Impacts of water availability on macronutrients in fruit and leaves of conilon coffee

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Abstract – The objective of this work was to evaluate the concentrations and accumulation of macronutrients in conilon coffee (*Coffea canephora*) fruit, and their concentrations in leaves, over two years, in irrigated and nonirrigated coffee plants. Three-year-old conilon coffee plants of the cultivar Emcapa 8111 genotype 02 were used. An experimental design was carried out in randomized complete blocks, in a split-plot arrangement, with 14 replicates. The main plot factor was irrigation versus nonirrigation of coffee plants, and the split-plot factor was different fruit and leaf collection times. Collections began 10 days after the beginning of flowering and were performed on average every 28 days, until full fruit ripening. At each sampling date, five plants per treatment were picked out, by collecting one plagiotropic branch by plant, separated into fruit and leaves. Each part was dried, weighed, and subjected to the chemical analysis. Macronutrient accumulations and their accumulation rates were determined. According to the regression analysis of the data, fruit macronutrient accumulation curves fit best to sigmoidal equations. Irrigation affects the macronutrient dynamics in fruit and leaves during the fruiting phase of conilon coffee, and increases the accumulation of nutrients in the plant tissues. The macronutrients found in greater quantities are N, K, and Ca, in fruit and leaves, regardless of the irrigation treatment.

Index terms: coffee, mineral nutrition, nutrient accumulation, water deficit.

Impactos da disponibilidade hídrica sobre macronutrientes em frutos e folhas de café conilon

Resumo – O objetivo deste trabalho foi avaliar as concentrações e o acúmulo de macronutrientes em frutos de cafeeiro conilon (*Coffea canephora*), e as concentrações nas folhas, ao longo de dois anos, em plantas irrigadas e não irrigadas. Utilizaram-se plantas de café conilon, cultivar Emcapa 8111 genótipo 02, com três anos de idade. Um delineamento experimental de blocos ao acaso foi realizado em parcelas subdivididas, com 14 repetições. Os fatores das parcelas principais consistiram de irrigação versus não irrigação dos cafeeiros e, os das subparcelas, de distintas épocas de coletas de frutos e folhas. As coletas iniciaram-se aos 10 dias após a primeira florada e foram realizadas a intervalos de aproximadamente 28 dias, até a maturação completa dos frutos. A cada data de amostragem, foram selecionadas cinco plantas por tratamento, com a coleta de um ramo plagiotrópico por planta, separado em frutas e folhas. Cada parte foi seca, pesada e submetida à análise química. Foram calculados os acúmulos de macronutrientes e suas taxas de acúmulo. De acordo com a análise de regressão dos dados, as curvas de acúmulo de macronutrientes dos frutos ajustam-se a equações sigmoides. A irrigação afeta a dinâmica dos macronutrientes nos frutos e nas folhas, ao longo do período reprodutivo do cafeeiro conilon, com maior acúmulo de nutrientes nos tecidos dessas plantas. Os macronutrientes mais encontrados são N, K e Ca em frutos e folhas, independentemente do tratamento de irrigação.

Termos para indexação: café, nutrição mineral, acúmulo de nutrientes, deficit hídrico.

Introduction

Coffea Arabica L. (Arabica coffee) and *Coffea canephora* Pierre ex A. Froehner (Robusta coffee) are the main worldwide cropped coffee species (Davis et al., 2012), responsible for a production of 8,6 million tons, 41.2% of which were *C. canephora* (ICO, 2017) that became increasingly important in the last years.

Climate changes, mostly related to global warming and reduced water availability, are important limiting

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factors to coffee production. In fact, recent modelling studies estimate that this crop will suffer significant changes in the agroclimatic zoning by loosing suitable areas of cultivation, which is mainly linked to rising temperatures above the optimum for *C. arabica* and *C. canephora* (Bunn et al., 2015; Martins et al., 2015; Rodrigues et al., 2016). Low-water availability and extreme temperatures (high and low) are expected to become more frequent as a result of climate change (Ramalho et al., 2014). Drought is one of the main limiting factors to this crop (DaMatta & Ramalho, 2006). Low-water availability decreases the stomatal opening, resulting in low-CO_2 uptake and decreased production of photoassimilates (Sakai et al., 2015). These facts affect the shoot development of coffee plants, decreasing their leaf area, plant growth and yield (DaMatta & Ramalho, 2006; Ramalho et al., 2014). Coffee plant productivity is strongly influenced by an adequate supply of water (Sakai et al., 2015). In fact, water deficit can further compromise coffee productivity and quality, if occurring on flowering and fruiting stages – until approximately 18 weeks following flowering (Bonomo et al., 2008). For these reasons, conilon coffee is grown along the Brazilian Atlantic coast, mostly in irrigated areas.

The levels of nutrients accumulated in coffee plants vary with the location, time of year, plant age, developmental stage, plant organs and tissues (Bragança et al., 2007), as well as with genotype, related with early, intermediate, late, and very late ripening cycles (Partelli et al., 2014). Climate may advance or delay the stages of fruit formation, greatly influencing the rates of nutrient accumulation in fruit (Laviola et al., 2009). Because fruit are the main nutrient sink during the reproductive phase of coffee plants (Rena & Maestri, 1985), nutrient supply should precede the peaks of fruit nutrient accumulation (Laviola et al., 2008; Partelli et al., 2014). In fact, coffee plant productivity is strongly influenced by an adequate mineral nutrition, which can also promote a better metabolic performance (for C-assimilation), and allows of the plant better response to environmental stressful conditions (Ramalho et al., 1995; Carelli et al., 2006; Ramalho et al., 2013; Martins et al., 2014).

Therefore, the understanding of the mineral dynamics during fruit development in conilon coffee plants, and their relationship with water availability, constitutes an important tool for this crop management, to determine the periods of higher-nutrient demands and planning of the crop fertilization.

The objective of this work was to evaluate the macronutrient concentrations and accumulation in fruit, and leaf macronutrient concentrations, over two years, in irrigated and nonirrigated conilon coffee plants.

