Ciências Agrárias
SEMINA

DOI: 10.5433/1679-0359.2023v44n4p1265

Seasonal vegetative growth of *Coffea canephora* associated with two water management in the South-Western Amazon

Crescimento vegetativo sazonal de *Coffea canephora* associado a dois manejos hídricos na Amazônia Sul-Ocidental

Fernando Carlos Ribeiro Solimões[1]; Marcelo Curitiba Espindula[2]; Aristóteles de Jesus Teixeira Filho[3]; Andrey Luis Bruyns de Sousa[4]; Fábio Medeiros Ferreira[3]*

Highlights

Coffea canephora plants showed reduced vegetative growth during the dry season.
Non-irrigated coffee plants showed compensatory growth.
The variety Robusta showed higher growth under water availability.

Abstract

This study aimed to evaluate the vegetative growth of the species *Coffea canephora* from the orthotropic and plagiotropic branches of coffee plants of the botanical varieties Conilon and Robusta under irrigated and non-irrigated conditions during the rainy and dry seasons. The experiment was conducted in the municipality of Ouro Preto do Oeste, Rondônia, Brazil, during two periods defined between October 2019 and October 2021. Branch growth rates (mm day^{-1}) were obtained every 14 days and seasonal growth was plotted in series graphs. Average growth rates for each type of branch were compared by Tukey's test ($p \leq 0.05$). Vegetative growth was seasonal during the evaluation periods and seasons and varied according to genetic material and irrigation use. Growth rates were higher in the rainy season, regardless of water management and botanical variety. Irrigation of coffee plants conducted during periods of high temperatures and strong water deficit provided higher growth relative to non-irrigated plants. Furthermore, the growth of coffee plants subjected to non-irrigation was held back during the drought period and was compensated by high growth rates during the rainy season. Plants of the

[1] M.e in Science and Technology for Amazonian Resources, Universidade Federal da Amazonas, UFAM, Itacoatiara, AM, Brazil. E-mail: fcrsolimoes@gmail.com
[2] Dr., Researcher, Empresa Brasileira de Pesquisa Agropecuária, EMBRAPA Café, Brasília, DF, Brazil. E-mail: marcelo.espindula@embrapa.br
[3] Profs. Drs., Institute of Exact Sciences and Technology, UFAM, Itacoatiara, AM, Brazil. E-mail: aristoteles@ufam.edu.br; ferreirafmt@ufam.edu.br
[4] Doctoral Student of the Graduate Program in Tropical Agronomy, UFAM, Itacoatiara, AM, Brazil. E-mail: andreysousa12@gmail.com
* Author for correspondence

Received: Apr. 22, 2023 Approved: Aug. 28, 2023

botanical variety Robusta tended to grow more than those of the variety Conilon under water availability conditions (rain or irrigation), considering the climate conditions of the South-Western Amazon.
Key words: Conilon coffee. Compensatory growth. Water stress. Robusta. Growth rate.

Resumo

Neste estudo objetivou-se avaliar o crescimento vegetativo da espécie *Coffea canephora,* a partir dos ramos ortotrópicos e plagiotrópicos dos cafeeiros das variedades botânicas Conilon e Robusta, em condições irrigada e não irrigadas, durante as estações de chuva e estiagem. O experimento foi conduzido no município de Ouro Preto do Oeste, Rondônia, Brasil, durante dois períodos definidos entre os meses de outubro de 2019 a outubro de 2021. As taxas de crescimentos dos ramos (mm dia^{-1}) foram obtidas a cada quatorze dias e o crescimento sazonal foi plotado em gráficos em série. As médias das taxas de crescimento para cada tipo de ramo foram comparadas pelo teste de Tukey ($p \leq 0{,}05$). O crescimento vegetativo foi sazonal durante os períodos de avaliação e estações do ano e, variou conforme o material genético e uso da irrigação. As taxas de crescimento foram superiores no período chuvoso, independentemente do manejo hídrico e da variedade botânica. A irrigação de cafeeiros realizada durante as épocas de altas temperaturas e forte déficit hídrico proporcionou maior crescimento em relação a plantas não irrigadas. Além disso, o crescimento dos cafeeiros não irrigados ficou represado durante o período da estiagem e foi compensado pelas altas taxas de crescimento no período das chuvas. As plantas da variedade botânica Robusta, em condições de disponibilidade hídrica, mediante chuva ou irrigação, tenderam a crescer mais do que as da variedade Conilon, considerando as condições climáticas da Amazônia Sul-Ocidental.
Palavras-chave: Café Conilon. Crescimento compensatório. Estresse hídrico. Robusta. Taxa de crescimento.

Introduction

Understanding the seasonal fluctuations of vegetative growth in *Coffea canephora* under typical growing conditions in the South-Western Amazon is a valuable tool for evaluating plants to shape the nutritional planning of coffee fields, irrigation management, and other cultural practices. However, the literature is scarce on studies of this nature in the region.

Brazil is the world's largest producer and exporter of coffee beans and the second-largest producer of the species *Coffea canephora* (United States Department of Agriculture [USDA], 2023), standing out the State of Rondônia, the largest coffee producer in the South-Western Amazon and the North region of Brazil, with 98% of the regional production and almost 19% of the national production of this species (Companhia Nacional de Abastecimento [CONAB], 2023).

Coffee farming in Rondônia has an important social role, as it has focused on small family production units (S. J. M. Oliveira & Araújo, 2015). The state was recently recognized as the first Geographical Indication of the designation of origin of *Coffea canephora* in the world (Empresa

Brasileira de Pesquisa Agropecuária [EMBRAPA], 2021). The evolution of coffee farming in the Amazon is due to the change in the technological level and the expansion of fields, mainly in the state of Rondônia (Espindula et al., 2022), driven by clonal crops and more productive inter-varietal hybrids and intrinsic beverage quality and hence more profitable (Teixeira et al., 2020; Espindula et al., 2022).

The State of Rondônia has good climate suitability for the cultivation of *C. canephora* varieties, with average annual temperature between 23.2 and 26.0 °C and an average annual rainfall between 1,340 mm and 2,340 mm (M. J. G. da Silva et al., 2015). However, drought is the main environmental stress affecting coffee production in most growing areas (DaMatta et al., 2018), which together with high air temperatures - above 31.5 °C (Partelli et al., 2010) - can drastically reduce coffee growth due to physiological and biochemical changes (DaMatta & Ramalho, 2006; Kath et al., 2020) related to a decrease in photosynthetic activity and respiratory capacity and increased respiratory rate (Vara Prasad et al., 2005; Dubberstein et al., 2018; Venancio et al., 2020).

Supplementary irrigation in the driest months with extremely low rainfall (less than 20 mm) and water deficit between 200 and 400 mm per year (Cararo & Dias, 2015) has been used as an alternative during these drought periods in coffee-growing regions of the South-Western Amazon. Its application also has the function of standardizing flowering and, consequently, fruit maturation (M. J. G. da Silva et al., 2015).

C. canephora adapted to low altitude regions (DaMatta et al., 2018), typical in the Amazon, has two distinct botanical varieties, called Conilon and Robusta (Ramalho et al., 2016). Crops formed by genotypes of the botanical variety Conilon predominate in Brazil although the variety Robusta has comparatively higher vigor, superiority in grain quality, and resistance to diseases and pests (Rocha et al., 2021). Inter-varietal hybrids, natural or generated by targeted crossings, have formed many coffee fields in the South-Western Amazon (L. N. L. Oliveira et al., 2018; Moraes et al., 2020; Teixeira et al., 2020).

Investigations in Brazil on vegetative growth in *Coffea canephora* are represented by the use of typically Conilon genotypes (Partelli et al., 2010, 2013; Covre et al., 2016). The use of Robusta germplasm is more demanding in terms of water and has been promising in the Amazon due to the better-distributed rainfall volume in the region and, therefore, the reduce occurrence of severe water deficit (Souza et al., 2015). Therefore, comparative studies on growth rates between botanical varieties can answer how thermal variation and water stress affect seasonal growth in this type of coffee plants.

Another interesting behavior that needs to be observed in coffee plants in the Amazon concerns the existence of compensatory growth after post-drought water availability (Wang et al., 2016; Zhou et al., 2022). Coffee clones sensitive to water deficit have little control of transpiration, as the stomata respond limitedly to a reduction in water availability and, consequently, the plants have a low water absorption capacity due to their more superficial root management (DaMatta et al., 2007). However, productive *Coffea canephora* plants could maintain adequate leaf water potential during the drought period by combining root deepening with increased stomatal control (V. A. da Silva et al., 2010). Coffee plant growth is limited under moderate water deficits, but a post-drought compensatory growth is stimulated when the water tensions are released (Browning & Fisher, 1975; DaMatta et al., 2007; Zhou et al., 2022).

