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How is the fruit development of *Coffea canephora* trees modulated by the water supply? An analysis of growth curves for irrigated and rainfed systems

Como é modulado o desenvolvimento frutífero de *Coffea canephora* pelo abastecimento de água? Uma análise das curvas de crescimento para sistemas irrigados e não irrigado

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Highlights

Irrigated plants greater accumulation of biomass in the leaves than rainfed.
The accumulation of dry matter in fruits is explained by sigmoidal models.
Number of branches and biomass accumulation in leaves adjust to linear models.
The intensity of biomass accumulation is causally related to irrigation.

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Abstract

Conilon coffee trees can present divergent patterns for accumulation of dry matter and fruit development, which is resulted by genetic or environmental factors. The aim of this study was to quantify the accumulation of dry matter in aerial organs, as well as the productivity of Conilon coffee cultivated in irrigated or rainfed conditions. The experiment was carried out in Bahia State (Brazil), located in the Atlantic, along two years of evaluations. The experiment followed a completely randomized design, developed in scheme of split plot in time, with 14 repetitions. Treatments consisted of two cultivation scenarios during, irrigated or rainfed, in the plots and the time along the reproductive cycle in the sub-plots. The reproductive growth was assessed starting ten days after first flowering, and then, subsequently, every 28 days, until the complete ripeness of the fruits. The accumulation of dry matter in the fruits of Conilon coffee can be explained using sigmoidal models; while the number of branches and accumulation of biomass in the leaves present fit to linear models, regardless of the cultivation being irrigated or rainfed. The magnitude and intensity of the accumulation of biomass, however, is influenced by using irrigation, which prompts gains in accumulation of biomass per fruit.
Key words: Hydric deficit. Plagiotropic branches. Biomass.

Resumo

Os cafeeiros conilon podem apresentar padrões divergentes para o acúmulo de matéria seca e desenvolvimento de frutos, sejam eles resultantes de fatores genéticos ou ambientais. O objetivo deste estudo foi quantificar o acúmulo de matéria seca em órgãos aéreos e a produtividade do café conilon cultivado em condições de irrigação ou de sequeiro. O experimento foi realizado no Estado da Bahia (Brasil), localizado no Atlântico, ao longo de dois anos de avaliação. Foi utilizado o delineamento experimental inteiramente casualizado, em parcelas subdivididas, com 14 repetições. Os tratamentos consistiram de dois tipos de cultivo, sendo estes, irrigado e de sequeiro, nas parcelas e o tempo ao longo do ciclo reprodutivo nas sub-parcelas. O crescimento reprodutivo foi avaliado a partir de dez dias após a primeira floração e, em seguida, a cada 28 dias, até a completa maturação dos frutos. O acúmulo de matéria seca nos frutos do café conilon pode ser bem explicado usando modelos sigmoidais; enquanto o número de ramos e o acúmulo de biomassa nas folhas presentes se ajustam a modelos lineares, independentemente do cultivo irrigado ou de sequeiro. A magnitude e intensidade do acúmulo de biomassa, no entanto, é influenciada pelo uso da irrigação, o que provoca ganhos no acúmulo de biomassa por fruto.
Palavras-chave: Crescimento. Deficit hídrico. Ramos plagiotrópicos. Biomassa.

Introduction

Growth analysis of plants is considered a standard method for measuring the biological productivity of a crop in its production area. Studies about coffee growth, using data of dry matter accumulation, have been employed, mainly in Brazil, aiming to explain the growth differences caused by genetics or environmental modifications (Bragança et al., 2010; Prezotti & Bragança, 2013; Partelli et al., 2014; DaMatta et al., 2019; Dubberstein et al., 2019).

The genus *Coffea* groups at least 124 species (Davis et al., 2011), among them, *Coffea arabica* L. (*Arabica coffee*) and

C. canephora Pierre ex A. Froehner (Conilon or Robusta coffee) are the predominant species that are utilized in worldwide coffee production (Davis et al., 2012). Worldwide coffee production in 2020/21 exceeded 10,18 million tons of green coffee, and 34% of them contain *C. canephora*, mainly produced in emerging countries (International Coffee Organization [ICO], 2022).