Materials and Methods

The experiment was performed in two consecutive crop seasons, in the municipality of Itabela (16°42'13"S, 39°25'28"W, at 108 m altitude), in southern Bahia state (Atlantic region), Brazil. According to the Köppen and Geiger's classification system, the climate is classified as Aw, tropical with a dry winter and a rainy summer (Alvares et al., 2013). Maximum, mean, and minimum temperatures, global solar radiation, rainfall, and air relative humidity were recorded by an automatic meteorological station located 800 m from the experimental area (Figure 1). The meteorological data were employed to estimate the reference evapotranspiration (ETo), using the Penman-Monteith model (Allen et al., 1998).

Three-year-old plants of the *C. canephora* clonal variety Emcapa 8111 genotype 02 (Bragança et al., 2001), grown under full sunlight, spaced at 3.5x1.0 m, were used. The cultivation was performed with four productive stalks per hectare, under a cycle pruning program (Verdin Filho et al., 2014). The present study was conducted before the crop reached the pruning stage. Remaining crop handling procedures followed the technical recommendations for this crop.

The soil of the experimental area is a Latossolo Amarelo (Oxisol) (Santos et al., 2013) that was originally dystrophic, with a sandy loam texture. The chemical and physical characteristics at 0–20 cm soil soil depth are as follows: pH 6.25; available P, 28.5 mg dm^{-3}; K, 105 mg dm^{-3}; S, 15.5 mg dm^{-3}; B, 1.49 mg dm^{-3}; Cu, 1.9 mg dm^{-3}; Fe, 450 mg dm^{-3}; Mn, 20 mg dm^{-3}; and Zn, 4.2 mg dm^{-3}; Ca, 4.15 $cmol_c$ dm^{-3}; Mg, 1.55 $cmol_c$ dm^{-3}; potential acidity (H+Al), 2.85 $cmol_c$ dm^{-3}; soil organic matter content, 4.55 dag kg^{-1}; sand, 730 g kg^{-1}, silt, 110 g kg^{-1}; clay, 160 g kg^{-1}; and volumetric moisture contents at field capacity of 0.19 cm^3 cm^{-3} and at the permanent wilting point of 0.13 cm^3 cm^{-3}.

A experimental design was carried out in randomized complete blocks, in a split-plot

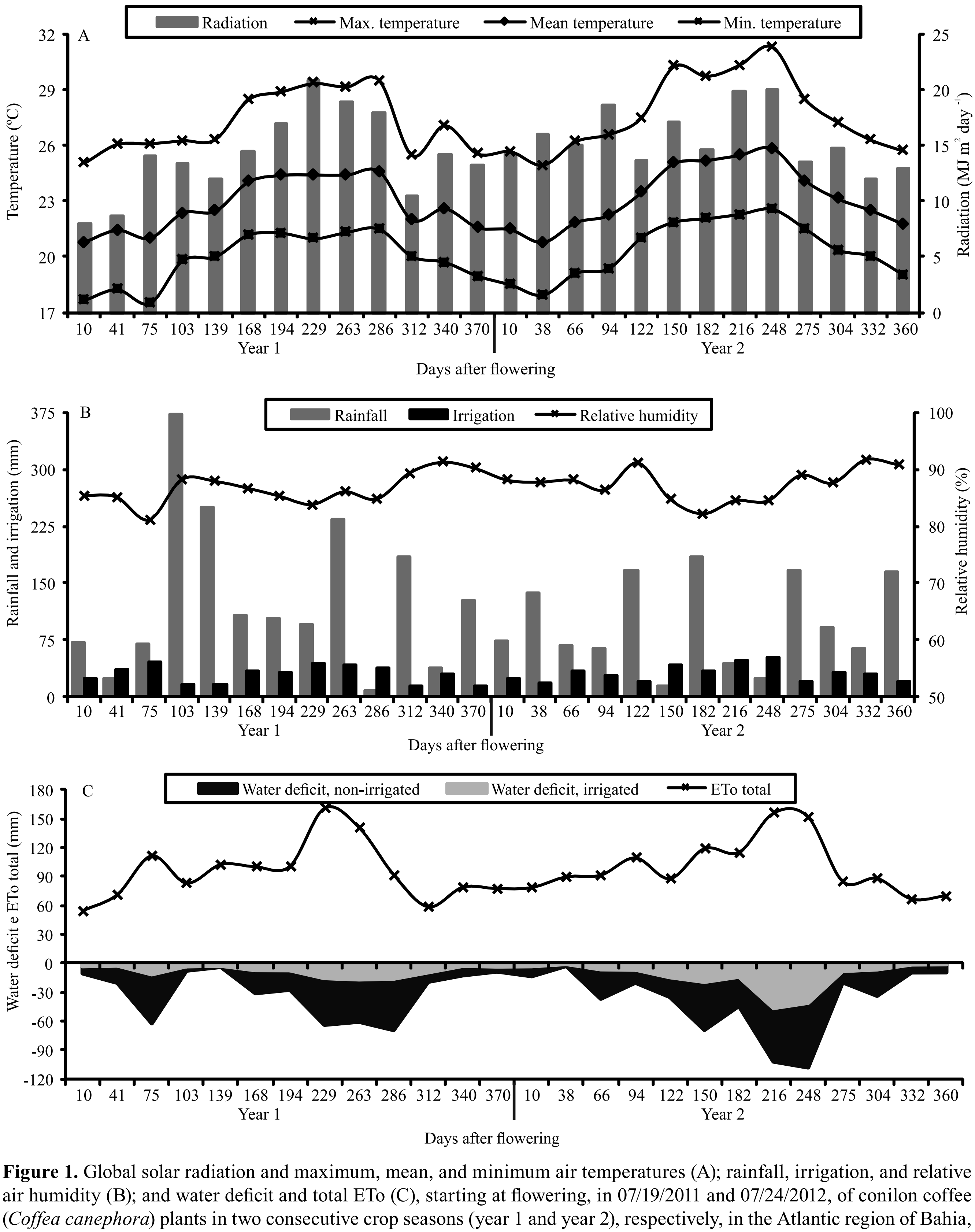

Figure 1. Global solar radiation and maximum, mean, and minimum air temperatures (A); rainfall, irrigation, and relative air humidity (B); and water deficit and total ETo (C), starting at flowering, in 07/19/2011 and 07/24/2012, of conilon coffee (*Coffea canephora*) plants in two consecutive crop seasons (year 1 and year 2), respectively, in the Atlantic region of Bahia, Brazil.