In this context, this study aimed to investigate the oscillations and differences in the vegetative growth of *Coffea canephora* between the botanical varieties Conilon and Robusta under irrigated and non-irrigated management at different times of the year in the South-Western Amazon.

Material and Methods

The experiment was conducted in the experimental field of the Brazilian Agricultural Research Corporation (Embrapa) in the municipality of Ouro Preto do Oeste, Rondônia (10°43'55" S and 62°15'19" W, altitude of 245 m), whose edaphoclimatic characteristics are typical of the southwest Amazon. The useful area of the test was 20 x 22 m and the flat topography land with non-compacted soil was characterized as a clay-textured Oxisol (EMBRAPA, 2018). The climate of the municipality is classified as a tropical wet climate (Am), according to Köppen (Alvares et al., 2013). It has two well-defined seasons: the rainy season (October/November to April/May) in the summer and the dry season in the winter. The annual temperature range varies from 21.2 to 30.3 °C, with the highest temperatures occurring in July and August. The average annual precipitation is 1,939mm, with an average relative humidity of 81% (Rocha et al., 2015; M. J. G. da Silva et al., 2015).

The two clonal genotypes belong to the germplasm bank of the Coffee Improvement Program of Embrapa Rondônia, consisting of good representatives of the characteristic phenotypes of the botanical variety Conilon and variety Robusta, both non-commercial and widely divergent from each other. The seedlings from the Embrapa nursery were transplanted in January 2017 at five months of age, with a spacing of 3.0 x 1.5 m and subjected to fertigation. The plants were kept with three orthotropic stems and their productive plagiotropic branches were pruned right after harvesting in all seasons, but they were evaluated before reaching the pruning phase.

Irrigation suspension in the water management with water unavailability was carried out from November 2017 to allow the plants to acclimatize to the environmental conditions. A surface drip system was used in irrigated management, consisting of one line of emitters per row, with two equidistant drippers per plant with a flow rate of 1.6 L h^{-1}, kept in daily operation for two hours, totaling 6.4 L day^{-1} $plant^{-1}$, which was managed with a fixed daily irrigation shift to supply approximately 970 L $plant^{-1}$. Supplementary irrigation was activated only in the dry season, being suspended with the resumption of the rainy season. Monitoring conducted by means of tensiometry showed that the plants were always within field capacity during the rainy season, with no need for irrigation at this time of year.

Fertilization and all other cultural treatments for both water management were conducted according to the requirements of each phenological stage of the coffee plant and followed the technical recommendations for *C. canephora* (Marcolan & Espindula, 2015a).

The minimum, average, and maximum air temperature, precipitation, and relative humidity data (Figure 1A) were collected in the experimental field by an Ambient Weather WS-2902C automatic station. The meteorological data allowed calculating the potential evapotranspiration (ETP), according to the method proposed by Camargo (1971) (Figure 1B) and following the selection criteria defined by Pereira et al. (2002), obtained by Eq. 1:

$$ETP = 0.01 \times Qo \times T \times ND \text{ (Eq. 1.)}$$

where ETP is the reference evapotranspiration (mm month^{-1}), Qo is the extraterrestrial global solar irradiance, expressed in mm of equivalent evaporation per day (mm day^{-1}), T is the average air temperature (°C) in the considered period, and ND is the number of days in the considered period.

A sequential water balance (Figure 2) based on ETP, and following Camargo (1962) was used. The available water capacity (AWC) of 100 mm, adopted for perennial crops such as coffee, was used (Pereira et al., 2002). The vapor pressure deficit (Δe or VPD) was calculated using the methodology described by Tetens (1930), obtained by the difference between the saturation pressure (ES) and the water vapor partial pressure in air (EA). ES (kPa) was determined from the average air temperature values, according to Eq. 2:

$$ES = 0.6108 \times 10^{[(7.5 \times T)/(237.3+T)]} \text{ (Eq. 2.)}$$

The water vapor partial pressure (EA, in kPa) was determined from the relative humidity (RH, in %) and ES (Eq. 3):

$$EA = (RH\ \% \times ES)/100 \text{ (Eq. 3.)}$$

Thus, the vapor pressure deficit (VPD or Δe, in kPa) was obtained by (Eq. 4.):

$$VPD = \Delta e = ES - EA \text{ (Eq. 4.)}$$

A 2^4 factorial arrangement, consisting of combinations of two periods (2019/2020 and 2020/2021), two seasons (rainy and dry), two botanical varieties (Conilon and Robusta), and two water management systems (irrigated and non-irrigated), was considered to analyze the differences between the levels of the investigated factors and their interactions. The experiment was conducted in a completely randomized design with 15 replications (growth rate measurements).

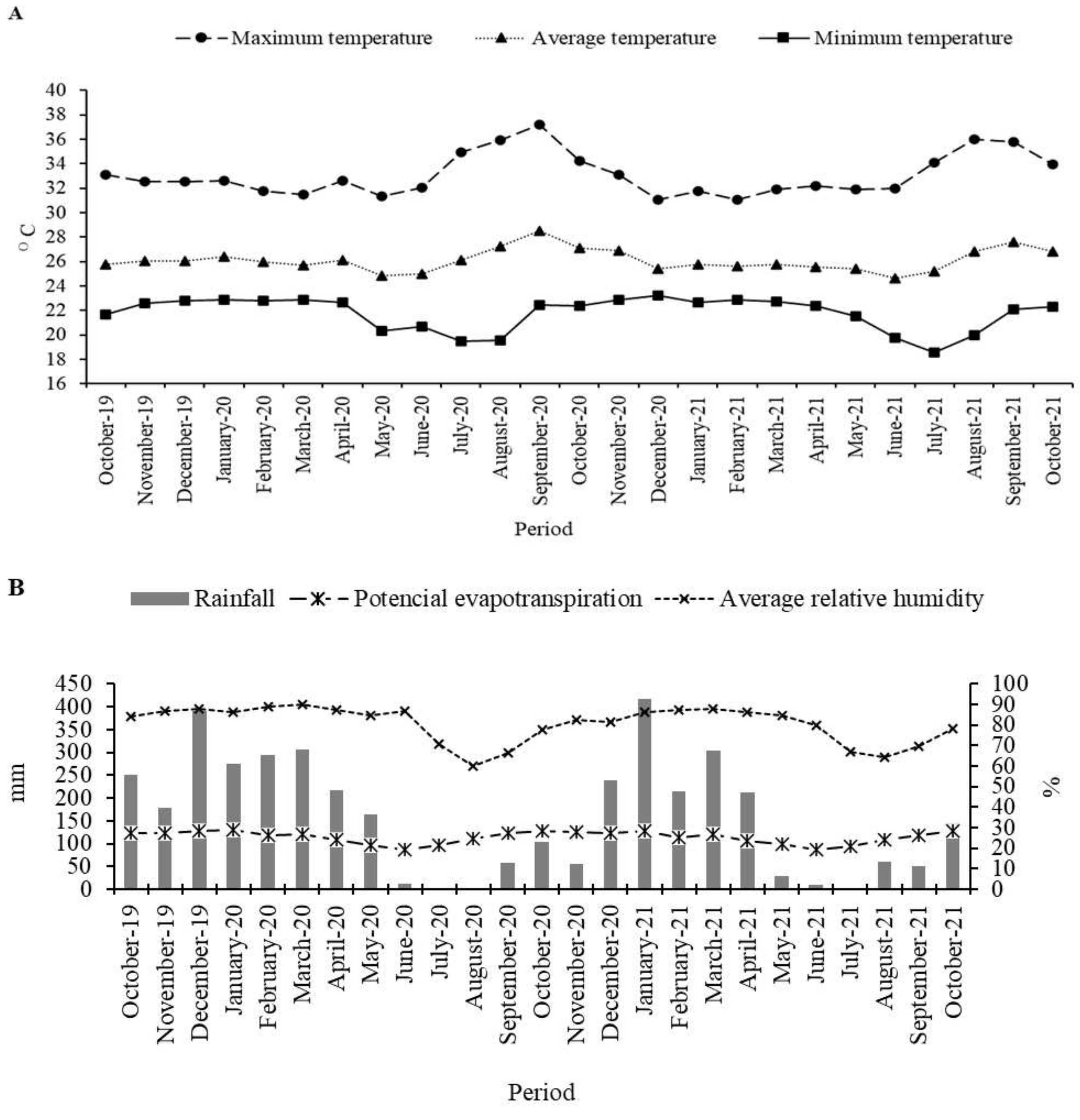

Figure 1. Monthly values of maximum, average, and minimum air temperature (A); precipitation, relative humidity, and potential evapotranspiration - ETP - (B) in the experiment in Ouro Preto do Oeste, Rondônia, Brazil, during the period from October 2019 to October 2021.

