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Research article

Water stress alters growth and fruit uniformity of arabica coffee genotypes in the Brazilian Cerrado

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ABSTRACT: This study aimed to evaluate the impact and duration of water stress on coffee growth, grain yield, and uniformity. The experiment was set up on Apr 2015 with water regimes denominated as follows: year-round irrigation with total water replacement (FI 100) and year-round irrigation with a 50 % reduction in total water replacement (FI 50); irrigation with application of water deficit from Apr to Sept with total water replacement (WD1 100) and irrigation with application of water deficit from Apr to Sept with 50 % of total water replacement (WD1 50); irrigation with application of water deficit from June to Sept with total water replacement (WD2 100), irrigation with application of water deficit from June to Sept with 50 % of total water replacement (WD2 50), and rainfed. A mechanized irrigation mobile Lateral Line sprinkler system was used. Irrigation management criterion was based on the climatological water balance and crop coefficients. Morphological variables, productivity, and fruit uniformity were evaluated. The growth variables had higher responses to water deficit treatment, with the highest reductions being recorded in rainfed treatments. The average productivity of the coffee tree in 2019 ranged from 14 to 120 bags ha^{-1}. Even under low water availability, Iapar 59 was the most productive genotype, and E237 was the least productive genotype. Long periods of stress and 50 % reduction in water availability reduced plant productivity. Thus, the use of irrigation to complement rainfall is essential to the sustainability of coffee production systems in the Cerrado.

Keywords: flowering uniformity, irrigation, rainfed, water deficit

Introduction

In the 21st century, agriculture worldwide faces two main difficulties: expansion in food production to meet the growing world population and low rainfall in agricultural regions associated with the increasing scarcity of water resources and high temperatures. Coffee is sensitive to long periods of water stress and high temperatures (Ahmed et al., 2021; DaMatta et al., 2010). As a result, drought becomes the main environmental factor that limits coffee growth and productivity, and leads to a severe reduction in yield where there is cultivation without irrigation (DaMatta and Ramalho, 2006; Moat et al., 2017; Ovalle-Rivera et al., 2015; Silva et al., 2022).

Water stress decreases cell expansion, plant photosynthesis, and plant development (Silva et al., 2022; Muller et al., 2011), and leads to early leaf senescence (DaMatta et al., 2010). In addition, water deficit also promotes plant metabolic changes (Ashraf, 2010; Mittler, 2002). Consequently, even under moderate water stress, flowering, grain filling, and grain development decrease, thereby compromising productivity, and severe water stress may lead to plant death (DaMatta et al., 2018; Marraccini et al., 2011).

Due to the increase in average temperatures and atmospheric CO_2 levels and more variable precipitation with more extended periods of drought (Naumann et al., 2018), it is critical to study the effects of climate change on the various management systems and create strategies to promote crop survival and increase the crop resistance in an environment of global change (Han et al., 2020). Therefore, a better understanding of the growth and development responses of plants cultivated under water stress and the mechanisms that plants use under low water availability is required. This study aims to test the following hypotheses: (i) do different periods and intensities of water deficit affect the maturation of the coffee tree [*Coffea arabica* (L.)]?; (ii) are the characteristics of vegetative growth and grain yield altered under water regimes?; (iii) do water regimes allow for a characterization of genotypes and a search for water regimes that promote fruit maturation and efficiency in the use of water in the coffee tree?.

Materials and Methods

The experiment was conducted at Planaltina DF, Brazil (15°35′ S, 47°42′ W, 1,007 m). According to the Köppen classification (Alvares et al., 2013), the climate is Aw, with well-defined dry and rainy seasons, average annual temperatures of 21.1 °C, and average precipitation of 1,345 mm (Figure 1). The soil is a clayey Oxisol (Soil Survey Staff, 2004).

The experiment was set up in Apr 2015 in an area of 7,359.5 m^2, and seven treatments or water regimes were carried out (six with irrigation during the dry period and one with rainfed water) (Table 1, Figure 2). In the irrigated area, a water regime was used for each treatment as follows. Irrigation during the entire dry period with total water replacement (FI 100) and irrigation during the entire dry period with a 50 % reduction in total water replacement (FI 50); irrigation with application of water deficit from Apr to Sept only with total water replacement (WD1 100) and irrigation with application of water deficit only from Apr to Sept only with 50 % of total water replacement (WD1 50); irrigation with application of water deficit from June to Sept only with total water replacement (WD2 100) and irrigation with application of water deficit from June to Sept only with 50 % of total water replacement (WD2 50); and rainfed. Irrigated treatments are an accumulation of both irrigation and rainfall.

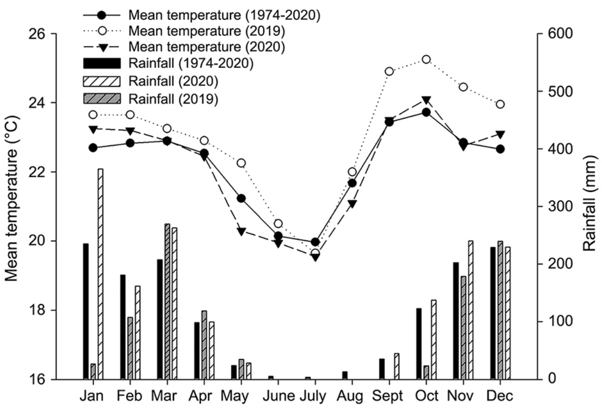

Figure 1 – Long-term minimum and maximum average climate data for the last forty-six years (1974 to 2020) in the experimental area.

Under irrigated water regimes, coffee trees were irrigated using a mechanized Mobile Lateral Line sprinkler system. The irrigation management criterion was based on a climatological water balance through the Cerrado Irrigation Monitoring Program (EMBRAPA, 2017), which supplied data on soil water availability in the experimental area and crop coefficients as defined for coffee by Guerra et al. (2007). It provided the amount of water to be applied and the interval between irrigations for adequate management. The Penman-Monteith method (Monteith, 1965) was adopted by the aforementioned program to estimate reference evapotranspiration (Et_o).

The following genotypes were used: Iapar 59, Catuaí 62, and E237. Iapar 59 is slightly tolerant to water stress (Rakocevic et al., 2023). Each plot comprised eight plants, spacing between rows of 3.50 m and 0.50 m between plants. In each season, each plot was fertilized with 400 kg ha^{-1} of N as urea and 400 kg of K_2O as potassium chloride; both were applied four times during the year (Feb, Mar, Sept and Dec). In addition, 300 kg ha^{-1} of P_2O_5 was applied in two doses (2/3 in Sept and 1/3 in Dec), and 100 kg ha^{-1} was applied as micronutrients (FTE-BR12).