Coffee crop in Brazil was initially developed in areas without records of hydric deficit (Martins et al., 2006). Although nowadays the expansion of the crop leaded to areas that were previously considered agronomically inappropriate, because of challenging climate conditions, hydric deficit has become the major factor that limits the growth and the production of coffee in several regions (Damatta & Ramalho, 2006; Farooq et al., 2009; V. A. Silva et al., 2010; Partelli et al., 2013; Covre et al., 2016; Magiero et al., 2017).

Irrigation increases the chance of higher yields, since crop productivity is compromised when critical periods of hydric deficit occur, especially during the stages of flowering and fruit formation until eighteenth week after flowering, when water is essential for the filling of coffee beans (Magiero et al., 2017). Under conditions of proper soil moisture, there is a bigger expansion of the fruits, which means increased grain size and better classification for sieves. Therefore, coffee productivity is strongly influenced by the appropriate supply of water and nutrients (Bonomo et al., 2013; Sakai et al., 2015; Magiero et al., 2017; Covre et al., 2018).

Numerous aspects of coffee growth have been studied, one of them being the accumulation of dry matter as a function of time (Bragança et al., 2010). Biomass' production is a feature of great importance when it comes to assessing the development of plants, and it complements the growth data. In relation to fruits, the knowledge of the growth's characteristics becomes crucial, because this process is conditioned by several factors, biotic and abiotic. As an example, the interaction of minimum and maximum air temperatures coupled with hydric deficit lead to the reduction of grain filling and to the formation of dry grains or beans (Cunha & Volpe, 2011).

Due to the wide genetic and phenotypic variability that exists within *C. canephora* (Leroy et al., 2014; Dalcomo et al., 2015), the dry matter accumulation over time (Partelli et al., 2014), the vegetative growth (Partelli et al., 2013) and the productivity of plants (Esther & Adomako, 2010), can differ severely among genotypes. These differences are genetically determined and controlled by several factors, which are related to the absorption, transport and use of nutrients by plants (Malik et al., 2013) and to the soil's water availability (Rao, 2016). In this context, this work aimed to quantify the accumulation of dry matter in aerial organs and the fruit production of Conilon coffee cultivated in irrigated or rainfed conditions.

Material and Methods

The test was carried out on a private property in Itabela, southern Bahia State (Atlantic), Brazil (latitude 16°42'13 S, longitude 39°25'28 W, at 108 m asl), during two consecutive harvests. The climate, according to Köppen is Aw, tropical, presenting a dry winter and a rainy summer (Alvares et al., 2013).

The plantation was formed with plants of *C. canephora,* genotype "02" from the clonal cultivar "EMCAPA 8111" (Bragança et al., 2001). The plants were three-year-old, grown under full sunlight, in a 3.5 x 1.0 m spacing, with four productive stems per plant, and cultivated following the cycled scheduled pruning system (Verdin et al., 2014). However, the crop was evaluated before reaching the moment for cutting orthotropic stems.

The soil was classified as dystrophic Yellow Latosol (Oxisol according to USDA soil taxonomy), with sandy texture. The values of the chemical and physical properties, related to 0-20 cm depth layer, were: 28.50 mg dm^{-3} of P; 105.00 mg dm^{-3} of K; 4.15 cmolc dm^{-3} of Ca; 1.55 cmolc dm^{-3} of Mg; 15.50 mg dm^{-3} of S; 1.49 mg dm^{-3} of B; 1.90 mg dm^{-3} of Cu; 450.00 mg dm^{-3} of Fe; 20.00 mg dm^{-3} of Mn; 4.20 mg dm^{-3} of Zn; pH level of 6.25; 2.85 cmolc dm^{-3} of potential acidity; 4.55 dag kg^{-1} of organic matter; 730 g kg^{-1} of sand; 110 g kg^{-1} of silt; 160 g kg^{-1} of clay; field capacity (-10 kPa) at 0.19 cm^3 cm^{-3} and permanent wilting point (-1,500 kPa) at 0.13 cm^3 cm^{-3}.

The weed control was performed with herbicides and mowing, preemergent herbicides were used and the soil fertility was managed through fertilization and liming. Both treatments were given 500 kg ha^{-1} $year^{-1}$ of N, 100 kg ha^{-1} $year^{-1}$ of P_2O_5 and 400 kg ha^{-1} $year^{-1}$ of K_2O. On the irrigated treatment, irrigation with fertilizers happened weekly; in non-irrigated treatment, fertilizers were spread by hauling and split in five applications per year (September, November, January, March and June).