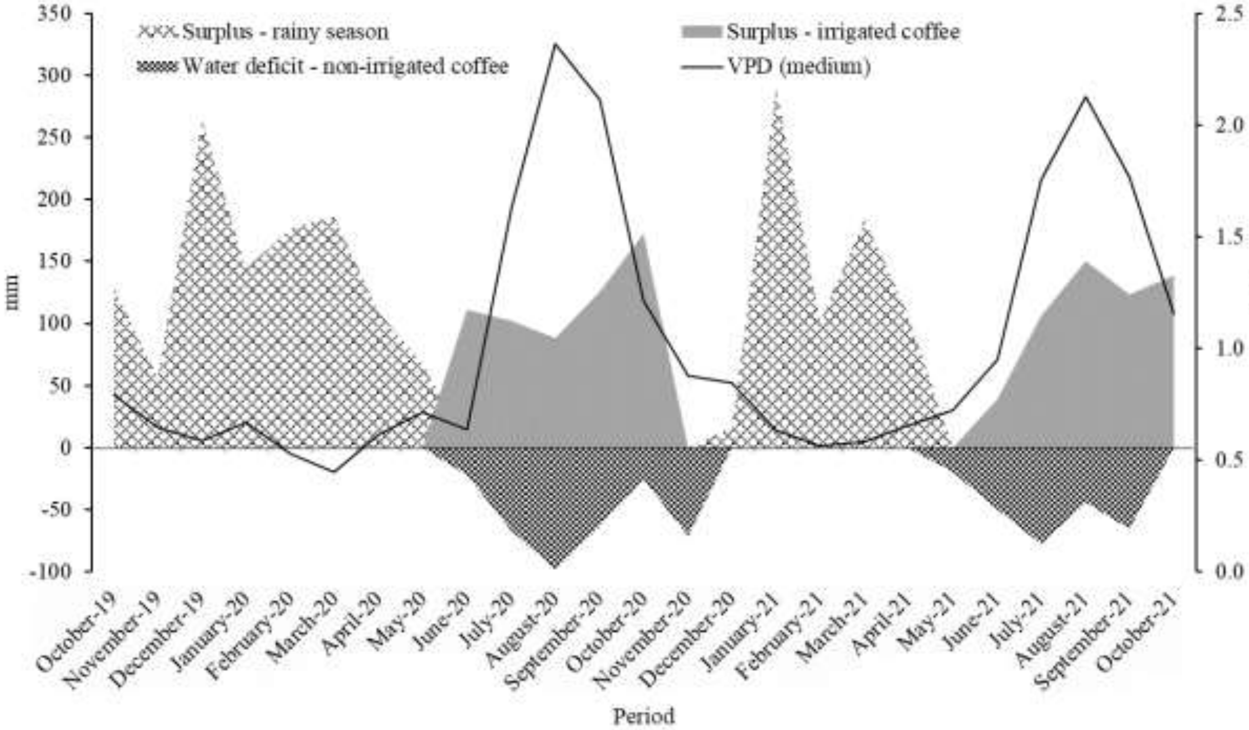

Figure 2. Sequential climatological water balance - AWC = 100 mm - with surplus during the rainy season (irrigated and non-irrigated management), surplus under irrigation and water deficit during non-irrigated management, and average air water vapor pressure deficit - VPD(medium) in the experiment in Ouro Preto do Oeste, Rondônia, Brazil, from October 2019 to October 2021.

The evaluations started on October 9, 2019, when the coffee plants reached two years and eight months. A newly released orthotropic stem (Ortho) and a plagiotropic branch (Plag_one) were marked on the plant. The stem was measured up to its terminal portion, that is, from the intersection with the plagiotropic branch to its apex (apical meristem). The plagiotropic branch was the last one emitted at the apex of the orthotropic stem. The measurements were taken every 14 days using a measuring tape, measuring from the marked base to the apex of the branches. Similarly, another plagiotropic branch (Plag_two) was marked and measured from October 21, 2020.

The first year of evaluation covered the rainy period, from the beginning of October 2019 to the end of May 2020, and the dry period, from June to October 2020. The second year of evaluation consisted of the rainy period, from the beginning of November 2020 to the end of May 2021, and the dry period, from the beginning of June to October 14, 2021.

The lengths of orthotropic and plagiotropic branches allowed the calculation of their daily growth rate (mm day^{-1}), based on the difference between the last measurement taken on the respective branch and the previous measurement, dividing this difference by the interval of 14 days between them. Ten plants were measured to represent the average growth rate at each measured interval. Serial graphs based on these daily rates were plotted with means and standard errors of the mean for each type of branch to interpret fluctuations in vegetative growth.

The data on growth rates of orthotropic stems underwent transformation to meet the assumptions of normality and homogeneity of variances of errors, using the function $Y^*_{ijkl} = \sqrt{Y_{ijkl}}$, where Y^*_{ijkl} represents the value of the transformed daily rate for year i in season j in water system k of variety l. The functions $Y^*_{jkl} = \sqrt[3]{Y_{jkl} + 0.03}$ and $Y^*_{jkl} = \sqrt[3]{Y_{jkl}}$ were used for the branches Plag_one and Plag_two, respectively.

The data were subjected to analysis of variance ($p \leq 0.05$). The comparison of means in the slicing was conducted using the Tukey test ($p \leq 0.05$) for individual factors and significant interactions. The statistical analyses were performed using the software Genes version 1990.2022.23 (Cruz, 2016).

Results and Discussion

The growth rates of orthotropic stems and plagiotropic branches in the rainy season were higher than in the dry season regardless of the genotype and year of evaluation (Figure 3A). It corroborates the results reported for *C. canephora* var. Conilon (Partelli et al., 2013) and *Coffea arabica* (Ferreira et al., 2013) are associated with adequate environmental conditions, especially precipitation and temperature.