DOI: 10.1590/S0100-204X2018000900006

arrangement, with 14 replicates. The main plot factor was composed of irrigation and nonirrigation of coffee plants, and the split-plot factor was composed of different fruit and leaf collection times. For the nonirrigation treatment, plot irrigation was suspended in March 2011, four months before the beginning of collections, to allow of plant acclimation to the low-water availability. A surface drip irrigation system was used for the irrigated treatment, with one line of emitters per plant row, spaced 0.5 m apart, with a flow rate of 2.0 L per hour. Irrigation management was based on daily water balance calculated using the crop evapotranspiration (ETc = ETo × Kc), the rainfall measured at the experimental site, and the soil-water holding characteristics (Figure 1). The daily soil-water balance was also calculated for the two treatments (irrigation and nonirrigation), in order to determine the periods of water deficit.

Crop management consisted of weed control using herbicides and mowing, preventive plant health management, liming, and fertilization, with irrigation of the irrigated plot only. Both treatments received 500, 100, and 400 kg ha^{-1} per year N, P_2O_5, and K_2O, respectively, applied depending on plant requirements and phenological stages. For the irrigated treatment, fertilization was applied through weekly fertigation, and, for the non-irrigated treatment, by broadcasting, which was divided into five applications per year, in September, November, January, March, and June. Soil micronutrients were corrected by applying 2 kg ha^{-1} per year Zn, 1.0 kg ha^{-1} per year B, 2.0 kg ha^{-1} per year Cu, and 10 kg ha^{-1} per year Mn in a single application performed in August.

Fifty plagiotropic branches per plot, with 12 productive nodes and 24 fully developed leaves, were marked in 2011 and 2012, during pre-flowering stage. Plant material was collected at intervals of approximately 28 days, beginning from 10 days after flowering (DAF) until full fruit ripening. Five branches were randomly collected from each irrigation treatment, at each sampled date, and immediately separated in leaves, stem, peduncles, and fruit. Because of the reduced fruit size, branches collected up to 66 days after flowering exhibited peduncles, which were placed together with the fruitlet-phase fruit. Furthemore, 56 leaves were collected per treatment from the third and fourth nodes of the plagiotropic branches located in the upper middle third of the plants. However, these leaf collections were extended until ca. three months after fruit harvesting (22/07/2012 for the 1st year, and 20/07/2013 for the 2nd year), in order to investigate the pattern of leaf nutrient concentrations after fruit harvest.

The collected fruit and leaves were oven dried at 70°C until a constant weight was achieved. The N, P, K, Ca, Mg, and S concentrations in fruit and leaves were quantified in triplicate, and followed well established methods (Ramalho et al., 1995; Silva 2009; Martins et al., 2014). The N concentration in plant tissues was determined by the Kjeldahl method (hot acid digestion). For P, K, Ca, Mg, and S, a nitro-perchloric digestion was used; and P and S were determined by spectrophotometry in the ultraviolet-visible, K was determined by flame photometry, and Ca and Mg, by spectrophotometry of atomic absorption. Fruit nutrient accumulation was calculated based on the dry weight, the number of fruit per branch, and the fruit nutrient concentrations.

Leaf and fruit nutrient concentrations and fruit nutrient accumulation data were subjected to a variance analysis, at 1% probability, using the Assistat 7.7 beta (Silva, 2015). A regression analysis was performed for fruit nutrient accumulation. Graphs were plotted using the means and standard errors in SigmaPlot 11.0 (Systat Software, Inc, 2008).

Results and Discussion

The fitted curves for N, P, K, Ca, Mg, and S accumulation in fruit displayed similar (sigmoid) patterns, irrespectively of the irrigation treatment, on both crop seasons, although with different global accumulated contents (Figures 2, 3, and 4). Fruit macronutrient accumulation was considerably higher in the second than in the first crop season under both water regimes (Figures 2, 3, 4). This was likely associated with the greater number of fruit per node observed during the first crop season, causing higher competition for minerals, with reduced fruit growth and dry weight, causing smaller grain size, as compared with the second crop season.

All nutrients showed an initial phase of low-accumulation rates, followed by a phase with the highest accumulation rates, and a final phase with lower rates at the end of fruit formation (maturation). However, it should be noted that the last phase was