The experiment followed a completely randomized design, developed in scheme of split plot in time, with 14 repetitions. Treatments consisted of two cultivation scenarios during, irrigated or rainfed, in the plots and the time along the reproductive cycle in the sub-plots. The irrigation was suspended in the designed rainfed plots four months before the experiment started, as acclimation strategy. On the irrigated treatment, drip irrigation was used along the cycles. There was a column of transmitters, spaced every 0.5 m and with a flow of 2.0 L h^{-1}, per row of plants. The irrigation management was established based on the daily water balance. It was based on the crop's evapotranspiration, on the precipitation measurement at the location and on the characteristics of water storage in the soil.

Values of maximum, minimum and average temperature, global solar radiation, precipitation and relative humidity were collected in an automatic weather station (AWS), located 800 m of the experimental area (Figure 1A and 1B). The meteorological data were used to estimate reference evapotranspiration (ETo), according to Penman-Monteith model (Allen et al., 1998). The daily soil water balance was held considering the two conditions evaluated (irrigated and rainfed), in order to determine the hydric deficit periods (Figure 1C). After 10 days of the flowering, 50 productive plagiotropic branches per plot (14) were identified and marked, each one of them containing 12 productive nodes and 24 fully developed leaves. This was performed in two consecutive seasons (cycle 1 and cycle 2). The representative branches were collected, starting 10 days after flowering, and thereafter, approximately each 28 days until the end of the maturation of the fruits (crop harvest). In each assessment, five random plagiotropic branches were collected in each plot.