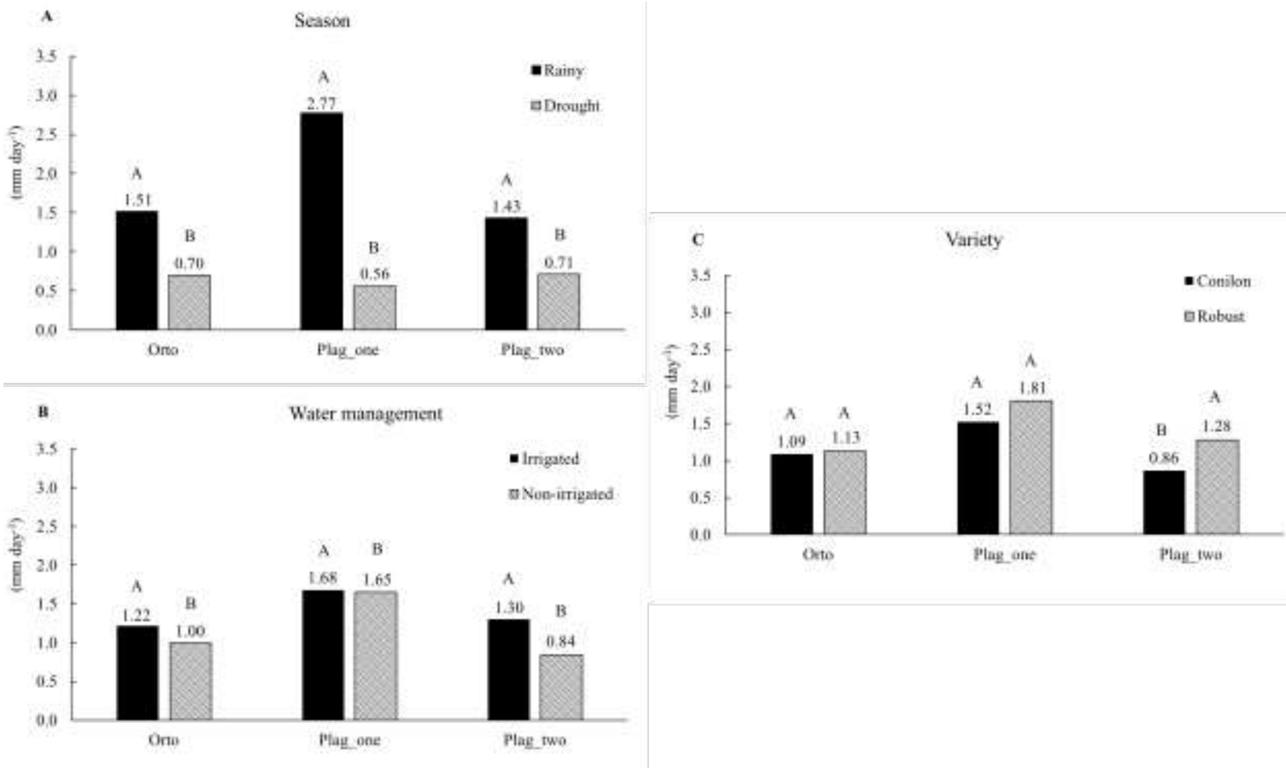

Figure 3. Comparison of means of growth rates (mm day^{-1}) of orthotropic stems (Ortho) and plagiotropic branches measured from October 2019 to October 2020 (Plag_one) and October 2020 to October 2021 (Plag_two) in *Coffea canephora* plants, considering the seasons of the year (A), water management (B), and botanical varieties (C) in Ouro Preto do Oeste, Rondônia, Brazil. Means followed by the same uppercase letter do not differ statistically by Tukey's test ($p > 0.05$). The coefficients of variation for Ortho, Plag_one, and Plag_two were 28.71, 17.92, and 27.28%, respectively. Statistical analyses were performed on the transformed data, as described in the methodology, but here they are presented in their original form, allowing the biological understanding of the phenomenon.

The stress caused by water deficit during the dry season reduces the sap flow and, consequently, the turgor pressure by the conducting vessels (Taiz et al., 2017), whose trend is to decrease cell elongation and, thus, reduce the growth rate of orthotropic stems and plagiotropic branches of coffee. In addition, the lower temperatures observed in the rainy season, compared to the dry season (Figure 1A), were determinant for this higher growth.

The vegetative growth rate in *C. canephora* increases linearly as a function of temperature, as already observed in the northern region of the States of Rio de Janeiro and Espírito Santo (Partelli et al., 2010, 2013), but high temperatures can result in lower growth during the dry season due to reduced photosynthesis and increased respiration (Dubberstein et al., 2018), leading to protein denaturation and aggregation, increased production of reactive oxygen species

(DaMatta & Ramalho, 2006), and ethylene synthesis, impacting on the photosynthetic machinery. They also increase the plant “maintenance respiration” rates to support protein turnover and maintain transport of active ions across the cell membrane (Taiz et al., 2017). The consequences of the various biochemical and metabolic processes triggered lead to a decline in the availability of carbohydrates to provide energy to support plant growth.

Plants under irrigation had higher average growth of Ortho, Plag_one, and Plag_two branches compared to the non-irrigated management (Figure 3B). We decided not to conduct irrigation in the rainy season because rainfall is usually high at this time in the South-Western Amazon (Figure 1B), unlike the management carried out in southern Bahia in *C. canephora* (Covre et al., 2016) and the Cerrado of Goiás in *C. arabica* (Ferreira et al., 2013), whose plants submitted to irrigated treatment received water throughout the year. Water supplementation via irrigation is recommended for regions where the annual water deficit exceeds 200 mm to meet the coffee demand, otherwise the activity would not be viable (M. J. G. da Silva et al., 2015).

The botanical variety Robusta showed a higher average daily growth rate compared to the variety Conilon in the plagiotropic branches measured in the second study period (Plag_two) (Figure 3C). These varieties have different adaptive strategies because they have different centers of origin in the African continent (Souza et al., 2015). The botanical variety Robusta has its center of origin in African regions of tropical rainforest and Conilon has its center of origin in regions of low altitudes and elevated temperatures (Dalazen et al., 2019). Robusta plants are commonly taller and more vigorous, with larger leaves than Conilon genotypes (Rocha et al., 2021; G. N. Silva et al., 2022).

Ortho stems grew more in the second evaluation period (2020-2021) during the dry season than in the first one (2019-2020) (Figure 4A). The water deficit calculated for the dry season in the first period (346 mm) was higher than that in the second period (257 mm) (Figure 2). Also, the hottest month in the first year of evaluation (September) reached the highest average maximum temperature, with 37.1 °C in 2020, surpassing the same month in 2021 by 1.41 °C (Figure 1A), contributing to increase the water loss by plants. High leaf and air temperatures and high radiation caused a reduction in the photosynthetic rate, stomatal conductance, and transpiration in *C. arabica,* regardless of the genotype, and photosynthetic inhibition was complete when these factors occurred simultaneously with water restriction (Almeida et al., 2020).

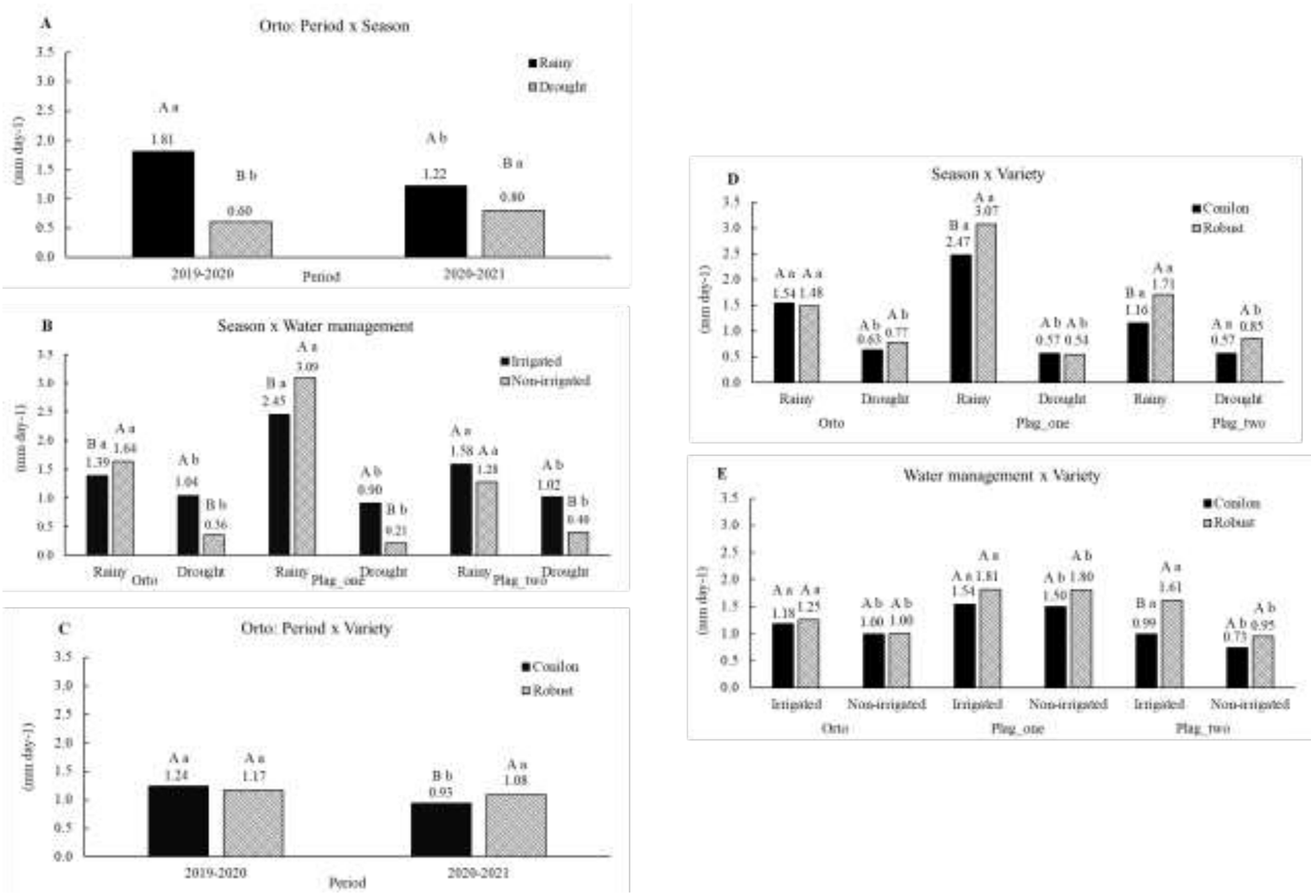

Figure 4. Comparison of means of growth rates (mm day^{-1}) of orthotropic stems (Ortho) and plagiotropic branches measured from October 2019 to October 2020 (Plag_one) and October 2020 to October 2021 (Plag_two) in *Coffea canephora* plants, considering the consequences of interactions between factors: evaluation periods vs seasons of the year (A), periods vs botanical varieties (B), seasons vs water management (C), seasons vs varieties (D), and management systems vs varieties (E) in Ouro Preto do Oeste, Rondônia. Means followed by the same uppercase letter when comparing juxtaposed columns and means followed by the same lowercase letter when comparing columns of the same color for the same type of branch do not differ statistically by Tukey's test ($p > 0.05$). The coefficients of variation for Ortho, Plag_one, and Plag_two were 28.71, 17.92, and 27.28%, respectively, for data transformed according to the functions adopted in the methodology.