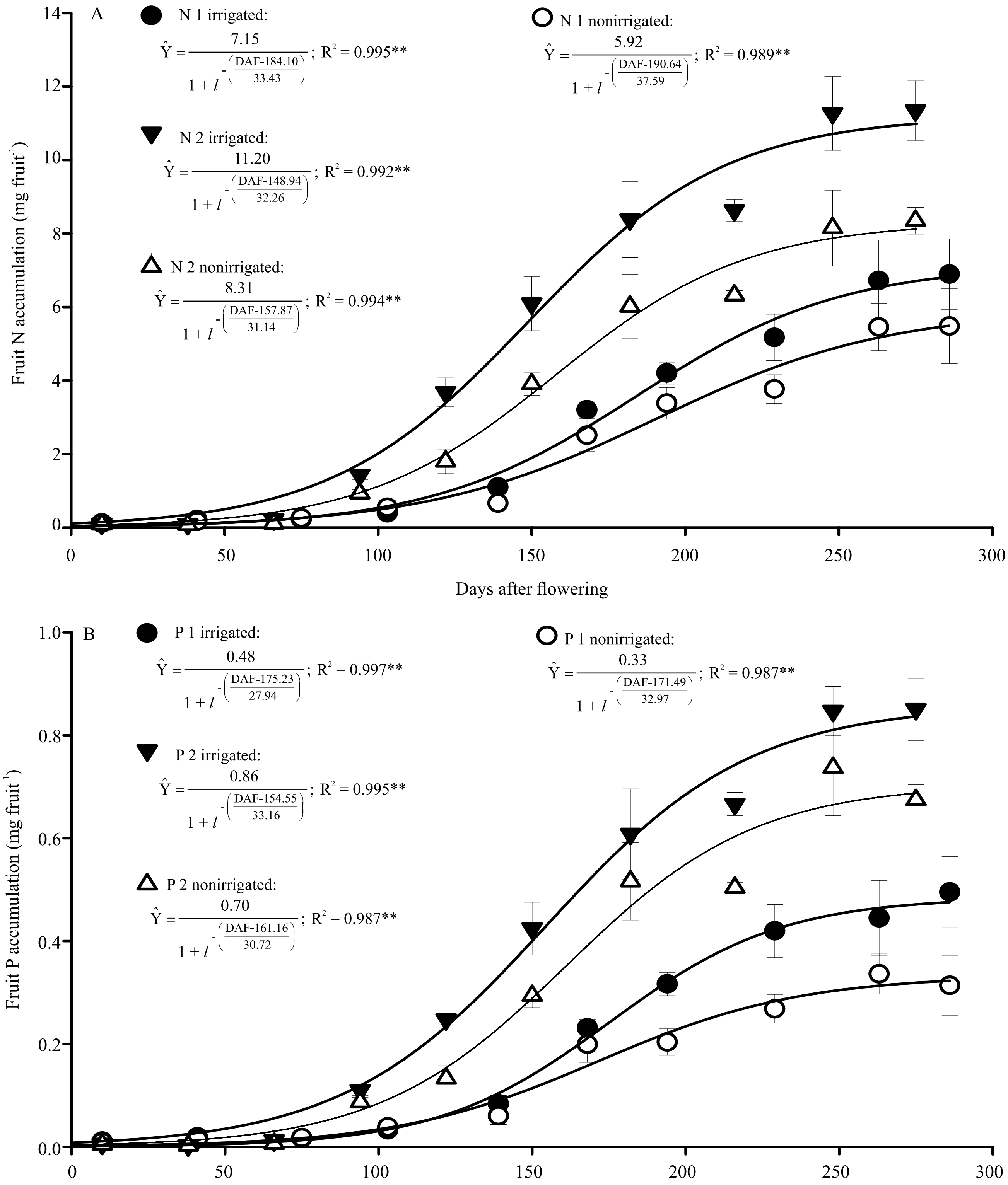

Figure 2. Accumulation of nitrogen (A) and phosphorus (B) in fruit of irrigated and nonirrigated conilon coffee (*Coffea canephora*) plants, from flowering to fruit ripening, in two consecutive crop seasons (Year 1 – N 1, P 1; Year 2 – N 2, P 2), in the Atlantic region of Bahia, Brazil. Each data point represents the mean±standard error (n=5). **Significant at 1% probability.