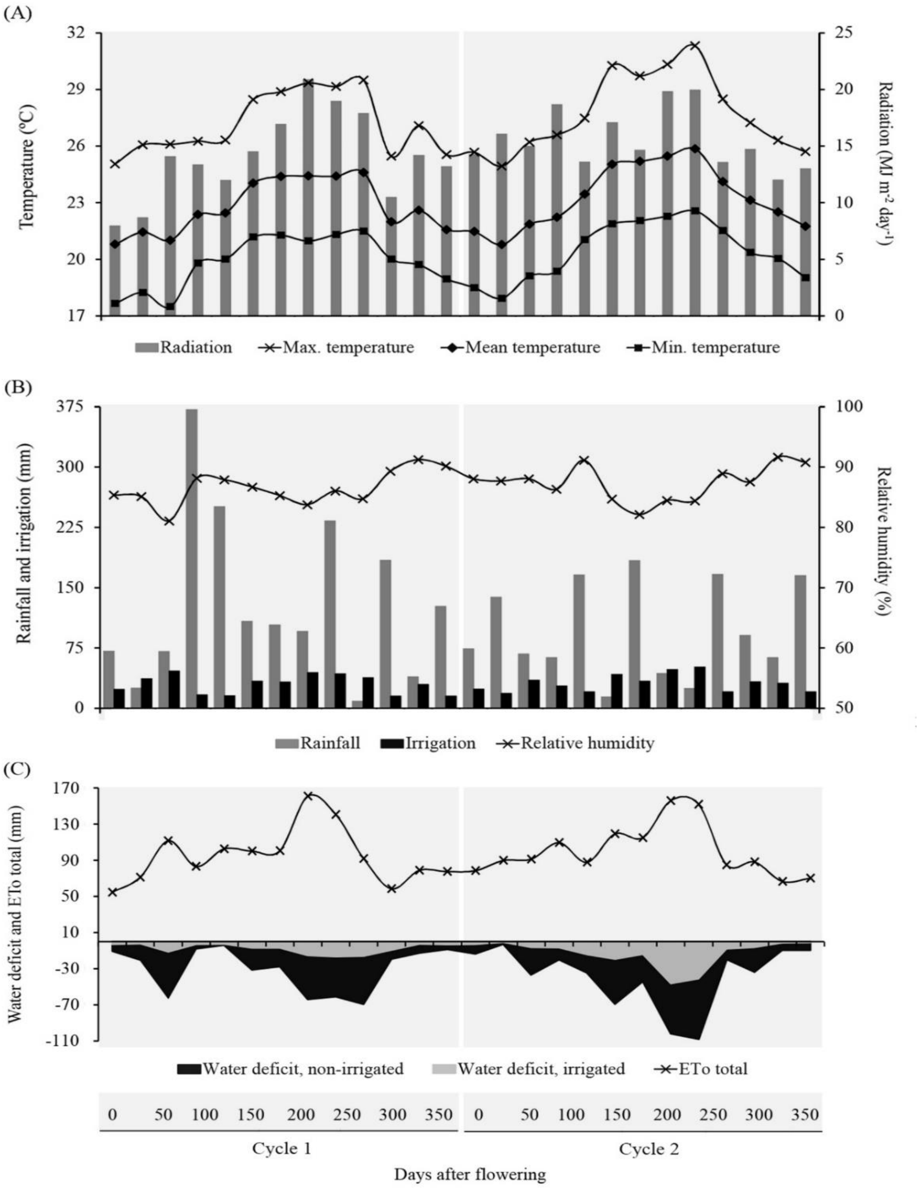

Figure 1. Global solar radiation values, maximum, medium and minimum air temperature (A); water input by rainfall and irrigation, and relative air humidity (B); hydric deficit and total ETo (C), along the time after flowering, in two consecutive cycles.

The selected branches were cut, and the plant organs were separated in leaves, stems and fruits. The number of fruits per branch was quantified. Branches gathered 75 days after flowering presented peduncles due to reduced fruit size, being allocated among green coffee. The fresh leaves was dried in laboratory oven, with forced air circulation, at 70 °C. After drying, the leaves was weighed on an analytical balance (0.001 g) to quantify the dry matter accumulated in each organ. The accumulation of biomass per fruit (mg fruit^{-1}) was calculated considering the fruit dry matter and number of fruits per plagiotropic branch.

The data was subjected to analysis of variance, using the statistical software Assistat 7.7 beta (F. A. S. Silva et al., 2015). Regression analysis was carried out for the quantitative variables and graphics were built using the software SigmaPlot 13.0 (Systat Software Inc., San Diego, CA, USA).

Results and Discussion

The dry matter accumulation curves per fruit and for number of fruits per plagiotropic branch were similar, in model, for both irrigated or rainfed conditions (Figures 2 and 3).