Ortho stems of coffee plants in the rainy season of 2019-2020 grew more than in the second rainy season of 2020-2021 (Figure 4A), with precipitation reaching 2075 mm in the first evaluation period and 1387 mm in the second period (Figure 1B). This growth event may be associated with water restriction or reduction, which affect the metabolic processes of plant growth (Carvalho et al., 2006), and the loss of vigor from one year to the next due to the natural aging of coffee branches (Espindula et al., 2015a).

Coffee plants submitted to non-irrigated management during the rainy season showed similar or higher growth in the Ortho and Plag_one branches compared to coffee plants irrigated during the dry season before the rainy season (Figure 4B). The phenomenon of equal or superior growth of non-irrigated plants with those of irrigated plants can be explained by a compensatory effect (Wang et al., 2016; Zhou et al., 2022), i.e., growth becomes stagnant during the dry period and is resumed with a higher intensity from the beginning of water availability in the rainy season (Browning & Fisher, 1975; DaMatta et al., 2007). Coffee plants subjected to continuous annual cycles of controlled water stress showed higher height, number of productive branches, and number of nodes per branch than plants irrigated throughout the year (Guerra et al., 2005).

Well-managed coffee plantations not only satisfactorily resist prolonged periods of drought but also recover very quickly after the end of a dry period (Ferreira et al., 2013; Covre et al., 2015; Martins et al., 2019). Non-irrigated Conilon coffee plants had higher surface area and length and volume of roots per soil volume in the upper and subsurface layers compared to irrigated plants (Covre et al., 2015). Therefore, plants that underwent water stress had an increase in roots and this root compensation promoted better absorption and use of water and nutrients during the rainy season, directly interfering with their growth in the rainy season.

In the first period, with higher annual precipitation (Figure 1B), Conilon plants presented a higher average growth of Ortho branches relative to the second period (Figure 4C), while Robusta plants showed no significant difference in growth between the evaluated years. However, they showed a statistically higher average growth than Conilon plants in the second period (Figure 4C). Robusta plants also showed superior growth compared to Conilon in plagiotropic branches in the rainy season. However, these botanical varieties did not differ in periods of drought in terms of growth rate for all types of branches (Figure 4D).

Robusta plants under irrigated management also showed superior growth compared to Conilon clones for the branch Plag_two, but the branch growth was similar for both Robusta and Conilon under rainfed conditions (Figure 4E). Thus, the branches of Robusta coffee plants under the same conditions of water availability developed more than those of Conilon plants.

The highest growth rates of Ortho stems in the rainy season were recorded from October to March in both evaluated periods. Moreover, they grew more during the dry season from May to September 2021 than from June to October 2020 (Figure 5).

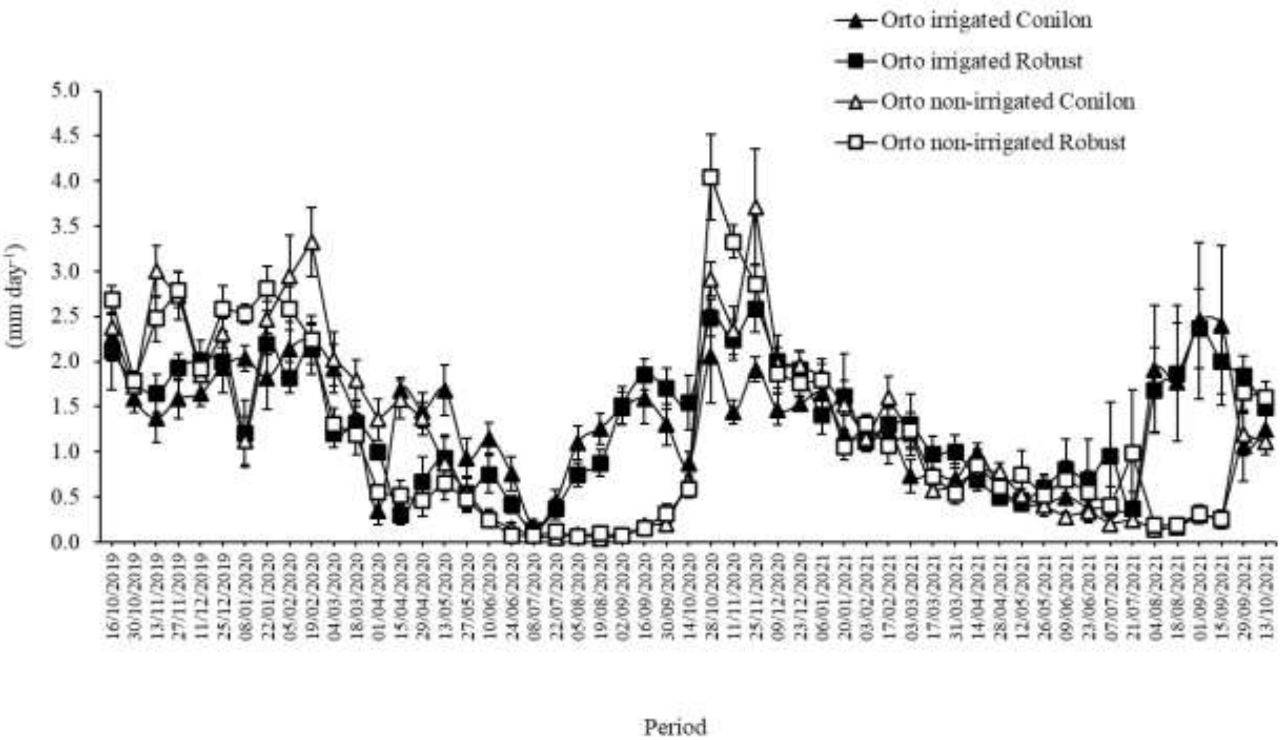

Figure 5. Absolute growth rate of orthotropic (Ortho) stems of *C. canephora* from botanical varieties Conilon and Robusta as a function of water management (irrigated and non-irrigated) between October 2019 and October 2021 in the municipality of Ouro Preto do West, Rondônia, Brazil. The graph was plotted using means ± standard errors of the mean every fourteen days.

Increasing temperature (Figure 1A) resulted in higher evapotranspiration (Figure 1B) and atmospheric vapor pressure deficit (Figure 2). The dry season had an increase in the evaporative demand of the atmosphere associated with a reduction in precipitation, providing a drastic reduction in soil water storage relative to the rainy season (Figure 2), reaching levels below 10 mm in June and July 2021 and zero in July and August 2020 (Figure 1B). The increase in temperature under field conditions can increase the air vapor pressure deficit (Figure 2) and result in a decrease in stomatal conductance and the canopy of Coffea spp. plants due to the high sensitivity of the stomata (Thioune et al., 2017). The transpiration rate decreases as soil water availability decreases because of stomatal closure. It is one of the important defense mechanisms that plants have against excessive water losses and eventual death due to water deficit (Larcher, 2004; Martins et al., 2019).

A gradual decline in growth was observed from January in both periods, both for the Ortho stem (Figure 5) and for the branches Plag_one and Plag_two (Figure 6 A and B) in the two water management systems, probably because the coffee plants are at the fruiting stage at that time (Marcolan et al., 2009). This stage has a high demand for nutrients for fruit formation and, therefore, fruits become priority drains, restricting branch growth (Partelli et al., 2014).

The climate in the state of Goiás is characterized by well-defined seasons, with a rainy season, which normally occurs from September/October to March, and a dry season, which begins in April/May. Branches of non-irrigated *C. arabica* coffee plants showed a marked reduction in growth during the dry season under these conditions when compared to other plants that were irrigated or underwent only a 30-day water deficit. However, non-irrigated plants showed a rapid gain in growth rate when the rains started (Ferreira et al., 2013), similarly to what was observed in the present study in Ortho stems (Figure 5) when precipitation started in October (Figure 1B).

