. On days with recorded rainfall during the cultivation cycle, the volume was subtracted from the ETo. The daily ETo was calculated using the FAO Penman-Monteith method (Allen et al., 1989).

Irrigation was performed using a localized drip system, consisting of a drip tape with a nominal diameter of 16 mm and emitters with a flow rate of 7.5 L h^{-1}, spaced every 0.20 m, and operating under a 98 kPa pressure. For system automation, a set of six solenoid valves actuated by a six-station programmer was adopted. The times required to replace the respective rates were recorded in the programmer to actuate and interrupt the operation of the irrigation system.

Soon after planting, 4.0 L ha^{-1} of the pre-emergent selective herbicide Primestra Gold® (Atrazine 1.480 g i.a. ha^{-1} and s-metolachor 1.160 g i.a. ha^{-1}, Syngenta Proteção de cultivos Ltda) were applied. The first topdressing fertilization was performed at 22 DAS, with 112 kg ha^{-1} of urea (45% N). At 25 DAS, 0.15 L ha^{-1} of the insecticide Karatê Zeon 50 CS® (lambda-cialotrina 7.5 g i.a. ha^{-1}, Syngenta Proteção de cultivos Ltda) was applied to control the fall armyworm (*Spodoptera frugiperda* L.). Thirty DAS , 0.5 L per 100 L of water of the herbicide Roundup Original® (glyphosate acid 185 g i.a. ha^{-1}, Monsanto do Brasil Ltda) was applied to control weeds with the jet directed between planting rows. The second topdressing fertilization was performed 54 DAS, with 112 kg ha^{-1} urea (45% N). In the period between 35 and 45 DAS, some insects such as wasps, human botflies (*Dermatobia hominis*), and beetles (*Oncideres impluviata*) appeared in the experimental area and were controlled with the application of the insecticide Connect® (beta-ciflutrina 9.4 g i.a. ha^{-1} and imidaclopride 75 g i.a. ha^{-1}, Bayer S/A) at a dose of 0.75 L ha^{-1}.

Leaf gas exchange evaluations were performed 72 DAS at phenological stage R1. The CO_2 assimilation rate (A) (μmol m^{-2} s^{-1}), stomatal conductance to water vapor (gs) (mol m^{-2} s^{-1}), transpiration (E) (mmol m^{-2} s^{-1}), vapor pressure deficit (VPD), and leaf temperature (LT) (°C) were measured, and the instantaneous water use efficiency (WUEi) [(μmol m^{-2} s^{-1}) (mmol m^{-2} s^{-1})$^{-1}$] was calculated from the A/E ratio (Isla et al., 2016). Measurements were performed on +3 leaves in the morning (8-10 hour) using a portable infrared gas analyzer (IRGA), LI-6400XT.

Leaf area (LA) measurements were performed 72 DAS at phenological stage R1. The length (L) and width (W) of the +3 leaves were measured, and the number of green leaves (NL) was quantified in five plants in the central row of each plot. The LA was estimated using the expression LA = [(L*W*0.75)*(NL + 2)], according to Francis et al. (1969). The leaf area index (LAI) was also estimated by the LA to the area occupied by the plant ratio (AP), using the expression LAI = [LA/(AP)].

Harvest was performed 120 DAS, at physiological maturity (R6), in the central row of each plot, corresponding to a usable area of 12 m^2. After removing the straw from the dry ears, the grains were manually collected from the cob, followed by the determination of the grain mass and subsequent estimation of grain yield in tons per hectare (t ha^{-1}). The results were corrected to a moisture content of 130 g kg^{-1} in the grains (Araújo et al., 2016). The water use efficiency (WUE kg ha^{-1} mm^{-1}) was determined by the relationship between grain yield and the rate of water applied (Sousa et al., 2015).

The data were standardized as zero mean and unit variance. The multivariate structure of the results was evaluated by principal component analysis (PCA), condensing the amount of relevant information contained in the original data set into a smaller number of dimensions, resulting from linear combinations of the original variables generated from the highest eigenvalues in the correlation matrix. Afterward, percentages of ETo repositioning were grouped based on scores from each PC using Ward's minimum variance hierarchical method. Statistical analyses were performed using the software Statistica v. 7 (Statsoft, 2004). WUE data were not included in the PCA because they are collinear with grain yield.