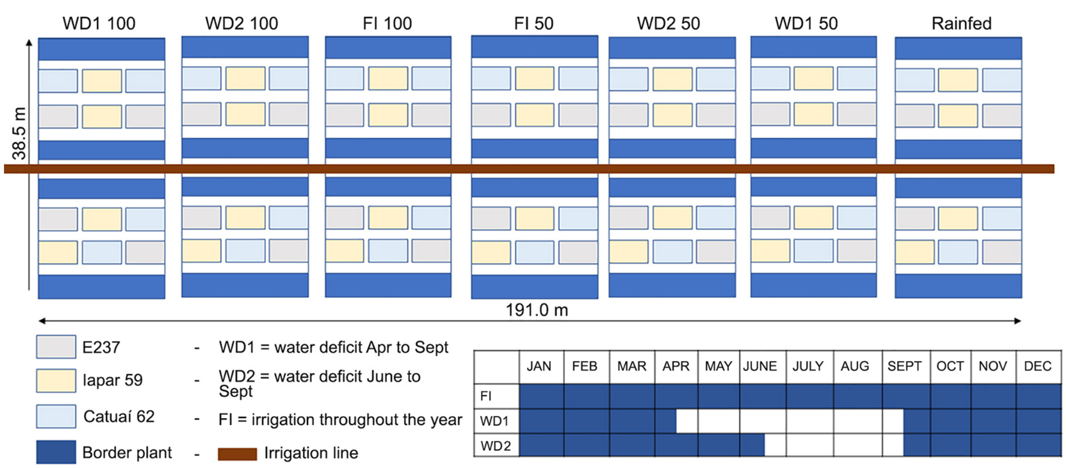

Figure 2 – Sketch of the experimental area.

Table 1 – Treatments evaluated in the experimental area of Embrapa Cerrados – Planaltina DF.

Treatments	Description
FI 100	Irrigation throughout the year
FI 50	Irrigation throughout the year and 50 % reduction in the water requirement for coffee
WD1 100	Water deficit with suspension of irrigation from Apr to Sept
WD1 50	Water deficit with suspension of irrigation from Apr to Sept and 50 % reduction in water requirement for coffee
WD2 100	Water deficit with suspension of irrigation from June to Sept
WD2 50	Water deficit with suspension of irrigation from June to Sept and 50 % reduction in the water requirement for coffee
Rainfed	Without irrigation

The water regimes started in Apr 2017, and between 2017 and 2021, we evaluated the water consumption of coffee genotypes. The water applied was measured using collectors installed in the area. In irrigated water regimes, the irrigation management criterion was the soil water balance, based on the Cerrado Irrigation Monitoring System, which provided information to determine both the amount of water and the interval (EMBRAPA, 2017).

Morphological evaluations were carried out in Nov and Dec of 2019 and 2020. The variables evaluated were: stem diameter; plant height; length of the plagiotropic branch of the middle third of the plant on the right side (PL_R) and on the left side (PL_L); the number of nodes of the plagiotropic branches on the right side (PN_R) and on the left side of the plant (PN_L); number of nodes in the orthotropic (ONN); crown length (CL), obtained by adding the stem diameter with the length of the right and left plagiotropic branches.

Between Apr and June 2020 and 2021, the fruits were harvested by stripping them on cloth, dried in the open air and the fruit volume was quantified. Coffee samples were taken to determine fruit uniformity, maturation, and percentage of green, cherry, and dry fruits. The weight and volume of grains were weighed. After correcting the grain humidity to 13 %, the yield was transformed in bags ha^{-1}. Productivity data from 2020 and 2021 were used because the morphological evaluation was carried out in Nov of each year, and the plants had already shown growth for the following year's production.

The experiments consisted of seven water treatments; within each water regime, three genotypes were arranged in randomized blocks with four replications. Initially, an analysis of variance (ANOVA) was performed in randomized blocks for each variable within each water regime. Subsequently, the Hartley F Max test was carried out using the mean square error of each variable in each treatment. The result of this test was used to validate the experiments as a group, and the joint analysis of groups of experiments was used. Subsequently, water regimes and genotypes were considered sources of variation, and a new ANOVA was performed. The analysis of variance was determined using the F test, and Tukey's test ($p < 0.05$) was used to compare the means. To carry out the statistical analysis, the SAS software, version 9, and RStudio, version 4.3.1. Sigma plot software, version 10 were used to create the figure. Next, Pearson correlation between the variables was ascertained for each arabica coffee genotype, using Past software, version 2.18.

Results

Pearson correlation

Pearson correlation was used to evaluate the relationships between the variables assessed (Figure 3A-C). For the genotypes Catuaí and E237, the length of the plagiotropic branches had strong positive correlation with CL (Figure