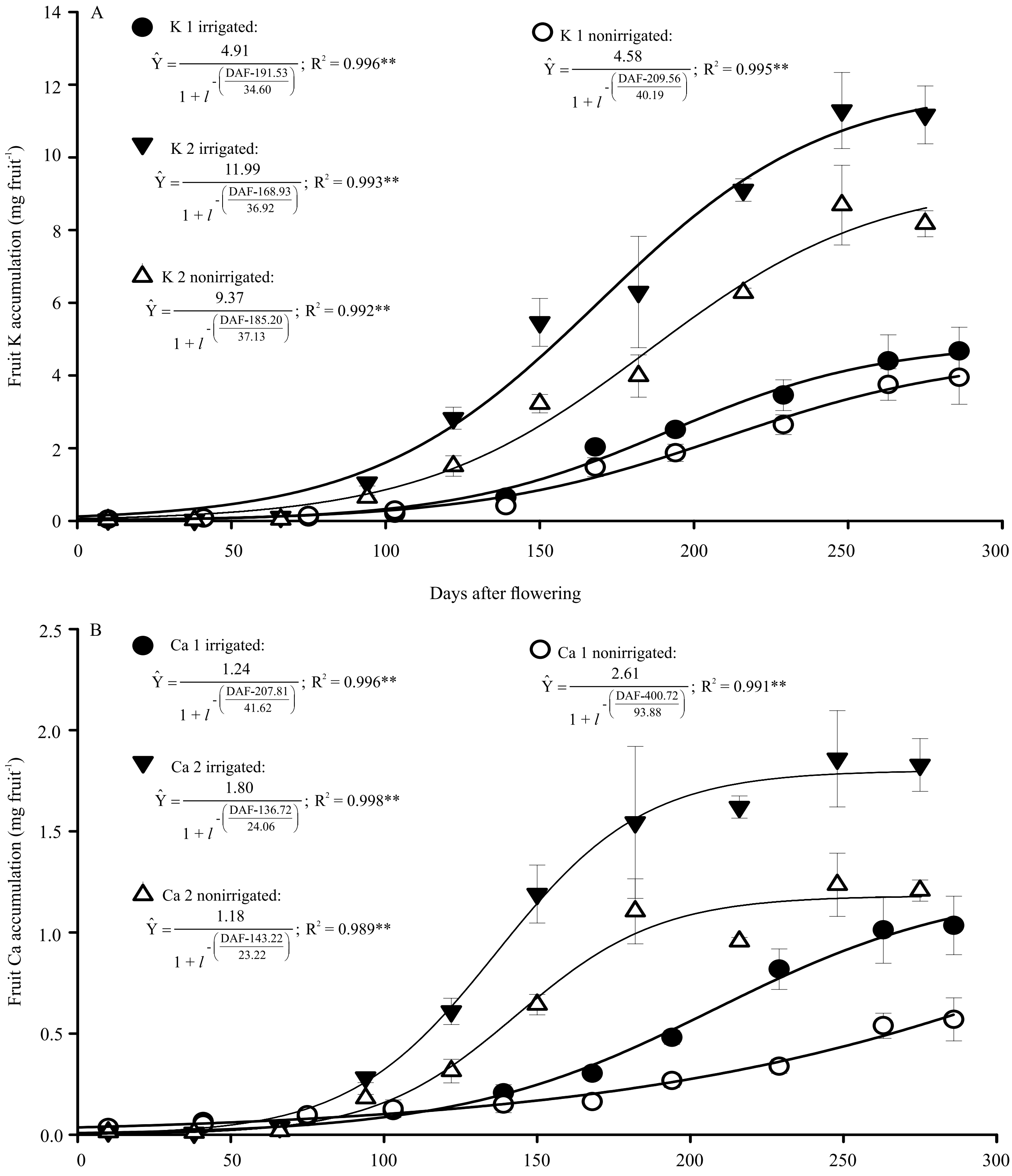

Figure 3. Accumulation of potassium (A) and calcium (B) in fruit of irrigated and nonirrigated conilon coffee (*Coffea canephora*) plants, from flowering to fruit ripening, in two consecutive crop seasons (Year 1 – K 1, Ca 1; Year 2 – K 2; Ca 2), in the Atlantic region of Bahia, Brazil. Each data point represents the mean±standar error (n=5). **Significant at 1% probability

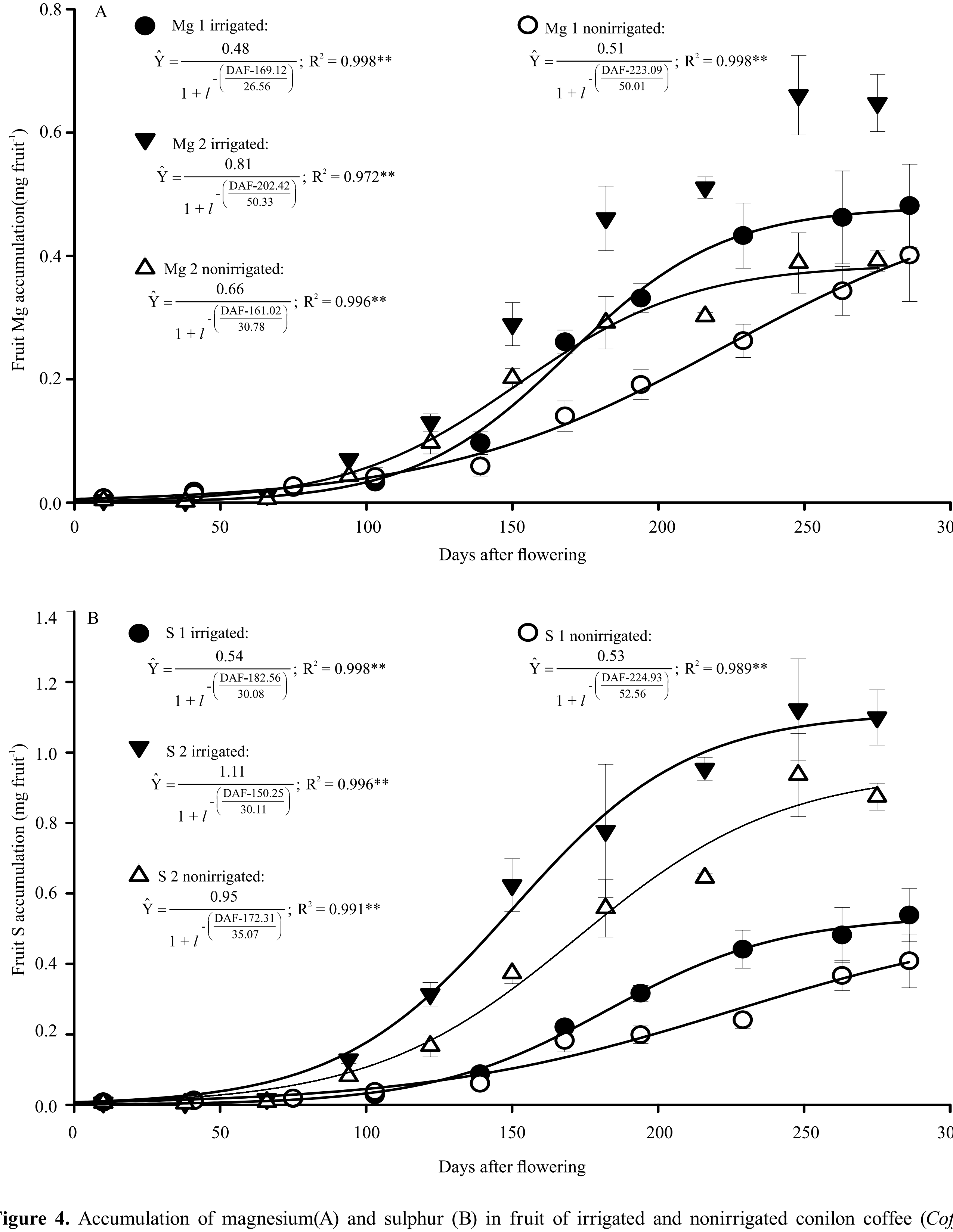

Figure 4. Accumulation of magnesium(A) and sulphur (B) in fruit of irrigated and nonirrigated conilon coffee (*Coffea canephora*) plants, from flowering to fruit ripening, in two consecutive crop seasons (Year 1 – Mg 1, S 1; Year 2 – Mg 2, S 2), in the Atlantic region of Bahia, Brazil. Each data point represents the mean±standard error (n=5). **Significant at 1% probablity.

less clear for Ca, Mg, and S, under nonirrigated conditions in the 1st year. Similar result was previously observed in conilon coffee plants grown in northern Espírito Santo state (Partelli et al., 2014). As to water availability conditions, in the two years, a higher-fruit accumulation was observed for N, P, K, Ca, Mg, and S contents in irrigated plants than in nonirrigated ones (Figures 2, 3, and 4). In the first three evaluations performed between 10 and 75 days after flowering (DAF), the fruit nutrient accumulation rate was very low, and there were no significant differences between water treatments. During this period, fruit were in the fruitlet phase, characterized by low growth and dry weight accumulation, with lower-nutrient accumulation in tissues (Dubberstein et al., 2016), as similarly noted in Arabica plants (Laviola et al., 2008). However, the rates of nutrient accumulation in the fruit can also occur at earlier stages, beginning 48 days after flowering, irrespectively of the length of the maturation cycle (Partelli et al., 2014).