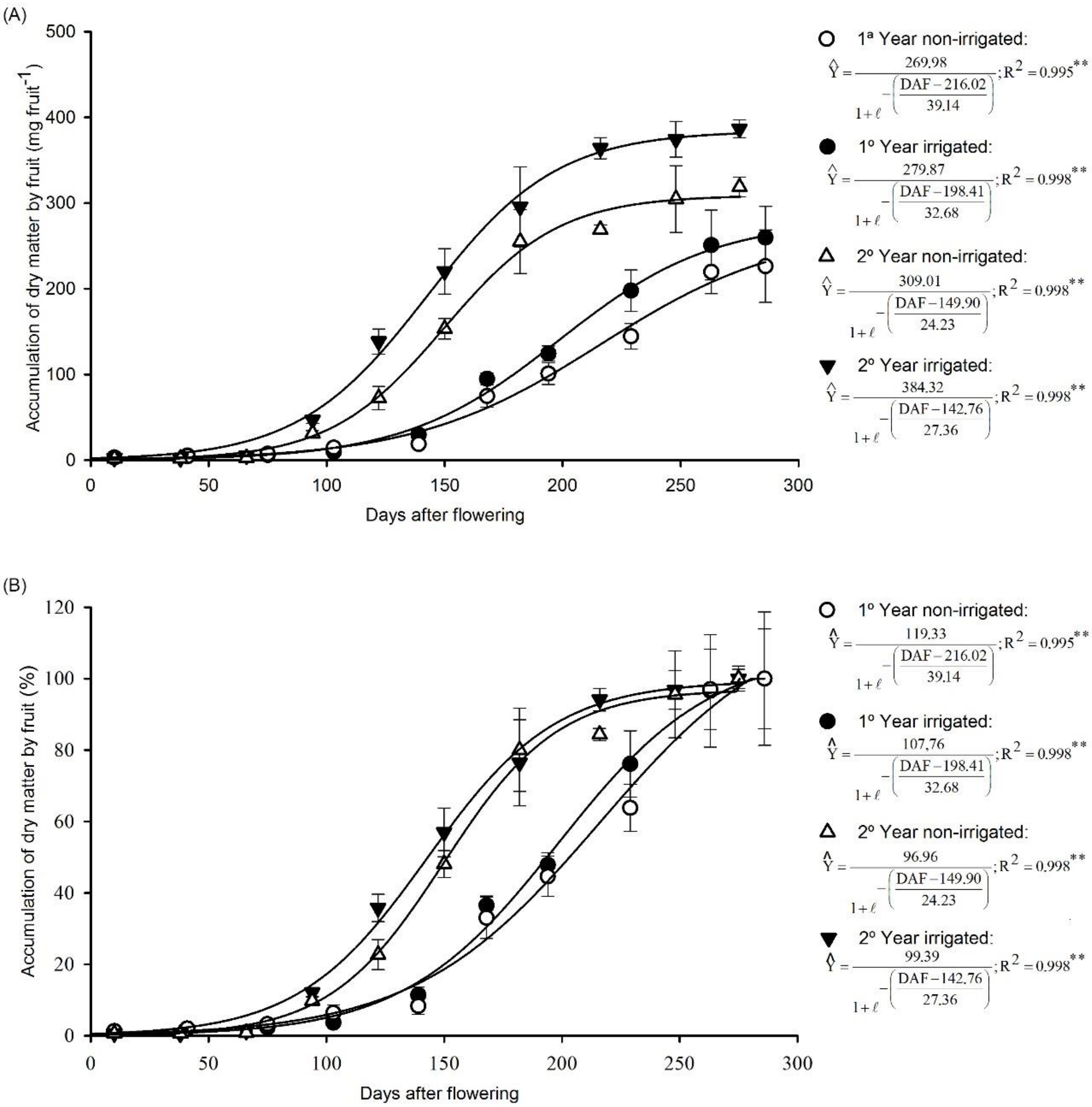

Figure 2. Accumulation per fruit (A) and relative accumulation (B) of dry matter in fruits of Conilon coffee cultivated under irrigated or rainfed conditions, as function of the time from flowering to fruit maturation, along two consecutive cycles (Year 1 and Year 2).