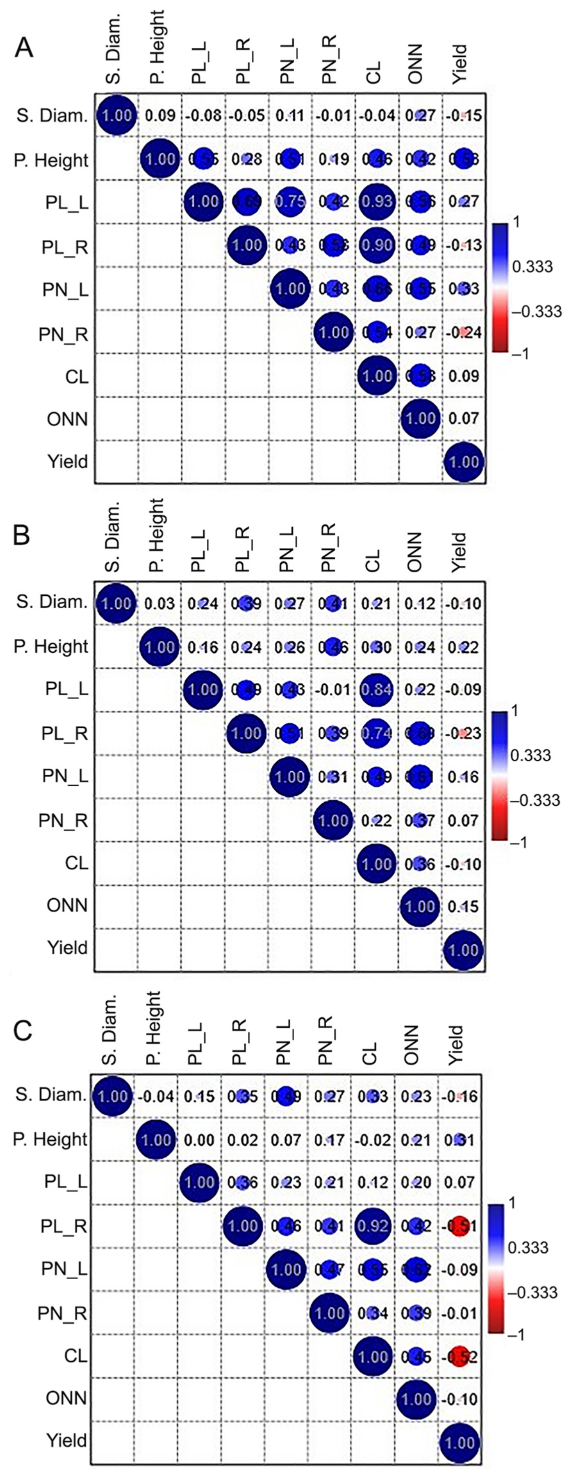

Figure 3 – Correlogram of Pearson correlation estimates between growth and productivity variables. A) Catuaí 62; B) E237; C) Iapar 59. S. Diam. = stem diameter; P. Height = plant height; PL_L = length of the left plagiotropic branch; PL_R = length of the right plagiotropic branch; PN_L = number of nodes in the left plagiotropic branch; PN_R = number of nodes in the right plagiotropic branch; CL = crown length; ONN = number of nodes in the orthotropic.

3A and B). The correlation between ONN and PL_R and PN_L was moderate in all genotypes. Productivity correlated positively and moderately only in terms of height for the Catuaí 62 genotype. The variable height in Catuaí also correlated with PL_L, PN_L, CL and ONN. In turn, for Iapar 59, productivity had negative correlation with plant height and CL (Figure 3C).

Plant growth

The plants received an average annual accumulated water depth (precipitation + irrigation) of 1,706 mm (FI 100), 1,367 mm (FI 50), 1,435 mm (WD2 100), 1,217 mm (WD2 50), 1,270 mm (WD1 100), 1,137 mm (WD1 50) and 1,026 mm of precipitation (rainfed).

The water regimes did not alter the stem diameter independent of genotype (Figure 4C and D). However, full irrigation and water deficit treatments promoted greater vegetative growth of plants (Figure 4A and B). In contrast, plants under rainfed conditions had their growth reduced by 20 to 31 % compared to plants under full irrigation (Figure 4A and B). Furthermore, the evaluation of the genotypes within each regime showed that height is an intrinsic characteristic linked to the genetics of each material, where E237 and Iapar 59 have the highest and lowest height, respectively, in all treatments (Figure 4A and B).

The length of branches showed a similar pattern to the height of the plants, with lower growth in rainfed conditions and longer branches in treatments with water deficits 50 and 100 (Figure 5A-D). Therefore, under full irrigation and WD1 100, in 2019, the Iapar 59 genotype showed a reduction in growth and larger branches in rainfed conditions. Iapar 59 has smaller plagiotropic branches compared to the other genotypes studied. In opposition, it has longer branches and more nodes under rainfed conditions than Catuaí 62 and E237 (Figures 5 and 6A-D), which is different from what happened in the other treatments.

The number of nodes in the plagiotropic left (NP_E) and right (NP_D) branches was evaluated. In 2020, the number of nodes in the left branches was higher under treatments with water deficit (Figure 6B), similar to the results found for the length of the branches. The results show a deficiency of nodes in the branches of E237, which was lower than the other genotypes in rainfed areas and FI in 2020 (Figure 6C and D).

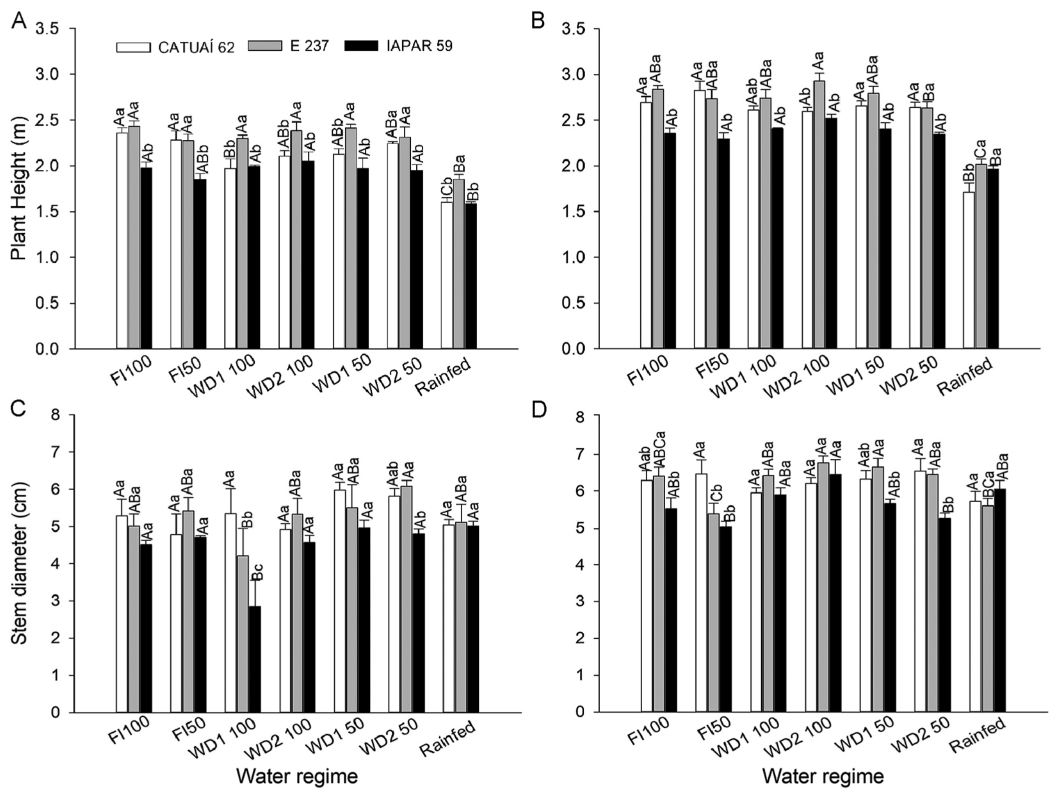

Figure 4 – Plant height and Stem diameter in the years 2019 (A and C) and 2020 (B and D), respectively, of three coffee genotypes (Iapar 59, Catuaí 62 and E237) submitted to seven water regimes (FI 100 %, FI 50 %, WD1 100 %, WD2 100 %, WD1 50 %, WD2 50 % and rainfed) during stress under water deficit treatments in 2019 and 2020. FI = irrigation throughout the year; WD1 = water deficit from Apr to Sept; WD2 = water deficit from June to Sept 50 % reduction in the water requirement for coffee; Rainfed = without irrigation. Capital letters compare water regimes for each genotype and lowercase letters compare genotypes within each water regime. The same letters do not differ from each other by the Tukey test at 5 % probability.