The highest average and maximum monthly air temperatures and the reduction in relative humidity were observed in August and September in both years, with maximum monthly temperatures above 35.76 °C (Figure 1A) and relative humidity varying from 60.1 to 69.81% in the two years of evaluation (Figure 1B). Ortho stems (Figure 5) and Plag_one and Plag_two branches (Figures 6A and B) under non-irrigated management showed almost zero growth rate in that period, during the dry season in 2020, with higher water deficit (Figure 2).

The vegetative growth of coffee branches did not respond immediately with the beginning of irrigations in June 2020 and 2021. The branch elongation response was observed after about 45 days, even in the hottest and driest months (Figures 5 and 6). In general, the growth rates of Robusta and Conilon coffee plants evaluated in Ouro Preto do Oeste showed values and ranges higher than those found in other studies with Coffea spp. from different Brazilian regions (Amaral et al., 2007; Partelli et al., 2010; Covre et al., 2013; Ferreira et al., 2013). However, the growth rates were similar in magnitude to those obtained in the State of Espírito Santo, Brazil, for different Conilon genotypes (Partelli et al., 2013).

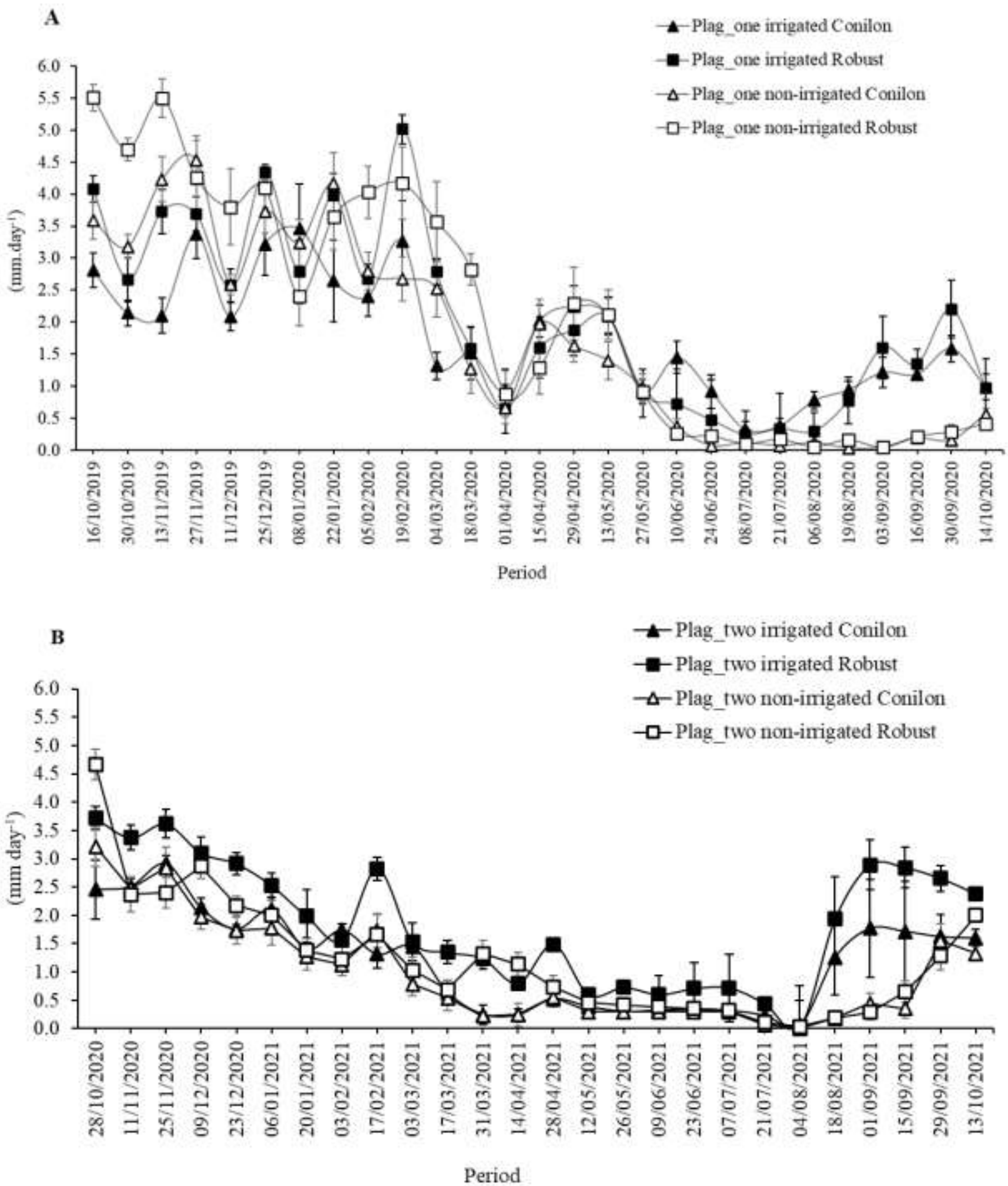

Figure 6. Absolute growth rate of plagiotropic branches of *Coffea canephora* as a function of water management (irrigated and non-irrigated) and botanical varieties Conilon and Robusta from October 2019 to October 2020 - Plag_one - (A) and October 2020 to October 2021 - Plag_two - (B) in the municipality of Ouro Preto do Oeste, Rondônia, Brazil. The graph was plotted using means ± standard errors of the mean every fourteen days.

The growth rates of the Ortho stem and of the Plag_one and Plag_two branches showed a growth pattern in the evaluated period, whose highest rates were observed in the rainy season, between the beginning of October and the end of March (Figures 5 and 6). The lowest growth values were recorded between early June and early August and were associated with the joint effects of climate elements active during this period, such as lower rainfall (Figure 1B) and, consequently, higher water deficit (Figure 2), increase in air temperature (Figure 1A), vapor pressure deficit (Figure 2), and drop in relative humidity (Figure 1B).

In practice, the use of irrigation assists in maintaining the vigor and growth of productive branches of *C. canephora* plants in the Amazon, as many genotypes are inter-varietal hybrids from crosses with the Robusta type. Furthermore, the compensatory growth presented by *C. canephora* plants typifies it as a resilient species that can respond advantageously to the challenges imposed by the abiotic stresses resulting from climate change.

The use of an irrigation system in the Amazon region allows anticipating the planting of coffee plantations and, therefore, not depending on rainfall, increasing productivity in the first commercial harvest, requiring an increase in the amount of growth fertilization (Marcolan et al., 2015b). This management enables the growth fertilization for a longer period of the year, as this region has no growth restriction due to low temperatures. Production fertilization in irrigated systems can start early in late August or early September and can be split until just before the fruit maturation stage in March or April (Espindula et al., 2015b).

Further studies should be conducted to show how much water deficiency interferes with the productivity of *C. canephora* in the region and reveal the costs and benefits of implementing complementary irrigation in the most critical periods.

Conclusions

Coffea canephora plants show a seasonal growth pattern throughout the year under the conditions of the Brazilian South-Western Amazon, with higher growth rates in the rainy season and lower ones in the dry season.

Growth seasonality of *C. canephora* plants is attenuated using supplementary irrigation in the dry season, a condition applied to some crops in the South-Western Amazon region.

Growth seasonality of *C. canephora* plants is accentuated in non-irrigated plantations due to the occurrence of compensatory growth, in which plants under stress grow little during the dry season but present a compensatory growth at the beginning of the rainy season.

Plants of the botanical variety Robusta under water availability conditions (rain or irrigation) tend to have higher vegetative growth relative to the variety Conilon.

Acknowledgments

The authors would like to thank the Coordination for the Improvement of Higher Education Personnel (CAPES) and the Fundação de Amparo à Ciência e Tecnologia do Estado do Amazonas (FAPEAM) for supporting the Graduate Programs in Science and Technology for Amazon Resources (PPGCTRA-UFAM) and Tropical Agronomy (PPGATr-UFAM). To the Brazilian Coffee Research and Development Consortium - CBP&D/Café, the Brazilian Agricultural Research Corporation (EMBRAPA Rondônia) and the Federal University of Amazonas (UFAM) for the facilities made available for the development of this research.

