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Production and Vegetative Development of Coffee Tress Grown under Solar Radiation and Fertilization Levels, During Years of High and Low Yield

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Abstract: The objective of the experiment was to evaluate the effect of the levels of photosynthetically active radiation (PAR) and nutrients on the production and vegetative characteristics of coffee trees in years of high and low yield. The coffee trees were covered, at the top and sides with shade screens (PAR reduction by 0, 16, 32 and 48%) and fertilized with either 100, 80, 60 or 40% of the recommendation from 2001 on. In 2005 and 2006, the following characteristics were determined in per branch basis: number of total nodes, size of the internodes, number of productive nodes, number of leaves and leaf area, besides one leaf area and tree production. Besides these variables, the following characteristics were determined in 2005: specific leaf area, berry mass, number of berries per tree, leaf area per berry, size and uniformity of maturation of the berries. In 2006, a dry branch index was determined. There was not any effect of the fertilization on any characteristics evaluated. With the increment of shading, it was observed an increase in the length of the internodes, leaf area, leaf area per branch and specific leaf area. There was a reduction in the production per tree and number of berries per tree with the increase of shading. The trees under the highest level of shade presented heavier and bigger berries than the trees under full sun. The trees under 48% of shade presented late and uniform maturation. In 2005, the leaf area per berry was higher in more shaded trees. In 2006, these trees presented fewer dead branches. The conclusions are: full sun condition results in coffee trees with shorter branches, a smaller leaf area per branch and smaller and thicker leaves. Shading favors the formation of fewer berries per tree and results in smaller production, although the berries are bigger and heavier. Coffee trees under high levels of shading present later ripening than the unshaded ones, although both conditions result in uniform berry ripening.

Key words: Photosynthetically active radiation, Leaf area, Berry mass, Maturation, *Coffea arabica*

INTRODUCTION

In agroforestry systems the production of wood and the increase of the local biodiversity are considered benefits that may compensate the decrease in coffee production [1]. Another advantage of these systems is the possibility of trading coffee in special markets, which provide a better and more stable price for coffee with high quality or produced under favorable conditions for biodiversity [2], although the effects of shading on beverage quality may be ambiguous [3].

The level of coffee yield trees in agroforestry systems presents great variation due to the great diversity of weather, soils and management conditions in which the crop is grown [4]. There is a sharp decrease in the production of the coffee trees associated to trees when in comparison to coffee trees under direct sunlight in Minas Gerais state, Brazil [5]. In Paraná state, Brazil, the intercropping of coffee with Pigeon pea (*Cajanus cajan* L.) resulted in trees with a smaller number of nodes and fewer plagiotropic branches and a decrease in the berry production, although berries were larger than the ones in coffee trees under full sun [6]. Other studies did not find any differences of production between shaded or full sun coffee crops [7-9].

Coffee trees present adaptability to low luminosity conditions, but the competition for light is one of the most limiting factors for the production under agroforestry systems [4]. Under conditions of restricted water and nutrients availability, the negative effect of the lowest radiation on production becomes more evident [10].

In agroforestry systems the effects of light limitation and competition for water and nutrients are tangled, what makes the results on shaded coffee performance look contradictory and non-conclusive [4]. More knowledge about the vegetative development and

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productive response of coffee trees under different nutrient and light conditions would contribute for the balance between yield and biodiversity and resource conservation. The objective of this work was to evaluate the productive behavior and the vegetative development of coffee trees under limiting conditions of PAR and fertilizer supply in years of high and low production.

MATERIALS AND METHODS

General Aspects: The work was carried out in Viçosa (MG - Brazil) (20° 45' South and 42° 51' West; 693 m.a.s.l.). The region presents cold and dry winter and hot and rainy summer, with average temperature of 19.4°C (maximum 26.4°C and minimum 14.8°C); average precipitation of 1221 mm $year^{-1}$ and average global solar radiation of 1416 kJ m^{-2} day^{-1}.

The soil is classified as dystrophic red-yellow latosol, with 40% declivity and northeastern exposition. Before the beginning of the experiment the soil presented: pH (H_2O) 5.1; 3.84 $cmol_c$ dm^{-3} exchangeable basis and 3.94 $cmol_c$ dm^{-3} effective cation exchange capacity (t); 36.4 and 134 mg dm^{-3} of P and K respectively and 2.5 and 1.0 $cmol_c$ dm^{-3} of Ca and Mg. The aluminum content was 0.1 $cmol_c$ dm^{-3} and the H+Al content was 4.3 $cmol_c$ dm^{-3}.

The *Coffea arabica* L. trees, Catuaí Vermelho cultivar (CH 2077-2-5-99), were planted in 1989 and received a drastic prune (30 cm aboveground) in 1999. The spacing consisted in 1 m between trees and 3 m between rows, with 3,333 trees ha^{-1} density.

Treatments and Experimental Design: The coffee trees underwent four shade levels (0, 16, 32 and 48% of Photosynthetically Active Radiation, PAR) and four levels of fertilization (100, 80, 60 and 40% of the recommended amount for the crop in full sun). The 4x4 factorial design was set up in casualized blocks with 3 replicates. The blocks were established perpendicularly to the inclination of the field.

Each plot, formed by 12 trees (10 border trees and 2 measured ones in the inner part of the plot), was covered and encircled with shade screens, which allowed the blocking of the Photosynthetically Active Radiation (PAR) in the previously mentioned levels. The plots were distributed in the experimental area according to the position of the sun during the day and the year, preventing shade interference amidst them. The fertilization and liming (Table 1) were applied based on the yield estimate and on the soil analysis of the unshaded trees.