The number of nodes in the orthotropic (ONN) is a critical variable, as it provides an estimate of the number of productive branches (plagiotropic branches) of the plant (Figure 7A and B). The highest number of nodes in the orthotropic (ONN) in 2019 was in the WD1 50 treatment, and the lowest values were in WD1 100, WD2 100, and rainfed treatments (Figure 7A and B). In 2020, the results were similar, and only plants under rainfed treatment showed a reduction in the number of nodes. The branch length and stem diameter directly alter the crown length (CL) of the genotypes. Thus, the highest CL was found in the water deficits treatments (Figure 7C and D), and the lowest CL was found in the rainfed treatment in 2020. Iapar 59 genotype showed the lowest CL.

Crop productivity and uniformity

Coffee productivity under the different treatments ranged from 14 bags ha^{-1} in rainfed to 120 bags ha^{-1} under full irrigation in 2020 (Figure 8A). In that same year, the productivity of the genotypes can be divided into the following three groups: high productivity (FI 100), median productivity (FI 50, WD2 100 and WD1 100) and low productivity (rainfed, WD1 50 and WD2 50). In 2021, the highest productivity was subjected to the treatment with moderate water deficit (WD2 100) (Figure 8B). Treatments FI 100 and FI 50 % evapotranspiration had median productivity, and treatments rainfed and WD1 100, depending on the genotype, had the lowest performance (Figure 8A).

In 2021, the genotypes E237, Iapar 59, and Catuaí 62 under WD2 100 increased grain productivity by 66, 37 and 40 %, respectively, compared to plants in rainfed (Figure 8B). Iapar 59, in general, had better performance. The E237 and Catuaí 62 genotypes in the same year yielded 13 and 45 % higher in FI 100 than rainfed.

The sum of productivity in 2020 and 2021 is shown in Figure 8C. The results in 2021 were similar to those in 2020, with higher productivity in FI 100 and median productivity in FI 50 and WD2 100. Additionally, Iapar 59 showed higher productivity in treatments with water deficit and lower productivity of E237 in treatments with higher water availability (FI 100, FI 50, and WD 100).

The percentage of cherry fruit in FI 100 was around 60 % in the E237 and Iapar 59 genotypes and 80 % in Catuaí 62. In turn, the WD2 100 resulted in a single, uniform flowering with a cherry percentage greater than 80 % (Figure 9A and B). The evaluation of the grain average uniformity in both years showed

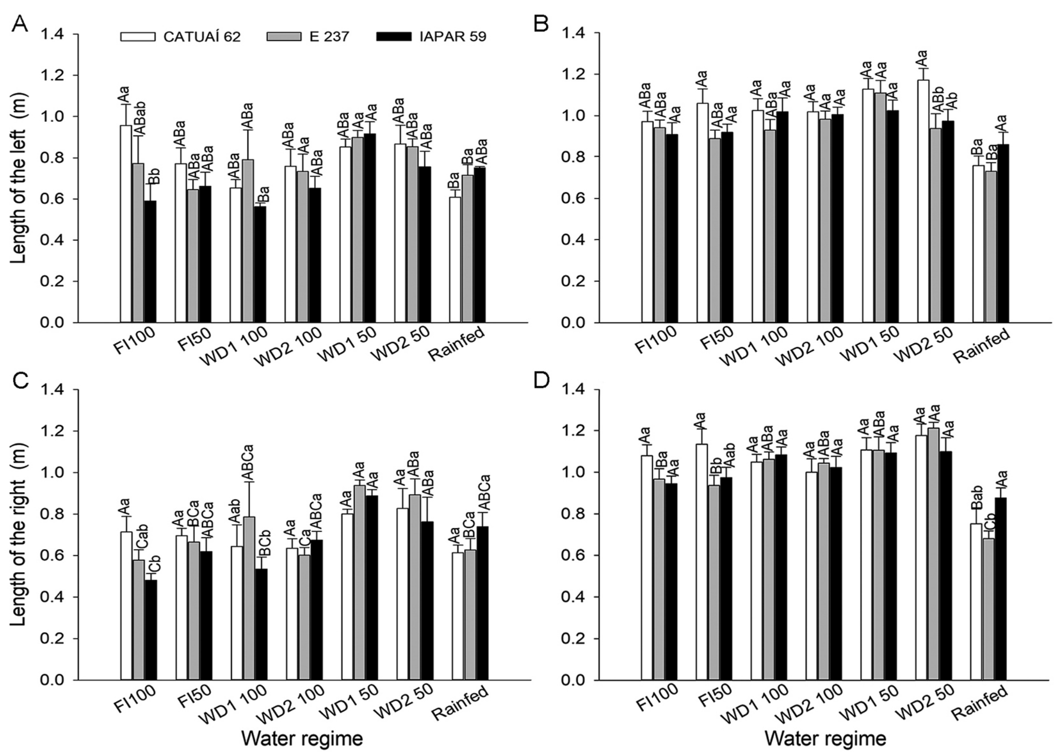

Figure 5 – Length of the left and right plagiotropic branch in the years 2019 (A and C) and 2020 (B and D), respectively, of three coffee genotypes (Iapar 59, Catuaí 62 and E237) submitted to seven water regimes (FI 100 %, FI 50 %, WD1 100 %, WD2 100 %, WD1 50 %, WD2 50 % and Rainfed) during stress under water deficit treatments in 2019 and 2020. FI = irrigation throughout the year; WD1 = water deficit from Apr to Sept; WD2 = water deficit from June to Sept 50 % reduction in the water requirement for coffee; Rainfed = without irrigation. Capital letters compare water regimes for each genotype and lowercase letters compare genotypes within each water regime. The same letters do not differ from each other by the Tukey test at 5 % probability.