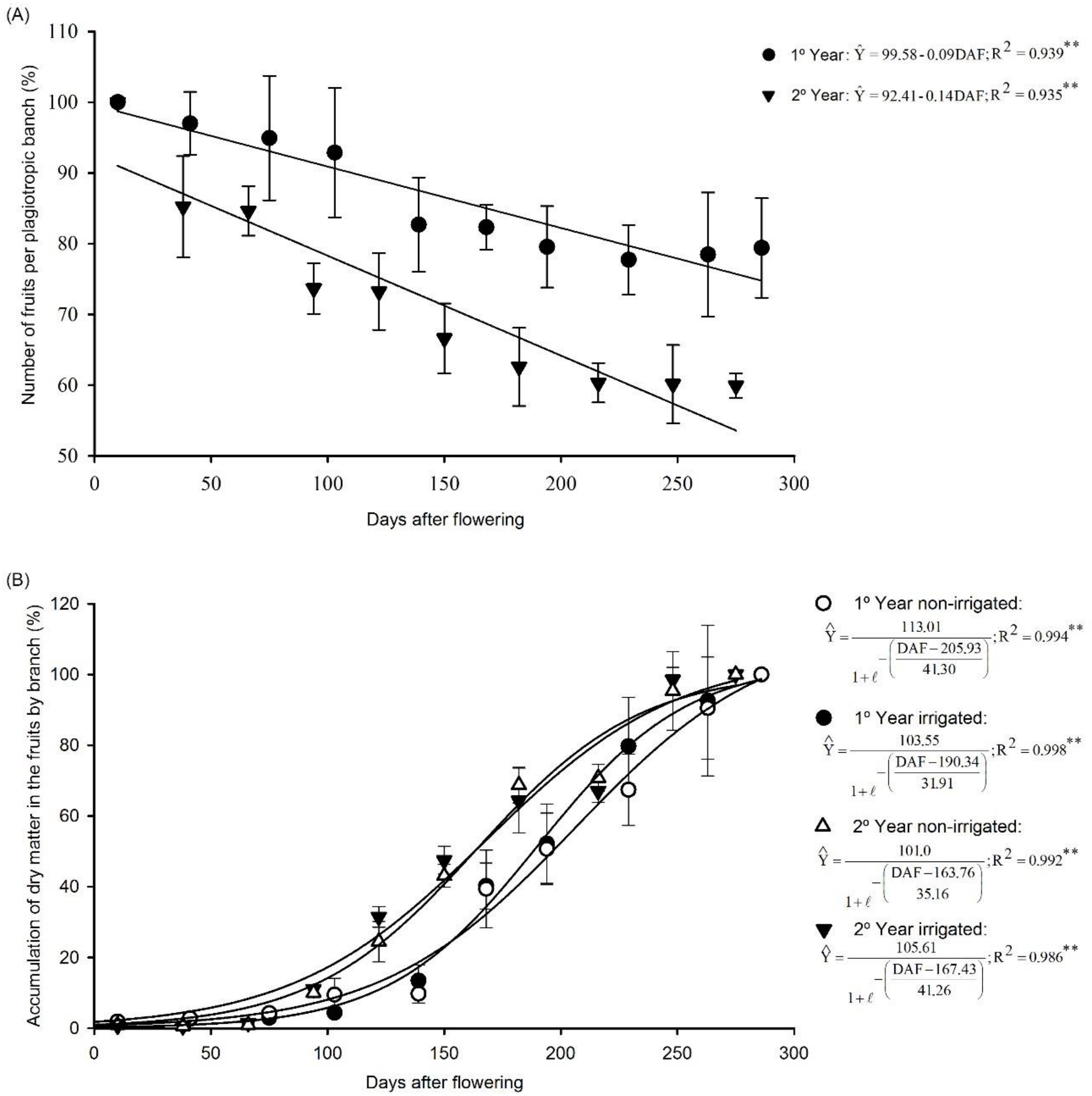

Figure 3. Number of fruits per plagiotropic branch (A) and relative accumulation of dry matter in fruits (B) of Conilon coffee cultivated under irrigated or rainfed conditions, as function of the time from flowering to fruit maturation, along two consecutive cycles (Year 1 and Year 2).

The low accumulation rates during early stages of fruits formation was followed by a stage with high rates (when fruits expand quickly) and a final stage with less expressive rates (when it is the end of fruits' formation), being best explained by sigmoidal functions. Similar result was found by Partelli et al. (2014) and Marré et al. (2015) for plants of Conilon coffee cultivated in the Nothern region of the Espírito Santo State, Brazil. Dubberstein et al. (2016) in Western Amazonia and Covre et al. (2018) in Bahia also corroborate with the observed stages of fruit formation (Partelli et al., 2014): growth, rapid expansion, overhead growth and maturation.

Dry matter accumulation per fruit was higher during the second cycle, regardless of water supply (Figure 2A). The percentage of dry matter accumulated per fruit in the second crop was higher, mainly between 100 and 250 days after flowering (Figure 2B). However, the number of fruits per plagiotropic branch was higher in the first cycle (Figure 3A). The fruits of the first cycle showed lower growth and, consequently, less gain in dry matter (Figure 2A). This behavior is probably due to a bigger competition for space in the buds, as well as adverse and unfavorable weather conditions. This culminated in a lesser grain growth during this cycle.

In the second cycle, fewer fruits per branch and higher fall-down of fruits were observed, in relation to the previous cycle (Figure 3A). In addition, it was observed that these fruits showed a higher and more pronounced rate of dry matter accumulation in relation to the previous cycle, due to a lower amount of fruits per plagiotropic branch, and consequently, lesser competition per bud (Figure 2).

The fall-down of fruits from plagiotropic branches is a phenomenon that occurs naturally in coffee, and can be linked to several factors, either biotic or abiotic. The higher rate of fruit fall-down observed in the second cycle can be linked to the combination of a smaller volume of rain, higher temperatures and more pronounced water deficit in relation to the previous cycle (Figure 1C). Variations in air temperature and the low incidence of rainfall are factors that strongly influence the flowering and fruitification, especially considering that Conilon coffee may present multiple flowering moments throughout the year.