From the reduction of the dimensions, the values of the variables of each PC were subjected to multivariate analysis of variance (MANOVA) using the Hotelling test at $p \leq 0.05$, as a function of the percentage of ETo repositioning. The PC variables associated with grain yield (GY) were subjected to multiple linear regression analysis, considering GY as a dependent variable and the other variables contained in the same PC, plus percentages of ETo repositioning, as independent variables, in order to fit a GY prediction model. We used a multiple linear regression model with k independent variables according to Eq. 1 (Barbosa et al., 2019).

$$GY = \alpha + \sum_{i=1}^{k} \beta_i X_{ij} + \varepsilon_j \qquad (1)$$

where:

- GY - grain yield
- α - linear coefficient
- β_i - regression coefficient of the independent variable X_i
- X_{ij} - independent variable X_i in observation j
- ε_j - error associated with the GY variable in observation j
- k - number of independent variables

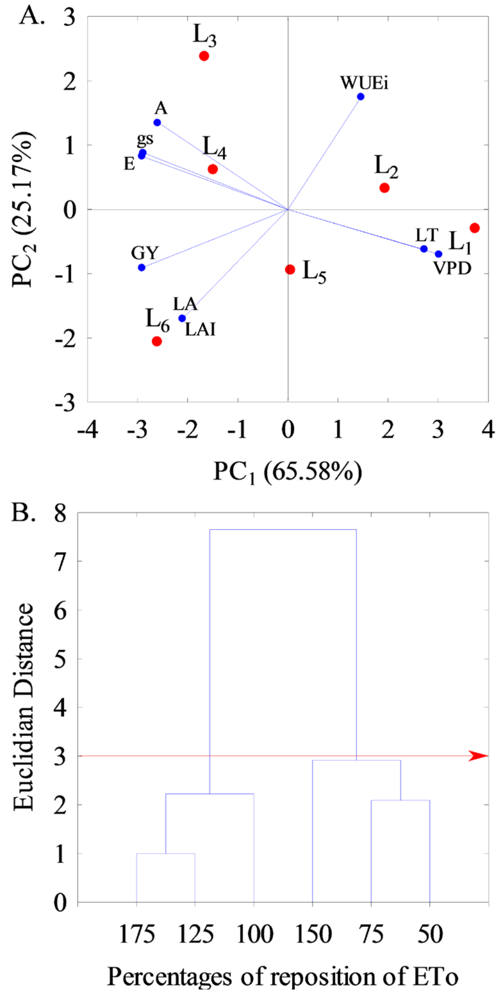
Results and Discussion

From the principal component analysis (PCA), two eigenvalues greater than the unit ($\lambda > 1$) were verified, indicating a reduction in the multidimensional space of the original variables into two principal components (PC), which together accounted for 90.75% of the total variance. Two processes were identified: the first (PC_1) was related to leaf gas exchange (A, gs, E, and VPD), LT, and GY, explaining 65.58% of the accumulated variance; the second (PC_2) accounted for 25.17% of the remaining variance, related to LA, LAI, and WUEi .

There was a significant effect of the percentage of ETo repositioning on the set of PC_1 variables ($p \leq 0.01$), while in PC_2 the irrigation depths did not differ ($p > 0.05$). Strong correlations were verified between PC_1 and its respective variables, while in PC_2, one variable (WUEi) had a strong correlation and two (LA and LAI) had moderate correlation (Table 2).

Figure 2A illustrates the two-dimensional projections of the two principal components (PC_1 and PC_2). In PC_1, the percentages of ETo repositioning L_1 and L_2 differed from L_6, L_3, and L_4 (Figure 2B).

The greatest values of CO_2 assimilation rate (22.49 μmol m^{-2} s^{-1}), stomatal conductance (0.09 mol m^{-2} s^{-1}), and transpiration (4.46 mmol m^{-2} s^{-1}) were recorded under the 100% ETo replacement (L_3), representing increments of 51%, 55%, and 49%, when compared to 11.01 μmol m^{-2} s^{-1}, 0.04 mol m^{-2} s^{-1}, and 2.27 mmol m^{-2} s^{-1} recorded under the 50% ETo replacement (L_1) (Table 3).