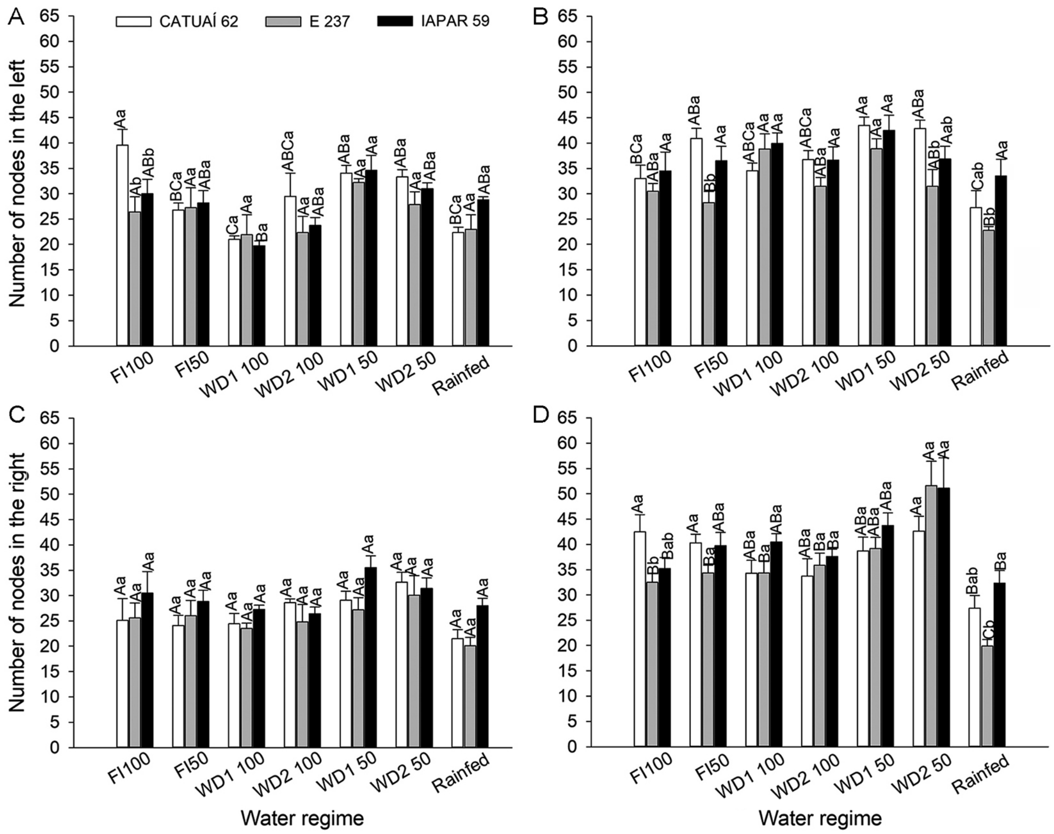

Figure 6 – Number of nodes in the left and right plagiotropic branch, in the years 2019 (A and C) and 2020 (B and D), respectively, of three coffee genotypes (Iapar 59, Catuaí 62 and E237) submitted to seven water regimes (FI 100 %, FI 50 %, WD1 100 %, WD2 100 %, WD1 50 %, WD2 50 % and Rainfed) during stress under water deficit treatments in 2019 and 2020. FI = irrigation throughout the year; WD1 = water deficit from Apr to Sept; WD2 = water deficit from June to Sept 50 % reduction in the water requirement for coffee; Rainfed = without irrigation. Capital letters compare water regimes for each genotype and lowercase letters compare genotypes within each water regime. The same letters do not differ from each other by the Tukey test at 5 % probability.

a result similar to those evaluated separately (Figure 9C). The percentages of cherry grains were higher under treatments with water deficit. Depending on the genotype, the uniformity of maturation was under treatments with water deficit and a 50 % reduction in the water required by the crop and in the rainfed (Figure 9C).

Discussion

Correlation between variables

Correlation analysis showed that the increase in the coffee cup is directly related to the size of the plagiotropic branches (Figure 3A-C). Productivity, in general, showed a weak correlation with growth variables. This indicates that these genotypes specifically suffer little influence from these characteristics. However, the number of plagiotropic branches is directly associated with the number of nodes in the orthotropic branch, as obtained by Vieira et al. (2019). These variables showed a high correlation with productivity.

The correlation of productivity with height in the genotype Catuaí 62 shows that the genotype's height positively influences productivity. In turn, this correlation was negative in the Iapar 59 genotype attributable to its lower height (Figure 4A and B) and high productivity (Figure 8A-C). Therefore, breeding programs should not necessarily use plant height as a selection criterion for productivity, although lower height facilitates harvesting.

The effects of water regimes on the growth of coffee genotypes

Several factors affect coffee growth, and drought is one of the most important as it directly impacts photosynthetic potential (Silva et al., 2022) and, consequently, plant development. Compared with rainfed, full irrigation and water deficit used in the experiment with the temporary suspension of irrigation promoted greater plant growth as measured by its height, length, and number of nodes in the right and left plagiotropic branches and the number of nodes