In the first three evaluations, C. canephora have a tendency of showing shorter accumulation rate of dry matter between 10 and 75 days after flowering. During this period, fruits are young and green, presenting slow growth and low dry matter accumulation (Laviola et al., 2007, 2008), which will only intensify from the fourth month after flowering. Higher rates of dry matter accumulation in the fruits were observed from the fourth month (120 days after flowering). Similar results were observed in Conilon coffee cultivated in Rondônia State, North of Brazil (Dubberstein et al., 2016); however, Partelli et al. (2014) noticed increasing rates of dry matter accumulation in the fruits, from the 48th day after flowering, in the Espírito Santo State, located on the Southeast of Brazil.

During the first cycle, the dry matter accumulation in the fruits increased until the harvest of the fruits, 286 days after flowering. During the second cycle, the rates of dry matter accumulation in the fruits were stable between 248 and 275 days after flowering (Figure 2).

The biggest percentages of dry matter accumulation per fruit, and in number of fruits per plagiotropic branch are observed between spring and summer. That time coincides with the stages of rapid expansion and maturation, between 100 and 250 days after flowering (Figure 2B and 3B). During this season, the region southern Bahia State is often subjected to irregular rainfall, high air temperatures, high incidence of solar radiation and occurrence of hydric deficit, especially during summer (Figure 1B).

There are reports about significant biomass gains of coffee fruits at the stages of rapid expansion and maturation (Laviola et al., 2007, 2008). The water flow directed to the fruits is essential for the metabolic processes and biomass accumulation inside the grain during these stages of development (Dongliang et al., 2020). The rapid expansion phase is characterized by a quick stretching of the cells, the fruit reaches about 80% of its final size during this stage. Another noticeable gain is observed during the filling of the perisperm, which occurs during maturation stage (Laviola et al., 2007).

The results show a noticeable decrease in the percentage of dry mass accumulation per fruit from 216 days after flowering (Figure 2B), also observed for the allocation of biomass of the plagiotropic branch in the fruits (Figure 3B). This fact may be explained by the physiological ripening of the fruits, characterized by several chemical and metabolic processes which allow fruits to achieve the ideal point for harvesting (Nsumpi et al., 2020). Fruits are characterized as a strong metabolic drain in coffee trees, demanding water and nutrients during its development (Laviola et al., 2007, 2008). According to Bragança et al. (2010), these organs correspond to 8% of total dry mass of a Conilon coffee tree at 72 months of age; while Prezotti and Bragança (2013) observed that fruits are responsible for the accumulation of 12% of total dry material of the plant.

High temperatures and great hydric deficit are detrimental to the development of coffee fruits. The fruit formation stages can be advanced or delayed in response to weather conditions, and the environmental conditions have great influence over the accumulation of biomass in leaves and fruits (Laviola et al., 2007). Siqueira et al. (1985) highlighted that the hydric deficit can also decisively influence on the duration of phenological stages in coffee trees. In Arabica coffee, all the phenological stages of fruit development are strongly influenced by the water availability and thermic demand (degrees-day) (Damatta & Ramalho, 2006; DaMatta et al., 2019). The fruit ripening may be accelerated due to the occurrence of hydric deficit (Petek et al., 2009).

The proportion of dry matter being allocated in non-reproductive structures presented linear decrease along the time, for both irrigated or rainfed conditions (Figure 4), as result of the biomass being allocated in the fruits along the reproductive cycle.