The highest fruit-nutrient accumulation rates were observed from 100 to 250 DAF, on average, in the two years (Figures 2, 3, and 4). During this period, local climate is characterized by irregular rainfall distribution, increased air temperatures, high irradiance, and water deficits, especially during the summer season (Figure 1). Under such high irradiances, air temperature increases is considered one of the most limiting climatic factors (DaMatta & Ramalho, 2006), as it affects plant physiological processes and phenology (Petek et al., 2009; Rodrigues et al., 2016). Furthermore, water deficit can depress the photosynthetic C-assimilation (DaMatta & Ramalho, 2006) and affect the duration of coffee phenological stages, decreasing thermal requirements in degree-days, and accelerating fruit development (Petek et al., 2009).

Nitrogen was the most accumulated nutrient in fruit until ripening, in both water treatments and crop seasons (Figure 2 A), in agreement with observation in mature conilon plants (Bragança et al., 2007). These findings reflect the importance of N in fruit development, showing the benefits of N fertilization of coffee plants during their reproductive phase. Nitrogen accumulation rates in fruit increased between *ca*. 100 and 250 DAF. In the present study, the highest N accumulation occurred between the fifth and penultimate collections, a period that includes these phenological stages (Figure 2 A). Similar results were found by Partelli et al. (2014) for conilon coffee cultivars with late and very late maturation cycles.

Similarly to N, the highest P accumulation rates in fruit were observed between *ca*. 100 and 250 DAF, not phases (Figure 2 B). At the end of the fruit ripening phase, K accumulated as much as N in the second year, and showed the second highest-accumulation level in the first year (Figure 3 A). Since N and K accumulated in similar amounts and close patterns, it was considered that they should be applied together (Ramírez et al., 2002). Differences among water conditions were observed only in the first year, when irrigated plants showed significantly higher-K accumulation in fruit. This strong K accumulation was somewhat higher than the previous one reported for conilon coffee plants, in which it was the third highest accumulated mineral (Bragança et al., 2007). Observations in *C. arabica* 'Caturra' suggest the occurrence of two absorption peaks for K, with the accumulation of approximately 50% between 60 and 120 DAF, and another 20% between 210 and 240 DAF (Ramírez et al., 2002). Moreover, in partial contrast to N and P, the translocation of K to Arabica coffee fruits occurred at high rates at fruit ripening, as this mineral is required for the activation of several enzymes that are essential for the synthesis of organic compounds, which are synthesized during fruit ripening (Laviola et al., 2008). However, this pattern was not observed in the present study, as the highest-K accumulation was observed as beginning at 100 DAF and increasing until the fruit ripening phase at 280 DAF (Figure 3 A), thus, there is probably a significant difference for K accumulation among conilon and Arabica coffee.

Calcium was the third most accumulated element in fruit (Figure 3 B), although in some cases it can be the second highest-accumulated mineral in conilon coffee plants (Bragança et al., 2007). The highest accumulation rates of Ca (Figure 3 B) and Mg (Figure 4 B) in fruit were observed during *ca*. 150 and 200 to *ca*. 200 and 250 DAF (Figure 4 A). The highest sulphur accumulation rates occurred also in the first phases of the fruiting cycle of conilon coffee plants (Figure 4 B), similarly to what was reported for conilon coffee (*C. canephora*) (Partelli et al., 2014) and *C. arabica* 'Caturra' (Ramírez et al., 2002). However, Laviola et