References

Almeida, V. G., Sousa, C. M., Santos, S. G. F. dos, Sarti, J. K., Silva, D. P. da, & Pereira, W. (2020). Trocas gasosas de cafeeiros (*Coffea arabica*) em altas temperaturas no Cerrado goiano. *Research, Society and Development, 9*(11), e4779119973. doi: 10.33448/rsd-v9i11.9973

Alvares, C. A., Stape, J. L., Sentelhas, P. C., Gonçalves, J. L. M., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift, 22*(6), 711-728. doi: 10.1127/0941-2948/2013/0507

Amaral, J. A. T., Lopes, J. C., Amaral J. F. T., Saraiva, S. H., & Jesus, W. C., Jr. (2007). Crescimento vegetativo e produtividade de cafeeiros Conilon propagados por estacas em tubetes. *Ciência e Agrotecnologia, 31*(6), 1624-1629. doi: 10.1590/S1413-70542007000600004

Browning, G., & Fisher, N. M. (1975). Shoot growth in *Coffea arabica* L., II Growth flushing stimulated by irrigation. *Journal of Horticultural Science, 50*(3), 207-218. doi: 10.1080/00221589.1975.11514625

Camargo, A. P. (1962). Contribuição para a determinação da evapotranspiração potencial no estado de São Paulo. *Bragantia, 21*(12), 163-213. doi: 10.1590/S0006-87051962000100012

Camargo, A. P. (1971). *Balanço hídrico no Estado de São Paulo.* (Boletim Técnico, 116). IAC.

Cararo, D. C., & Dias, A. F. S. (2015). Irrigação em cafeeiros. In A. L. Marcolan, & M. C. Espindula (Eds.), *Café na Amazônia* (pp. 312-343). Brasília. https://www.embrapa.br/en/busca-de-publicacoes/-/publicacao/1023755/cafe-na-amazonia

Carvalho, C. H. M de, Colombo, A., Scalco, M. E., & Mrais, A. R. de. (2006). Evolução do crescimento do cafeeiro (*Coffea arabica* l.) irrigado e não irrigado em duas densidades de plantio. *Ciência Agrotécnica, 30*(2), 243-250. doi: 10.1590/S1413-70542006000200008

Companhia Nacional de Abastecimento (2023). *Acompanhamento da safra brasileira de café: 2º levantamento.* https://www.conab.gov.br/info-agro/safras/cafe

Covre, A. M., Partelli, F. L., Bonomo, R., Braum, H., & Ronchi, P. A. (2016). Vegetative growth of Conilon coffee plants under two water conditions in the Atlantic region of Bahia State, Brazil. *Acta Scientiarum: Agronomy, 38*(4), 535-545. doi: 10.4025/actasciagron.v38i4.30627

Covre, A. M., Partelli, F. L., Gontijo, I., & Zucoloto, M. (2015). Distribuição do manejo radicular de cafeeiro conilon irrigado e não irrigado. *Pesquisa Agropecuária Brasileira, 50*(11), 1006-1016. doi: 10.1590/S0100-204X2015001100003

Covre, A. M., Partelli, F. L., Mauri, A. L., & Dias, M. A. (2013). Initial growth and development of Conilon coffee genotypes. *Revista Agroambiente, 7*(2), 193-202. doi: 10.18227/1982-8470ragro.v7i2.944

Cruz, C. D. (2016). Genes Software-extended and integrated with the R, Matlab and Selegen. *Acta Scientiarum: Agronomy, 38*(4), 547-552. doi: 10.4025/actasciagron.v38i4.32629

Dalazen, J. R., Rocha, R. B., Espindula, M. C., Dias, J. R. M., & Dalazen, J. R. (2019). Base genética da cafeicultura e caracterização dos principais clones cultivados no estado de Rondônia. In F. L. Partelli, & M. C. Espindula (Orgs.), *Café Conilon: conhecimento para superar desafios* (pp. 165-178). Alegre, ES. https://ainfo.cnptia.embrapa.br/digital/bitstream/item/207167/1/Capitulo11LIVRO-Simpo769sio-2019-1.pdf

DaMatta, F. M., & Ramalho, J. D. C. (2006). Impacts of drought and temperature stress on coffee physiology and production: a review. *Brazilian Journal of Plant Physiology, 18*(1), 55-81. doi: 10.1590/S1677-04202006000100006

DaMatta, F. M., Avila, R. T., Cardoso, A. A., Martins, S. C. V., & Ramalho, J. C. (2018). Physiological and agronomic performance of the coffee crop in the context of climate change and global warming: a review. *Journal of Agricultural and Food Chemistry, 66*(21), 5264-5274. doi: 10.1021/acs.jafc.7b04537

DaMatta, F. M., Ronchi, C. P., Maestri, M., & Barros, R. S. (2007). Ecophysiology of coffee growth and production. *Brazilian Journal of Plant Physiology, 19*(4), 485-510. doi: 10.1590/S1677-04202007000400014

Dubberstein, D., Rodrigues, W. P., Semedo, J. N., Rodrigues, A. P., Pais, I. P., Leitão, A. E., Partelli, F. L., Campostrini, E., Reboredo, F., Scotti-Campos, P., Lidon, F. C., Ribeiro-Barros, A. I., DaMatta, F. M., & Ramalho, J. C. (2018). Mitigation of the negative impact of warming on the coffee crop: the role of increased air [CO_2] and management strategies. In A. Shanker (Ed.), *Climate resilient agriculture, strategies and perspectives* (pp. 57-85). Londres.

Empresa Brasileira de Pesquisa Agropecuária (2018). *Sistema brasileiro de classificação de solos* (5a ed.). EMBRAPA Solos.

Empresa Brasileira de Pesquisa Agropecuária (2021). *Cafeicultura da Amazônia recebe primeira denominação de origem para cafés canéforas sustentáveis do mundo.* https://www.embrapa.br/en/busca-de-noticias/-/noticia/62622381/cafeicultura-da-amazonia-recebe-primeira-denominacao-de-origem-para-cafes-caneforas-sustentaveis-do-mundo#:~:text=O%20dia%201%C2%BA%20de%20junho,e%20conilon)%20sustent%C3%A1vel%20do%20mundo

Espindula, M. C., Dalazen, J. R., Rocha, R. B., Teixeira, A. L., Diocleciano, J. M., Dias, M. J., Schmidt, R., Lima, P. P., Lima, G. M., & Gama, W. (2022). *Robustas Amazônicos: os cafeeiros cultivados em Rondônia.* EMBRAPA.

Espindula, M. C., Marcolan, A. L., Costa, R. S. C da, Ramalho, A. R., Diocleciano, J. M., & Santos, J. C. F. (2015b). Implantação da lavoura. In A. L. Marcolan, & M. C. Espindula (Eds.), *Café na Amazônia* (pp. 161-176). Brasília: EMBRAPA. https://www.embrapa.br/en/busca-de-publicacoes/-/publicacao/1023755/cafe-na-amazonia

Espindula, M. C., Partelli, F. L., Dias, J. R. M., Marcolan, A. L., Teixeira, A. L., & Fernandes, S. R. (2015a). Condução de cafeeiros *Coffea canephora.* In A. L. Marcolan, & M. C. Espindula (Eds.), *Café na Amazônia* (pp. 219-236). Brasília. https://www.embrapa.br/en/busca-de-publicacoes/-/publicacao/1023755/cafe-na-amazonia

Ferreira, E. P. B., Partelli, F. L., Didonet, A. D., Marra, G. E. R., & Braun, H. (2013). Crescimento vegetativo de *Coffea arabica* L. influenciado por irrigação e fatores climáticos no cerrado goiano. *Semina: Ciências Agrárias, 34*(6), 3235-3244. doi: 10.5433/1679-0359.2013v34n6Supl1p3235

Guerra, A. F., Rocha, O. C., Rodrigues, G. C., Sanzonowick, C., Sampaio, J. B. R., Helon, C. S., & Araújo, M. C. (2005). *Irrigação do cafeeiro no cerrado: estratégia de manejo de água para uniformização de florada.* (Comunicado Técnico, 122). EMBRAPA Cerrados. https://ainfo.cnptia.embrapa.br/digital/bitstream/CPAC-2009/27309/1/comtec_122.pdf

Kath, J., Byrareddy, V. M., Craparo, A., Nguyen-Huy, T., Mushtaq, S., Cao, L., & Bossolasco, L. (2020). Not so robust: Robusta coffee production is highly sensitive to temperature. *Global Change Biology, 26*(6), 3677-3688. doi: 10.1111/gcb.15097

Larcher, W. (2004). *Ecofisiologia vegetal.* RiMa.