A - CO_2 assimilation rate; gs - Stomatal conductance; E - Transpiration; VPD - Vapor pressure deficit; LT - Leaf temperature; WUEi - Instantaneous water use efficiency; LA - Leaf area; LAI - Leaf area index; GY - Grain yield;
L_1 = 50% (229 mm), L_2 = 75% (343 mm), L_3 = 100% (458 mm), L_4 = 125% (572 mm), L_5 = 150% (687 mm) and L_6 = 175% (801 mm)

Figure 2. Two-dimensional projection (biplot) of percentages of ETo repositioning (●L) and nine variables (●) in the two principal components (PC) 1 × 2 (A), and dissimilarity dendrogram of percentages of ETo repositioning in PC_1 (B)

Higher vapor pressure deficit (5.36 kPa) and leaf temperature (37.33 °C) were observed in plants cultivated under an irrigation deficit of 50% ETo (L_1). When irrigated with 100% ETo (L_3), there were reductions of 9% in VPD and 2% in LT, reaching 4.88 kPa and 36.60 °C, respectively. The irrigation depth L_6, 175% ETo, promoted higher maize grain yield (7.65 t ha^{-1}), representing a percentage difference of 46% in comparison to the yield of 4.10 t ha^{-1} obtained with the replacement of 50% ETo (L_1) (Table 3).

The photosynthetic apparatus (C_4) of maize responds significantly to water stress, whether this is deficient or in excess in the soil (Ghannoum, 2009). Indeed, the best

Table 2. Eigenvalues, percent of the explained variance, probability of significance of the effect of percentages of ETo repositioning and correlation coefficients between the principal components and the original variables

PCs	λ	σ²%	p	Loads of the variables (r)								
				A	gs	E	VPD	LT	WUEi	LA	LAI	GY
PC_1	5.90	65.58	0.0044	-0.82	-0.91	-0.92	0.95	0.86	0.46	-0.66	-0.66	-0.92
PC_2	2.27	25.17	0.0895	0.55	0.36	0.34	-0.28	-0.25	0.71	-0.69	-0.69	-0.37

PCs - Principal components; λ - Eigenvalues; σ²% - Portion of the explained variance; p - Probability for the effect of percentages of ETo repositioning by the Hotelling test; A - CO_2 assimilation rate; gs - Stomatal conductance; E - Transpiration; VPD - Vapor pressure deficit; LT - Leaf temperature; WUEi - Instantaneous water use efficiency; LA - Leaf area; LAI - Leaf area index; GY - Grain yield; r = 0.10-0.30 (weak); r = 0.40-0.60 (moderate); r = 0.70-1.00 (strong)

Table 3. Mean values of the original variables as a function of percentages of ETo repositioning

Irrigation depths	Mean values									
	A	gs	E	VPD	LT	WUEi	LA	LAI	GY	WUE
L_1 = 50% of ETo (229 mm)	11.01	0.04	2.27	5.36	37.33	4.87	8347.59	5.22	4.10	17.92
L_2 = 75% of ETo (343 mm)	15.91	0.06	3.24	5.27	37.33	4.81	8437.14	5.27	4.77	13.89
L_3 = 100% of ETo (458 mm)	22.49	0.09	4.46	4.88	36.60	5.07	8588.44	5.37	5.75	12.56
L_4 = 125% of ETo (572 mm)	19.69	0.09	4.41	4.96	36.93	4.44	8532.20	5.33	6.80	11.89
L_5 = 150% of ETo (687 mm)	14.52	0.06	3.18	5.09	36.86	4.66	8931.76	5.58	6.30	9.18
L_6 = 175% of ETo (801 mm)	17.87	0.08	4.11	4.99	36.85	4.37	9551.02	5.97	7.65	9.55