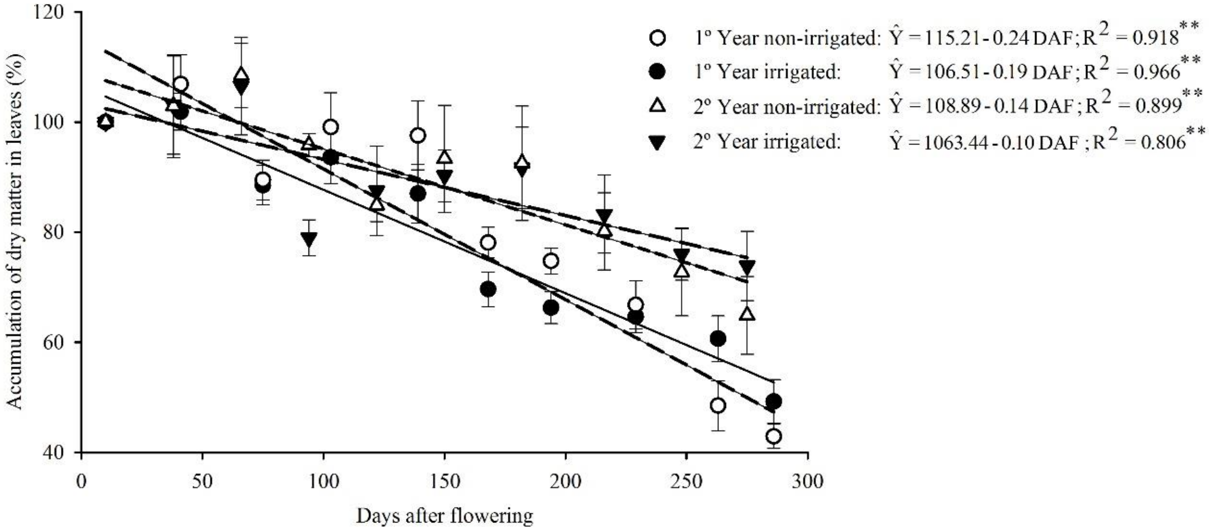

Figure 4. Relative accumulation of dry matter in leaves of Conilon coffee cultivated under irrigated or rainfed conditions, as function of the time from flowering to fruit maturation, along two consecutive cycles (Year 1 and Year 2).

Low accumulation of biomass in leaves was observed during the end of the reproductive cycle (Figure 4B?). A decrease in the dry matter accumulation of approximately 51%, for irrigated plants, and 67%, for rainfed plants, was observed in the leaves, during the first cycle. For the second cycle, the decrease was near 26%, for irrigated plants, and 35%, for rainfed plants (Figure 4B?). This reduction in the allocation of dry matter in leaves can also be associated to a defoliation of branches during the reproductive stages, since this mass ratio is directly related with the quantity of leaves per plagiotropic branch. The defoliation that occurs in plagiotropic branches is associated to a bigger translocation of photoassimilates to the fruits, which are preferential drains during coffee reproductive cycle (Martins et al., 2016), causing a competition between the vegetative and reproductive growth.

High air temperatures can cause an increase of ethylene synthesis, which is a hormone associated with the senescence of vegetal tissues, and consequently it can cause a premature leaf fall (Finger et al., 2006). A significant hydric deficit affects the development of the aerial part of coffee trees, causing a decrease of stomatic aperture and in the leaf area, which results in lower assimilation of CO2 (Damatta, 2004; Rodrigues et al., 2016). In this way, a decrease in photo-assimilation processes are observed (Farooq et al., 2009), as well as losses in growth (Partelli et al., 2013) and fruit yield (Sakai et al., 2015). The positive effect of irrigation was noticeable in the results, since plants cultivation with irrigation presented higher accumulation of biomass in leaves than rainfed plants (Figure 4).

Overall, the results showed that the growth of fruits and accumulation of biomass on the fruits as function of the development time can be well explained using sigmoidal models, for different reproductive cycles and for both scenarios (irrigated or rainfed). The magnitude of coefficients, however, showed potential gains in growth and biomass accumulation for the plants cultivated with irrigation, especially considering the gain in biomass per fruit. The sequential cycles present similar patterns, but its noticeable that the conditions of each cycle are modulated by environmental conditions and possibly due intrinsic characteristics originated from the aging of the tissues, as well as due to the growth and loss of vegetative and reproductive structures in the canopy along the time.

The main gain observed with the use of irrigation was regarding the formation of fruits with more biomass, which shows the tendency of irrigated plants to supply the reproductive cycle with more abundant resources and achieve larger and heavier fruits along the cycle. This may have a direct effect over the sieve classification of the grains after harvesting, being especially advantageous as the physical classification aggregates value to the product.

Conclusions

The accumulation of dry matter in the fruits of Conilon coffee can be well explained using sigmoidal models; while the number of branches and accumulation of biomass in the leaves present fit to linear models, regardless of the cultivation being irrigated or rainfed. The magnitude and intensity of the accumulation of biomass, however, is influenced by the use of irrigation, which prompts gains in the accumulation of biomass per fruit.

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Authors' Contributions

All authors contributed equally for the conception and writing of the manuscript. All authors critically revised the manuscript and approved of the final version.

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