Marcolan, A. L., & Espindula, M. C. (2015a). *Café na Amazônia.* EMBRAPA. http://www.sapc.embrapa.br/arquivos/consorcio/publicacoes_tecnicas/Livro_Cafe_na_Amazonia_2015.pdf

Marcolan, A. L., Espindula, M. C., Mendes, A. M., Souza, K. W. de, & Schlindwein, J. A. (2015b). Manejo nutricional. In A. L. Marcolan, & M. C. Espindula (Eds.), *Café na Amazônia* (pp. 219-236). Brasília. https://www.embrapa.br/en/busca-de-publicacoes/-/publicacao/1023755/cafe-na-amazonia

Marcolan, A. L., Ramalho, A. R., Mendes, A. M., Teixeira, C. A. D., Fernandes, C. de F., Costa, J. N. M., Vieira, J. R., Jr., Oliveira, S. J. de M., Fernandes, S. R., & Veneziano, W. (2009). *Cultivo dos cafeeiros Conilon e Robusta para Rondônia* (3a ed.). EMBRAPA Rondônia. https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/710755/1/sp33cafe.pdf

Martins, S. C. V., Sanglard, M. L., Morais, L. E., Menezes Silva, P. E., Mauri, R., Avila, R. T., Vital, C. E., Cardoso, A. A., & DaMatta, F. M. (2019). How do coffee trees deal with severe natural droughts? An analysis of hydraulic, diffusive and biochemical components at the leaf level. *Trees, 33*(6), 1679-1693. doi: 10.1007/s00468-019-01889-4

Moraes, M. S., Rocha, R. B., Teixeira, A. L., Espindula, M. C., Silva, C. A., & Lunz, A. M P. (2020). Adaptability and stability of *Coffea canephora* Pierre ex Froehner genotypes in the Western Amazon. *Ciência Rural, 50*(1), e20190087. doi: 10.1590/0103-8478cr20190087

Oliveira, L. N. L., Rocha, R. B., Ferreira, F. M., Spinelli, V. M., Ramalho, A. R., & Texeira, A. L. (2018). Selection of *Coffea canephora* parents from the botanical varieties Conilon and Robusta for the production of intervarietal hybrids. *Ciência Rural, 48*(4), e20170444, doi: 10.1590/0103-8478cr20170444

Oliveira, S. J. M., & Araújo, L. V. (2015). Aspectos econômicos da cafeicultura. In A. L. Marcolan, & M. C. Espindula (Eds.), *Café na Amazônia* (pp. 27-38). Brasília. https://www.embrapa.br/en/busca-de-publicacoes/-/publicacao/1023755/cafe-na-amazonia

Partelli, F. L., Espindula, M. C., Marré, W. B., & Vieira, H. D. (2014). Dry matter and macronutrient accumulation in fruits of Conilon coffee with different ripening cycles. *Revista Brasileira de Ciência do Solo, 38*(1), 214-222. doi: 10.1590/S0100-06832014000100021

Partelli, F. L., Marré, W., Falqueto, A., Vieira, H., & Cavatti, P. (2013). Seasonal vegetative growth in genotypes of *Coffea Canephora,* as related to climatic factors. *Journal of Agricultural Science, 5*(8), 108-116. doi: 10.5539/jas.v5n8p108

Partelli, F. L., Vieira, H. D., Silva, M. G., & Ramalho, J. C. (2010). Seasonal vegetative growth of different age branches of Conilon coffee tree. *Semina: Ciências Agrárias, 31*(3), 619-626. doi: 10.5433/1679-0359.2010v31n3p619

Pereira, A. R., Angelocci, L. R., & Sentelhas, P. C. (2002). *Agrometeorologia: fundamentos e aplicações práticas.* Agropecuária.

Ramalho, A. R., Rocha, R. B., Souza, F. F., Veneziano, W., & Teixeira, A. L. (2016). Progresso genético da produtividade de café beneficiado com a seleção de clones de cafeeiro 'Conilon'. *Revista Ciência Agronômica, 47*(3), 516-523. doi: 10.5935/1806-6690.20160062

Rocha, R. B., Ramalho, A. R., Teixeira, A. L., Souza, F. de F., & Cruz, C. D. (2015). Adaptabilidade e estabilidade da produção de café beneficiado em *Coffea canephora. Ciência Rural, 45*(9), 1531-1537. doi: 10.1590/0103-8478cr20141554

Rocha, R. B., Teixeira, A. L., Ramalho, A. R., Espindula, M. C., Lunz, A. M. P., & Souza, F. de F. (2021). *Coffea canephora* breeding: estimated and achieved gains from selection in the Western Amazon, Brazil. *Ciência Rural, 51*(5), e20200713. doi: 10.1590/0103-8478cr20200713

Silva, G. N., Barroso, L. M. A., Cruz, C. D., Rocha, R. B., & Ferreira, F. M. (2022). Factor analysis for plant and production variables in *Coffea canephora* in the Western Amazon. *Coffee Science, 17* e171981. doi: 10.25186/.v17i.1985

Silva, M. J. G. da, Saraiva, F. A. M., Silva, A. A. G. da, Santos, L. A., Neto, & Querino, C. A. S. (2015). Clima. In A. L. Marcolan, & M. C. Espindula, *Café na Amazônia* (pp. 41-54). Brasília, DF. http://www.sapc.embrapa.br/arquivos/consorcio/publicacoes_tecnicas/Livro_Cafe_na_Amazonia_2015.pdf

Silva, V. A. da, Antunes, W. C., Guimarães, B. L. S., Paiva, R. M. C., Silva, V. F., Ferrão, M. A. G., DaMatta, F. M., & Loureiro, M. E. (2010). Resposta fisiológica de clone de café Conilon sensível à deficiência hídrica enxertado em porta-enxerto tolerante. *Pesquisa Agropecuária Brasileira, 45*(5), 457-464. doi: 10.1590/S0100-204X2010000500004

Souza, F. de F., Ferrão, L. F. S., Caixeta, E. T., Sakiyama, N. S., Pereira, A. A., & Oliveira, A. C. (2015). Aspectos gerais da biologia e da diversidade genética de *Coffea canephora.* In A. L. Marcolan, & M. C. Espindula (Eds.), *Café na Amazônia.*

EMBRAPA. http://www.sapc.embrapa.br/arquivos/consorcio/publicacoes_tecnicas/Livro_Cafe_na_Amazonia_2015.pdf

Taiz, L., Zeiger, E., Moller, I. M., & Angus, M. (2017). *Fisiologia e desenvolvimento vegetal* (6a ed.). Artmed.

Teixeira, A. L., Rocha, R. B., Espindula, M. C., Ramalho, A. R., Vieira, J. R., Jr., Alves, E. A., Lunz, A. M. P., Souza, F. F., Costa, J. N. M., & Fernandes, C. F. (2020). Amazonian Robustas - new *Coffea canephora* coffee cultivars for the Western Brazilian Amazon. *Crop Breeding and Applied Biotechnology, 20*(3), 1-5. doi: 10.1590/1984-70332020v20n3c53

Tetens, V. O. (1930). Über einige meteorologische Begriffe. *Zeitschrift Geophysic, 6*(1), 297-309. doi: 10.23689/fidgeo-3212

Thioune, E. H., McCarthy, J., Gallagher, T., & Osborne, B. A. (2017). Humidity shock leads to rapid, temperature dependent changes in coffee leaf physiology and gene expression. *Tree Physiology, 37*(3), 367-379. doi: 10.1093/treephys/tpw129

United States Department of Agriculture (2023). *Coffee: world markets and trade.* https://apps.fas.usda.gov/psdonline/circulars/coffee.pdf

Vara Prasad, P. V., Allen, L. H., Jr., & Boote, K. J. (2005). Crop responses to elevated carbon dioxide and interaction with temperature. *Journal of Crop Improvement, 13*(1), 113-155. doi: 10.1300/J411v13n01_07

Venancio, L. P., Filgueiras, R., Mantovani, E. C., Amaral, C. H. do, Cunha, F. F. da, Silva, F. C. dos, Althoff, D., Santos, R. A. dos, & Cavatte, P. C. (2020). Impact of drought associated with high temperatures on *Coffea canephora* plantations: a case study in Espírito Santo State, Brazil. *Scientific Reports, 10*, 19719. doi: 10.1038/s41598-020-76713-y

Wang, X.-L., Wang, J.-J., Sun, R.-H., Hou, X.-G., Zhao, W., Shi, J., Zhang, Y.-F., Qi, L., Li, X.-L., Dong, P.-H, Zhang, L.-X., Xu, G.-W., & Gan, H. B. (2016). Correlation of the corn compensatory growth mechanism after post-drought rewatering with cytokinin induced by root nitrate absorption. *Agricultural Water Management, 166*, 77-85. doi: 10.1016/j.agwat.2015.12.007

Zhou, H., Hou, L., Lv, X., Yang, G., Wang, Y., & Wang, X. (2022). Compensatory growth as a response to post-drought in grassland. *Frontiers in Plant Science, 13*, 1004553. doi: 10.3389/fpls.2022.1004553