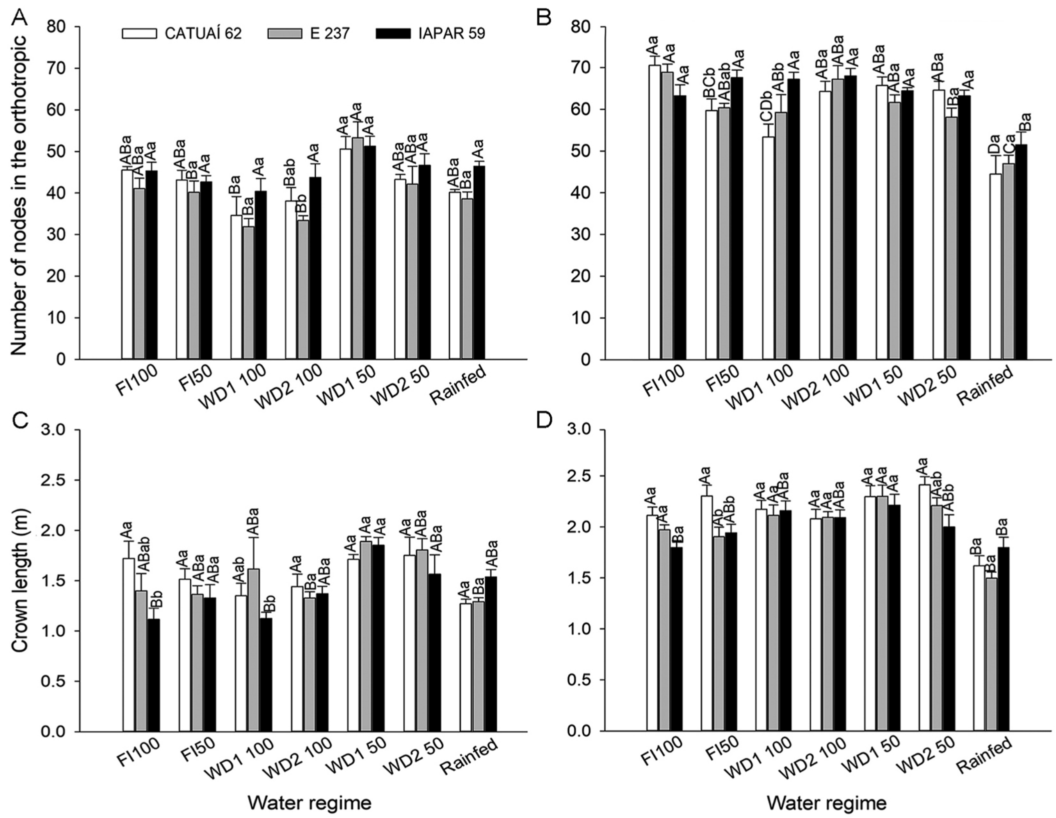

Figure 7 – Number of nodes in the orthotropic and crown length in the years 2019 (A and C) and 2020 (B and D), respectively, of three coffee genotypes (Iapar 59, Catuaí 62 and E237) submitted to seven water regimes (FI 100 %, FI 50 %, WD1 100 %, WD2 100 %, WD1 50 %, WD2 50 % and Rainfed) during stress under water deficit treatments in 2019 and 2020. FI = irrigation throughout the year; WD1 = water deficit from Apr to Sept; WD2 = water deficit from June to Sept 50 % reduction in the water requirement for coffee; Rainfed = without irrigation. Capital letters compare water regimes for each genotype and lowercase letters compare genotypes within each water regime. The same letters do not differ from each other by the Tukey test at 5 % probability.

in orthotropic branches (Figures 4 and 7A-D). The gas exchange was evaluated in the same treatments by Silva et al. (2022). The authors observed that recovery of photosynthesis in the WD2 100 and WD2 50 was slow at the beginning of the return of irrigation, indicating that the soil had low moisture and the plants had low water content in the leaves. However, photosynthesis evaluated at later stages increased in all genotypes except for E237.

Water regimes exert little influence on the stem diameter of the genotypes, even in the case of rainfed treatment (Figure 4C and D). This shows the limitation of this variable's use in the coffee selection process for drought tolerance. After four annual cycles of irrigation suspension, the coffee plants under the different water regimes subjected to controlled water stress showed greater height, number of plagiotropic branches, and number of nodes on the branches when compared to plants under the year-round irrigated treatment (Guerra et al., 2005). Equivalent results were observed by Veiga et al. (2019), in which the controlled water deficit led to an increase in the growth of orthotropic and plagiotropic branches after the restart of irrigation, designated as compensatory growth. Bearing this in mind, we emphasize that the imposition of water deficit was not harmful to the growth of the genotypes.

However, plants under rainfed conditions had their development compromised due to long periods without precipitation (Figures 4A-B and 5A-C), with a reduction of 20 to 31 % in plant height, compared to plants under full irrigation. This shows that irrigation is an appropriate practice for the Cerrado region. The lower height and length of plagiotropic branches under drought conditions are mainly attributed to the reduction in photosynthesis (Silva et al., 2022), which affects the production of photoassimilates. Consequently, there was a reduction in cell expansion and elongation (Manivannan et al., 2007) and grain filling. Moreover, studies show that plants subject to severe water deficit invest more in root elongation than in shoots, which increases the potential for water absorption at greater depths (Xu et al., 2015), and is reflected directly in crop productivity. However, root development was not evaluated in the present study.

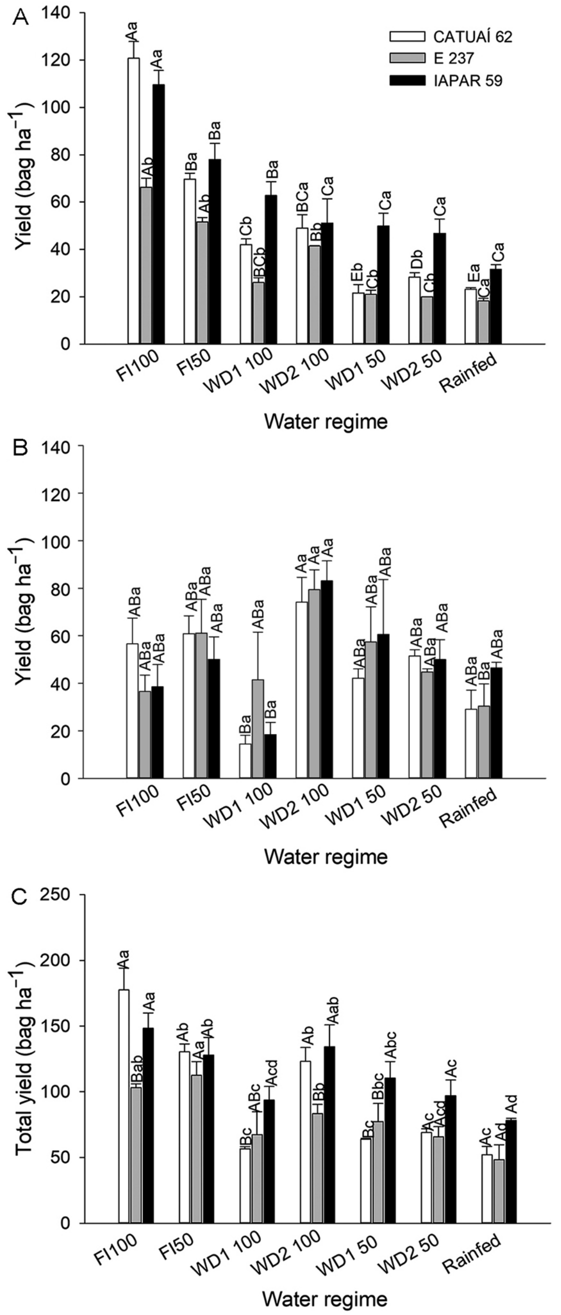

Figure 8 – Yield (bag ha^{-1}) of three coffee genotypes (Iapar 59, Catuaí 62 and E237), in the years 2020 (A) and 2021 (B), respectively, and total yield for the two years (C) of three coffee genotypes (Iapar 59, Catuaí 62 and E237) submitted to seven water regimes (FI 100 %, FI 50 %, WD1 100 %, WD2 100 %, WD1 50 %, WD2 50 % and Rainfed) during stress under water deficit treatments in 2019 and 2020. FI = irrigation throughout the year; WD1 = water deficit from Apr to Sept; WD2 = water deficit from June to Sept 50 % reduction in the water requirement for coffee; Rainfed = without irrigation. Capital letters compare water regimes for each genotype and lowercase letters compare genotypes within each water regime. The same letters do not differ from each other by the Tukey test at 5 % probability.