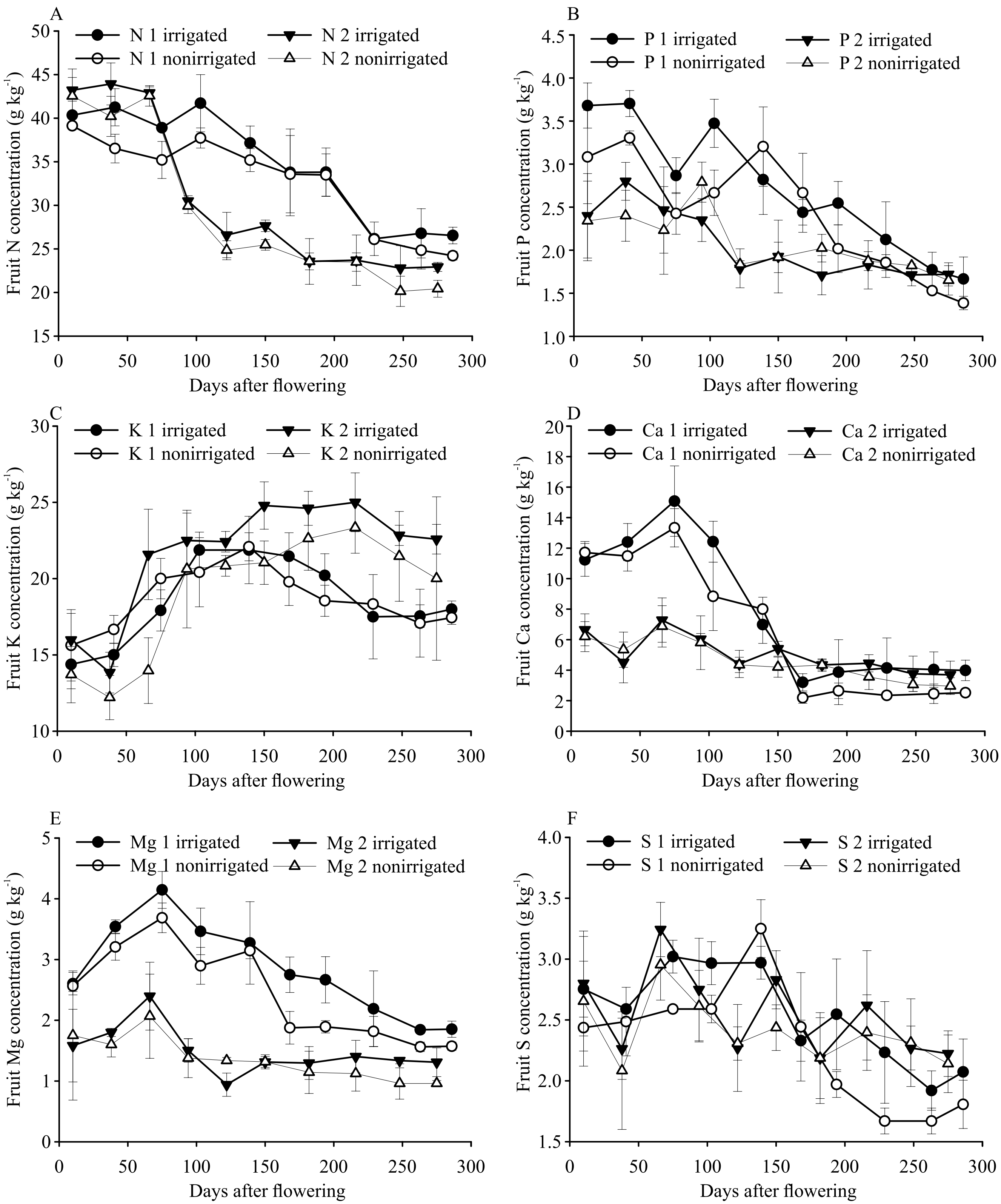

Figure 5. Concentrations of nitrogen (A), phosphorus (B), potassium (C), calcium (D), magnesium (E), and sulphur (F), in fruit of irrigated and nonirrigated conilon coffee plants, from flowering to fruit ripening, in two consecutive crop seasons (Year 1 – N 1, P 1, K 1, Ca 1, Mg 1, S 1; Year 2 – N 2, P 2, K 2, Ca 2, Mg 2, S 2), in the Atlantic region of Bahia, Brazil.

DOI: 10.1590/S0100-204X2018000900006

al. (2009) reported two S absorption peaks in Arabica coffee plants, grown in the Brazilian Zona da Mata region.

Fruit macronutrient concentrations varied greatly during the experimental period. For this reason, it was not possible to establish trend models (Figure 5). Nitrogen was the macronutrient exhibiting the highest concentration in fruit, followed by K and Ca, in both crop seasons, indicating the importance of these nutrients during fruiting in conilon coffee plants. The N, P, Ca, Mg, and S concentration patterns in fruit, along the year, were similar for irrigated and nonirrigated conilon coffee plants, with higher concentrations occurring in the initial phase of fruit development (Figure 5).

The highest-fruit concentrations of these nutrients fruitlet phase, due to the small increase in fruit dry matter. Still, the plants subjected to water shortage showed a tendency to lower the minerals concentration in some parts of the year, which is possibly related to a lower translocation through the transpiration flow due to a likely higher-stomatal closure. In fact, nutrient translocation into fruit occurs through mass flow resulting from high rates of water transport to fruit (Ramírez et al., 2002) in the well-watered plants. Following the initial stage, N, P, Ca, Mg, and S concentrations decreased between 100 and 250 DAF, showing some fluctuations, and reached the lowest values during fruit ripening (Figure 5). These decreases are related to a dilution effect of fruit nutrient contents because of an increase in fruit dry matter. However, K showed a distinct accumulation trend. The concentrations in fruit started low and greatly increased until reaching their highest values at 139 DAF, in the first crop season, and at 216 DAF, in the second crop season (Figure 5 C). C of K in fruit then began to decrease, showing the lowest values close to harvest. Concentrations of K in fruit were higher in the second than in the first crop season, especially starting at 150 DAF (Figure 5 C).

Similarly to the fruit-nutrient concentrations, trend lines could not be established for leaf-macronutrient concentrations due to their fluctuations during the experimental period, for both studied crop seasons (Figure 6). These fluctuations of leaf concentrations may have been influenced by the nutritional demands during fruit development, which tended to be higher during fruit expansion and grain filling (Partelli et al., 2014). Nitrogen was the nutrient found at the highest concentrations in the leaves, followed by Ca, and K (Figure 6).

The N and P concentrations in leaves showed close patterns, which were similar for both the irrigated and nonirrigated plants, with the highest concentrations in fruit in the fruitlet phase (Figure 6), when low translocation from leaves to fruit occurred. Along fruit development, N and P concentrations in leaves markedly decreased because of the high translocation of these nutrients into fruit, as also found in *C. arabica* (Valarini et al., 2005).

Since fruit are preferential nutrient sinks during the reproductive phase of coffee plants (Rena & Maestri, 1985), the lowest concentrations of N and P in leaves were observed at fruit harvest, when fruit were fully developed (Figure 6 A and B). Following fruit harvest, N and P concentrations in leaves clearly increased.

The concentration of K in leaves increased significantly between 10 and 100 DAF, in the first crop season, when the fruit were in the fruitlet phase, (Figure 6 C). Following this period, leaf-concentrations of K decreased markedly until harvest because of K translocation into fruit (Figure 5 C). This indicates a higher-K demand by conilon coffee plants, between the rapid expansion and grain filling/fruit ripening phases. Calcium concentrations in leaves decreased, and Ca concentrations in fruit were higher during the fruitlet phase, until 100 DAF, indicating the occurrence of Ca translocation into fruit during this phase (Figure 5 D). As fruit developed, Ca concentrations in them decreased (Figure 6 D), and Ca concentrations in leaves increased (Figure 6 D). A similar pattern was observed for Mg concentration in leaves (Figure 6 E). Foliar concentration of S varied little, and it was higher in the second than in the first crop season (Figure 6 F).