A - CO_2 assimilation rate (μmol m^{-2} s^{-1}); gs - Stomatal conductance (mol m^{-2} s^{-1}); E - Transpiration (mmol m^{-2} s^{-1}); VPD - Vapor pressure deficit; LT - Leaf temperature (°C); WUEi - Instantaneous water use efficiency [(μmol m^{-2} s^{-1}) (mmol m^{-2} s^{-1})$^{-1}$]; LA - Leaf area (cm^2); LAI - Leaf area index; GY - Grain yield (t ha^{-1}); WUE - Water use efficiency (kg ha^{-1} mm^{-1})

gas exchange results (A, gs, and E) were observed under a full irrigation with 100% ETo, whereas plants grown under deficient irrigation (50 and 75% ETo) exhibited significant reduction in these variables. Under moderate water deficit, maize increases resistance to water vapor by partially closing the stomata and reducing stomatal conductance, thereby resulting in lower rates of CO_2 assimilation and transpiration (Magalhães et al., 2009).

Under moderate water deficit, approximately two-thirds of the reduction in net CO_2 assimilation is due to the reduction in gs; under severe deficit, there are non-stomatal limitations (Grzesiak et al., 2006; 2007), such as the inhibition of biochemical metabolism, an increase in the chlorophyll a fluorescence, and a reduction in the activity of the carboxylation system (Ripley et al., 2007; Xu et al., 2008).

The photosynthetic apparatus of the plants maintained under full irrigation conditions functioned better, as indicated by the high gas exchange rates; the latter could be attributed to adequate water supply, which ensures the normal development of leaf anatomy and ultrastructure, full activity of photosynthetic enzymes, and reduced nitrate assimilation and early leaf senescence. It should be emphasized that in plants cultivated under deficient irrigation conditions, there may have been disorders in the aspects mentioned above (Ghannoum, 2009).

The high vapor pressure deficit recorded in plants cultivated under 50% ETo replacement is related to the combination of low water content in the soil-plant-atmosphere system and climatic factors, such as high global solar radiation (28.03 MJ m^{-2}), high air temperature (30.8 °C), and low relative air humidity (51%), recorded on the day of VPD measurement. These results are supported by Almeida (2016), who reported that low soil water potential and high VPD cause stress in maize plants. Indeed, water deficit causes a reduction in leaf water potential, gs, and leaf turgor, resulting in an increase in VPD (Martins et al., 2010).

In the present study, plants under full irrigation (100% ETo) had lower LT, which was due to the high transpiration (T) resulting from the greater opening of stomata compared to plants cultivated under deficit irrigation. As transpiration increases, there is a reduction in leaf temperature due to the dissipation of energy in the form of latent heat, balancing leaf temperature with air temperature (Vieira et al., 2014).

It was verified that the multiple regression was significant (p = 0.0025), with $R^2 = 0.66$, and R^2-adjusted = 0.54, and the following model was fitted to estimate grain yield (Eq. 2):

$$\begin{aligned} GY\left(t\ ha^{-1}\right) &= -47.4022 + 0.0020L - 0.2198A - \\ &- 88.6360gs + 2.3065E - 12.9372VPD + 3.2422LT \end{aligned} \quad (2)$$

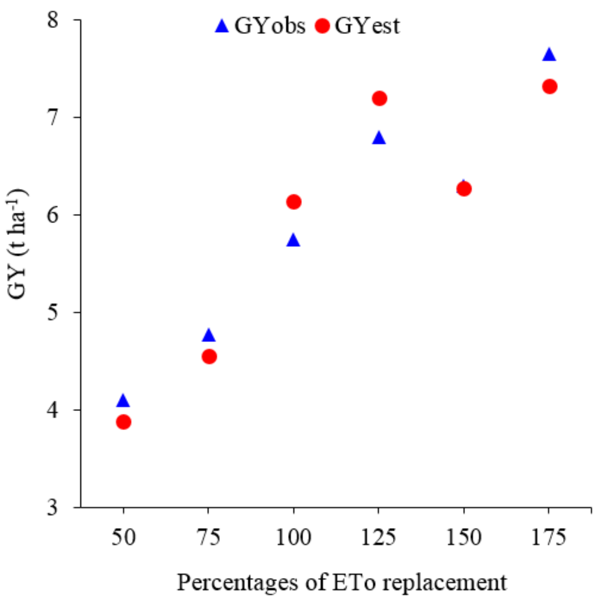
where:
- GY - grain yield;
- L - percentages of ETo repositioning;
- A - CO_2 assimilation rate;
- gs - stomatal conductance;
- E - transpiration;
- VPD - vapor pressure deficit; and,
- LT - leaf temperature.