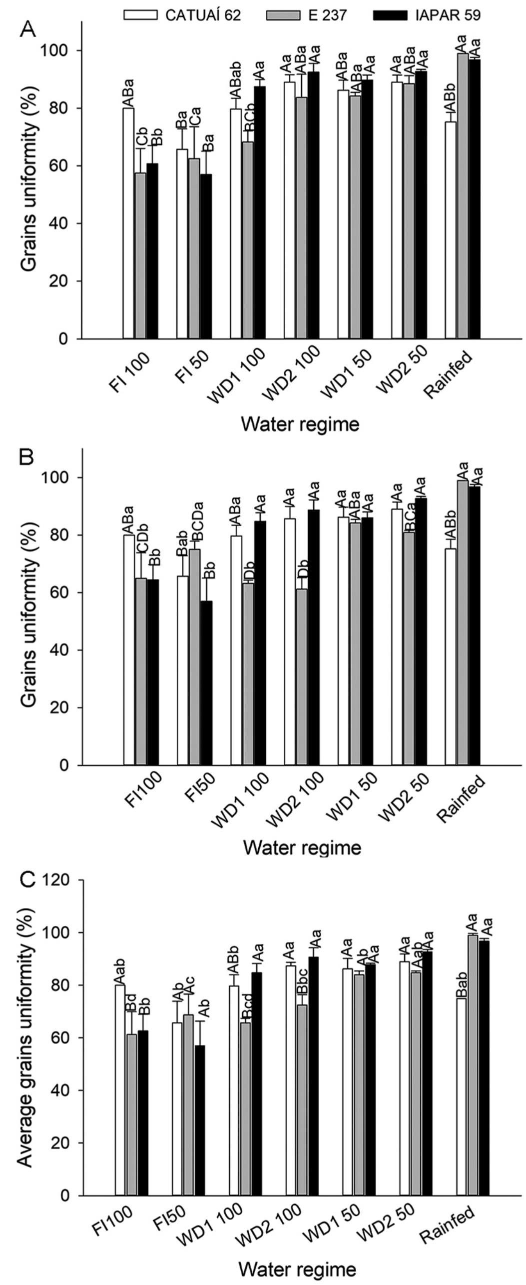

Figure 9 – Percentage of cherry beans of three arabica coffee genotypes (Iapar 59, Catuaí 62 and E237), in the years 2020 (A) and 2021 (B), respectively, and average grain uniformity for the two years (C) of three coffee genotypes (Iapar 59, Catuaí 62 and E237) submitted to seven water regimes (FI 100 %, FI 50 %, WD1 100 %, WD2 100 %, WD1 50 %, WD2 50 % and Rainfed) during stress under water deficit treatments in 2019 and 2020. FI = irrigation throughout the year; WD1 = water deficit from Apr to Sept; WD2 = water deficit from June to Sept 50 % reduction in the water requirement for coffee; Rainfed = without irrigation. Capital letters compare water regimes for each genotype and lowercase letters compare genotypes within each water regime. The same letters do not differ from each other by the Tukey test at 5 % probability.

Low water availability leads to reduced productivity

Grain productivity generally responds to water availability, as a high production of photoassimilates is necessary to grain production. According to the results obtained in 2021, there was greater productivity under treatment with moderate water deficit (WD2 100), like that observed in Guerra et al. (2005). WD2 100 treatment may indicate a more sustainable use of water. In addition, this treatment was classified as moderate because it had a period of stress that was recommended to standardize coffee flowering in the Cerrado region. Water stress for longer periods is exceptionally harmful to plants, and minor stress is not so efficient in the uniformization of flowering. On the other hand, the FI 100 treatment and treatments with a 50 % reduction in water availability had median productivity. Depending on the genotype, the lowest performance was observed in either the rainfed or the WD1 100 treatments. This is because water deficits affect the amount of water extracted by the roots, the spatial distribution of the root system, the size of the canopy, and the growth of coffee fruit (Amarasinghe et al., 2015). Iirrigation contributes to increased productivity (Sakai et al., 2015), better vegetative development of plants, and obtaining better quality grains and drinks (Rakocevic et al., 2023).

According to the data, in a negative biennial year (2021), there appeared a greater effect on the FI 100 and better productive potential in WD2 100. In this experiment, the E237, Iapar 59 and Catuaí 62 genotypes under WD2 100 increased by 66, 37, and 40 % in grain yield compared to the rainfed plants. These data show the importance of irrigation, as the WD1 50 treatment, which received small amounts of water but was distributed at critical times, was more productive than the rainfed. Therefore, the correct use of irrigation to improve the sustainability of the production system is fundamental to guaranteeing crop productivity in the Brazilian Cerrado. Under rainfed conditions, in addition to the water deficit, the plants are exposed to maximum temperatures above 30 °C from Aug to Sept, which can lead to the burning and abortion of the flower buds. Dry periods are often accompanied by high irradiance; a proportionally greater level of energy will be available to produce high levels of ROS (reactive oxygen species), which can potentially increase oxidative stress and impair the physiological and agronomic performance of the plant (DaMatta et al., 2018).

Although the FI 100 treatment is more productive in some years, with some irrigation shifts, according to Guerra et al. (2005), it is not recommended for planting coffee in the Brazilian Cerrado since, without the use of controlled stress management, it presents several flowering events during the reproduction cycle. As a result, the percentage of cherry beans was around 60 % in genotypes E237 and Iapar 59 and 80 % in Catuaí 62. The difference between genotypes may indicate the need to seek specific water regimes for each cultivar. In turn, WD2 100 resulted in a single and uniform flowering with a percentage of cherry above 80 % (Figure 9A and B). The high yield in treatments with water stress for approximately 70 days was associated with a better filling of coffee beans due to maturation uniformity and greater vegetative growth of the plants, as found by Guerra et al. (2005) and Veiga et al. (2019). Furthermore, WD2 100 saved 16 % of the irrigation water necessary compared to FI. Thus, WD2 100 appears to be an effective irrigation strategy that could save water and increase water use efficiency without significantly reducing crop yield in areas where water is scarce and dry periods are prolonged, thereby contributing to the rational use of irrigation.