In general, conilon coffee plants exhibit a high-nutrient demand during the fruiting phase. The supply of nutrients to the plants should be sufficient to meet the nutrient demands of both fruit and vegetative organs. To improve the efficiency of fertilization and avoid nutrient losses, fertilization should be divided along the year in accordance with the periods of higher-nutrient demands by the crop, which vary with the plant developmental phases.

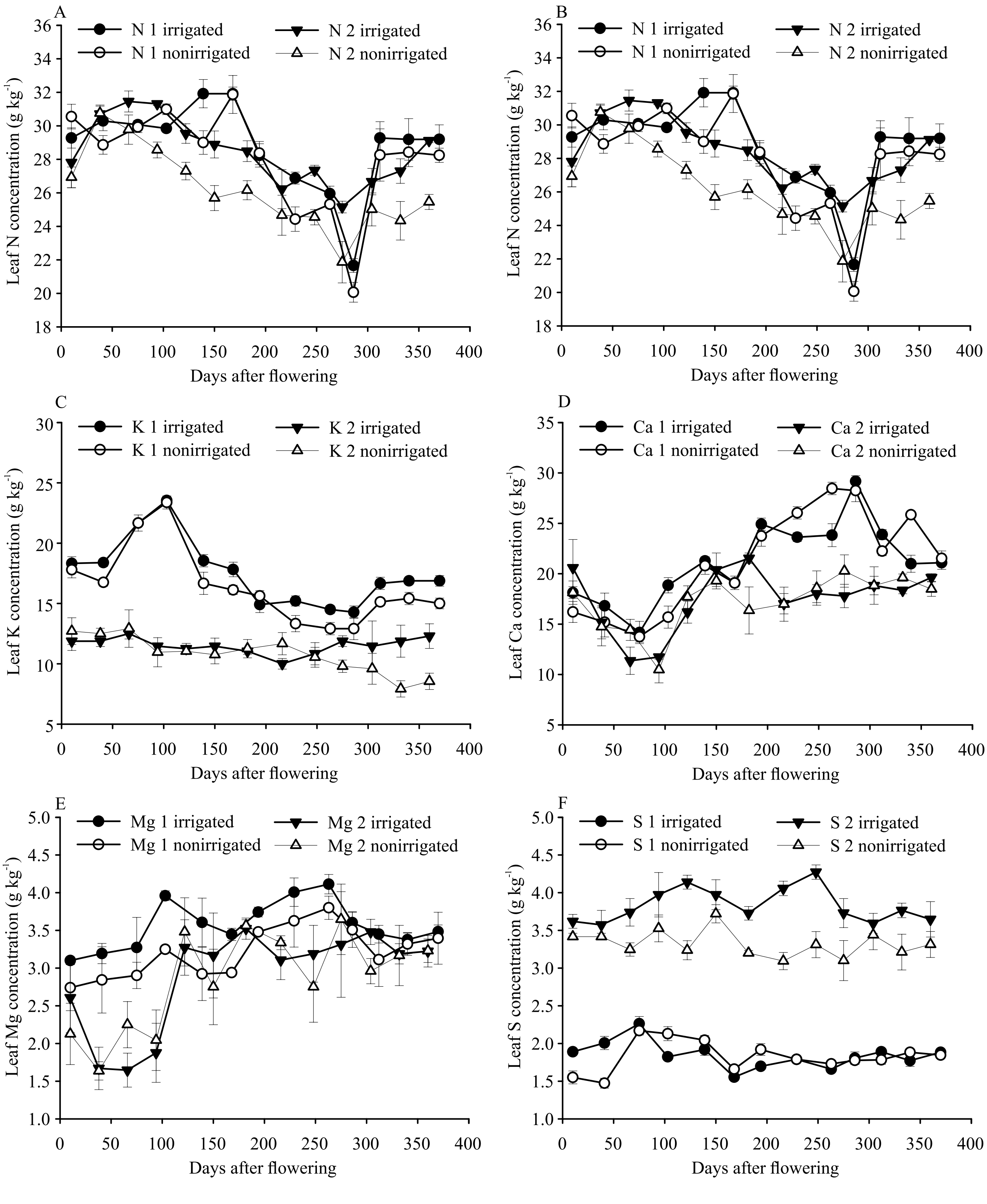

Figure 6. Concentrations of nitrogen (A), phosphorus (B), potassium (C), calcium (D), magnesium (E), and sulphur (F), in the leaves of irrigated and nonirrigated conilon coffee plants, starting at flowering stage, in two consecutive crop seasons (Year 1 – N 1, P 1, K 1, Ca 1, Mg 1, S 1; Year 2 – N 2, P 2, K 2, Ca 2, Mg 2, S 2), in the Atlantic region of Bahia, Brazil.

DOI: 10.1590/S0100-204X2018000900006

Conclusions

1. The accumulation curves N, P, K, Ca, Mg and S in fruit are similar in both irrigated and nonirrigated conilon coffee plants, and are best fitted by sigmoidal equations.

2. Well-watered plants show higher-fruit mineral accumulation.

3. Irrigation affects the macronutrient dynamics of fruit and leaves during the fruiting period of conilon coffee plants.

4. Nitrogen, potassium, and calcium are the macronutrients found in greater quantities in fruit and leaves of conilon coffee plants, irrespectively of water availability and fruiting phase.

Acknowledgments

To Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), to Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes), and to coffee producers Ademir Trevizani, Daniel Trevizani, and Luiz Antônio Covre, for support.

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Received on March 16, 2017 and accepted on November 29, 2017