Based on the relationships between the variables (Eq. 2), it was found that reductions in gs and A are associated with an increase in GY; for example, when the values obtained from the 100 and 175% ETo replacement treatments are compared, a reduction of 20.54% in A, 10.62% in gs, and 8.01% in E (Table 3) were verified. These variations are possibly due to stomatic adjustments to increase the E for the maintenance of LT, which had a low oscillation (0.69%), which justifies the inverse relationship between VPD and E. The occurrence of stomatal adjustments was confirmed by the reduction of WUEi (13.8%) and WUE (24%) with 175% of ETo, indicating that a replacement higher than 125% of ETo does not increase GY in the same proportion (Lopes et al., 2009).

Using the multiple linear regression model, the means of each input variable were used to estimate the grain yield at the respective percentages of ETo replacement. For L_1 50, L_2 75, and L_6 175% ETo, the model underestimated grain yield by 5.2, 4.5, and 4.3%, respectively, which represented differences of 0.214, 0.212, and 0.328 t ha^{-1}, respectively, compared to the observed means; for L_3 100 and L_4 150% ETo the model overestimated GY by 6.3 and 5.5%, respectively, with increments of 0.385 and 0.397 t ha^{-1}, respectively, compared to the observed means (Figure 3).

The GY of maize was reduced under water deficit (50% ETo) when compared to well-irrigated plants (100 and 175% ETo), which reflects the sensitivity of the crop to drought in the critical period throughout the cycle (Bergamaschi et al., 2004). This indicates the importance of evaluating gas exchange during the critical period of each phenological stage in order to identify strategies for the timely recovery of stressed plants.

In fact, these results show that, in maize plants cultivated under stress, providing an adequate water supply in the period preceding the appearance of anthers can prevent a 50% reduction in grain yield and evidence the need for evaluations in all phenological stages, as, if stress interruption occurs in



L_1 (50) = 229 mm, L_2 (75) = 343 mm, L_3 (100) = 458 mm, L_4 (125) = 572 mm, L_5 (150) = 687 mm, and L_6 (175) = 801 mm

Figure 3. Observed grain yield (▲GYobs) and grain yield estimated (●GYest) by the multiple regression model at each irrigation depth

full flowering, it is possible to prevent reductions of 20% in the first two days and up to 50% until the eighth day (Pegorare et al., 2009).

Gradual reductions in GY occur mainly because of the decrease in the number of grains per ear. It is worth pointing out that the reduction in GY under water deficit in the reproductive period is due to the physiological processes related to the formation of the zygote and the initial development of grains, especially due to the lower supply of photosynthates to the grains during development (Bergamaschi et al., 2006).

There are currently no models based on gas exchange variables (A, gs, and E), vapor pressure deficit, and leaf temperature to estimate maize grain yield during the critical period of water deficit. Thus, the multiple model presented in this study can increase the technological apparatus for the water management of the crop, as, according to Matzenauer et al. (1995), it is possible to provide estimates of the final yield of maize grains based on field data on water deficit. It is important to highlight that the effect of water deficit should be evaluated in more restricted and precise periods when water deficit is more severe (Bergamaschi et al., 2006).

Conclusions

1. The AG 7088 hybrid maize growing under a semi-arid climate in Brazil during the dry season (August to December), showed higher CO_2 assimilation rate, stomatal conductance, transpiration, and instantaneous water use efficiency, and reduced leaf temperature and vapor pressure deficit under full irrigation (100% ETo), with yields of 5.75 t ha^{-1}, reaching 6.8 t ha^{-1} and 7.65 t ha^{-1} with replacements of 125% and 175% of ETo, respectively.

2. Measurements of leaf gas exchange, vapor pressure deficit, and leaf temperature can be performed at phenological stage R1 to estimate grain yield when combined with percentages of ETo repositioning during the crop cycle.

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