The WD1 100 and 50 % treatments imposed on the plants caused a marked reduction in grain yield due to the prolonged period without irrigation (Figure 8A), indicating that the severe water deficit may have affected the flowering of the plants. Similarly, the monthly evaluation of the water deficit in coffee, showed that the water deficit in April occurs during bud development and influences coffee productivity in times of low productivity (Aparecido and Rolim, 2018). Meanwhile, the water deficit in June and Sept (at the end of bud dormancy) positively influenced coffee productivity. These results reinforce the importance of correct WD2 100 irrigations in coffee plantations in this region and explain why this treatment was considered moderate water stress.

Comparing the genotypes in each treatment, Iapar 59 is a high-productivity genotype, and E237 was the genotype with the lowest productivity. The lower productivity of E237 is associated with the length of the branches, the number of nodes in the orthotropics, and smaller plagiotropic branches, which directly interfere with the productivity of the grains due to the lower presence of reproductive buds. However, despite its low productivity, it has been used in the Embrapa Cerrados breeding program as a source of drought tolerance (Silva et al., 2022).

Iapar 59 generally performed better under water deficit and rainfed than the other genotypes and showed lower productivity under full irrigation (FI 100 and FI 50). Iapar 59 developed well under irrigation, water deficit, and rainfed conditions (Silva et al., 2022). This genotype is drought-tolerant (Rakocevic et al., 2023; Freire et al., 2013). The selection of drought-tolerant coffee cultivars, which can withstand periods of severe drought and produce acceptable yields under water scarcity conditions, is of the utmost importance (Silva et al., 2022). The phenotypic expression, as a characteristic related to the performance of cultivars in their cultivation environment, indicates the potential for adaptability and stability, where an ideal genotype presents high productivity, associated with high stability under unfavorable conditions and is capable of responding satisfactorily to favorable environments (Dutra Filho et al., 2021). Drought-tolerant coffee genotypes have greater water use efficiency, which is associated with greater root development and stomatal control (Pinheiro et al., 2005).

Is rainfed sustainable?

Under the rainfed treatment, the plants were cultivated only with rainfall, and depending on the year, they had a drought of four to five months and average annual precipitation over the years 2017-2021 of 1,026 mm. These levels of water availability are below those required for growing coffee, which is in the range of 1,200-2,700 mm of precipitation and a dry period of one to three months per year (Ovalle-Rivera et al., 2015). In addition, in the period without rain, there are high temperatures capable of reaching maximum temperatures above 33 °C (Figure 1) and low relative humidity values, and the association of these factors may lead to the burning and abortion of the flowers if they coincide with the period of pre-flowering, flowering, and post-bloom. In the tropics, the water deficit is more severe due to high temperatures and solar radiation (DaMatta, 2003).

Plants under rainfed conditions have their growth and production compromised by poorly distributed rainfall (Figures 4A-B and 5A-D), with a reduction of up to 31 % in plant height compared to plants under full irrigation. Water deficiency affects the development of the aerial part of the coffee tree (DaMatta, 2004). It reduces the leaf area, the growth of coffee branches, and the production of nodes, all of which promotes lower fruit production.

In addition, water scarcity caused by dry spells, mainly during the flowering, expansion, and granation phases of the grains results in low productivity in rainfed plants. Under adequate soil moisture, more significant expansion occurs, and consequently, the fruit is larger. (DaMatta et al., 2018). As shown above, drought is the primary environmental stress that affects fruit production, with sharp reductions of up to 66 % under rainfed conditions. However, despite the limitations of rainfed cultivation in tropical regions, producers often do not have access to irrigation and rainfed coffee production tends to be used.

Do treatments with water deficit standardize coffee flowering?

The uniformity of the harvest evaluated in these experiments is an indicator of grain quality (Figure 9A and B), as better beverage quality is expected in areas with a higher percentage of cherry fruit at harvest time. In turn, the harvest with a high percentage of green fruit produces a drink of lower quality (Velázques et al., 2019); additionally, more than one harvest should be reaped, which increases the cost of coffee production (DaMatta et al., 2007).

Water stress during pre-flowering is an important method for obtaining flowering uniformity so that, at harvest time, there are higher percentages of cherries, as is shown in this study (Figure 9A and B). Similar results were obtained by Ronchi and Miranda (2020) who studied Arabica coffee plants grown in a greenhouse and observed linear production of cherry grains compared to green grains. However, root growth limitations and luminosity quality may hinder comparisons under field conditions. Similarly, in several coffee regions in São Paulo, Silva et al. (2009) obtained a lower percentage of cherries in either irrigated treatments or a low level of water deficit in pre-flowering.

It is worth mentioning that treatments under water deficit have an earlier harvest than the full irrigation (FI) treatments, which, in turn, had several flowerings throughout the plant cycle, and at the time of harvest, there was a high percentage of green fruit. Thus, for irrigated coffee, the imposition of a controlled water deficit from June to early Sept results in the synchronization of flower buds with a single flowering and greater production of cherries in the Brazilian Cerrado. These results are close to those found by Guerra et al. (2005) in irrigated and well-managed coffee plants in the Brazilian Cerrado, where the suspension of irrigations from 15 June until the leaf water potential had been reached, –2.0 MPa, resulting in synchronization of the development of flower buds causing single and uniform flowering.

The results of this work indicate that the regimes with water deficit contributed to the uniformity of coffee fruits, harvested with higher percentages of grains in the cherry stage, and promoted greater vegetative growth of coffee. The growth analysis showed that the vegetative characteristics of the genotypes Iapar 59 and E237 explain the variation in productivity between them. Higher plants with long branches, such as E237, are not always more productive; the number of nodes in the orthotropic is the key factor in the production of genotypes, as observed in Iapar 59. The Iapar 59 genotype presents vegetative characteristics indicative of plants more tolerant to water stress due to longer branches and greater number of nodes under rainfed conditions.

In 2020, the long period of stress and the 50 % reduction in water availability reduced plant productivity for all genotypes compared with full irrigation. Thus, using irrigation as a complement to rainfall is fundamental to the sustainability of the coffee production system in the Cerrado. These data can be used to choose the appropriate genotype for each region and management condition.

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