Table 1: Yield estimates and doses of fertilizer and limestone applied in the plots under full sun with 100% of the fertilization recommendation for 2005 and 2006

Year	Yield estimate (bags ha^{-1})	N (kg ha^{-1})	P	K	Limestone (Mg ha^{-1})
2004 – 2005	66.0	340	20	450	0.65
2005 – 2006	0.0	200	20	150	0.67

The fertilizer was applied every year, divided in three applications in the months of November, December and January. The shade screens were placed in December, 2001. The control of weeds was carried out three times a year, through November to March. When necessary, the rust (*Hemileia vastatrix*) incidence and the ladybug infestation (Coccinelideae) were controlled in February with copper oxychloride or mineral oil respectively.

Evaluations

Availability of Photosynthetically Active Radiation: The real levels of shade were determined by the blocked PAR percentage by the shade screen, measured by the bar ceptometer (Sunfleck ceptometer type CEP®, Delta-T Devices Ltd, England) above the canopy of the coffee trees, at the beginning of the experiment. The average incidence of PAR at noon in sunny days was: 1050 µmol m^{-2} s^{-1} on full sun exposure trees, 882, 714 and 546 µmol m^{-2} s^{-1} for 16, 32 and 48 % shade, respectively.

Vegetative Development and Production of Coffee Trees: The vegetative development of the coffee trees was evaluated in 2005 and 2006, in four plagiotropic branches per tree. The branches were located in the middle third of the trees, oriented to the north, south, east and west directions. In these branches, we counted the number of total and productive nodes, the number of leaves (> 8 cm) and the length and width of the leaf (> 8 cm). The area of each leaf was determined from the dimensions of the rectangle circumscribed to the leaf limbs, adjusted by the equation Y= 0.667 X, where: Y= estimated leaf area (cm^2), X= Area of its circumscribed rectangle (cm^2), [11]. The leaf area of the branch was determined multiplying the average leaf area by the number of leaves per branch. The leaf area per berry was determined by dividing the leaf area of the branch by the number of berries present in each branch in the first month of the harvest. The length of the internodes was calculated by the division of the length of the branch by the number of total nodes.

The development of the leaf area of the branch was determined twice a year, with measurements carried out in the end of the period in which the tree reaches the maximum (March) and the minimum (September) leaf area, under the studied conditions [12]. The length of the internode was determined at the end of the period of greater growth (March).

In 2005, a year of high production, it was determined the specific leaf area (cm^2 g^{-1}). For such, eight leaves of the third or fourth pair of leaves in the branch, located in the middle third of the tree, were collected. The leaf area was measured by the LI-COR 3000® leaf area meter (Licor Inc., Lincoln, Nebraska, US) and then, the dry mass per leaf was determined.

In 2006, a year of low production, the number of dry branches of the sixteen branches evaluated per plot were counted in order to determine the number of dry branches per tree.

At harvest in 2005, the berries were picked in the cherry stage, in April, May, June and July. The collected berries were weighed and the production of fresh coffee per tree was determined. Later, the berries were dried until they reached 12 % of humidity. A sample of dry cherry berries from each plot was taken to be weighed and counted in order to determine the dry berry mass (g). The number of berries per tree was calculated based on the ratio between the production per tree and the mass of berries. The conversion factor of fresh cherry berry into dry cherry berry (0.36) was calculated and the value converted into hulled coffee adopting the conversion of 1g dry cherry coffee = 0.5g hulled coffee. The production was expressed in grams of hulled coffee per tree.

It was determined the percentage of maturation of berries per month, based on the ratio between the weight of the berries collected in each month from April to July and the total production (g $tree^{-1}$) of berries in the cherry stage. Four samples composed of berries of trees under each shade level were collected and the percentage of berries with sieve size of 17/18 was determined.

Analysis of the Data: The data were submitted to the variance analysis followed by regression ($P<0.05$). The models were chosen based on the significance of the regression coefficients, using the "F" test, in the determination coefficient and the phenomenon in study.

RESULTS

There was no significant effect of fertilizers rates application on the evaluated variables. The number of total nodes was decreased with shading in both years (Table 2). There was no effect of the shading on the number of productive nodes per branch, which presented an average value of 6.15 in 2005 and 1.44 in 2006. In 2005, there was an increase in the length of the internodes with the increase of shading (Table 2). In 2006, there was no shade effect on this variable, which presented the average value of 6.77 cm.

In 2005, the leaf area per branch increased linearly with the increase of shading, in periods of both greater and smaller growth (Figure 1). The adjusted equations that describe this behavior are found in Table 2.

Table 2: Adjusted regression equations of the effect of the percentage of PAR blockage (S) on the variables: number of total nodes in 2005 and 2006, maximum and minimum leaf area per branch (cm^2), number of leaves, maximum and minimum leaf area (cm^2); leaf area per berry (cm^2), specific leaf area (cm^2g^{-1}) in 2005 and in 2006 on the variable number of dry branches, in coffee trees (*Coffea arabica*)

Variable		Adjusted equation	R^2/ r^2
Number of total nodes	2005	Y = 17.60 – 0.08*S	0.85
	2006	Y = 25.91 – 0.14*S	0.81
Leaf area per branch	Maximum	Y = 327.27 + 6.15* S	0.81
	Minimum	Y = 29.59 + 2.70* S	0.67
Number of leaves	Maximum	Y = 10.37	-
	Minimum	Y = 1.35 + 0.049* S	0.56
Leaf area	Maximum	Y = 34.91 + 0.42* S	0.91
	Minimum	Y = 20.75 + 0.47* S	0.72
Leaf area per berry		Y= 10.12 – 0.19 S + 0.0064* S^2	0.63
Specific leaf area		Y = 120.45 + 0.36* S	0.76
Length of the internode		Y = 2.79 + 0.01* S	0.81
Number of dry branches		Y= 1.06 + 2.74* S	0.59

* P<0.05.

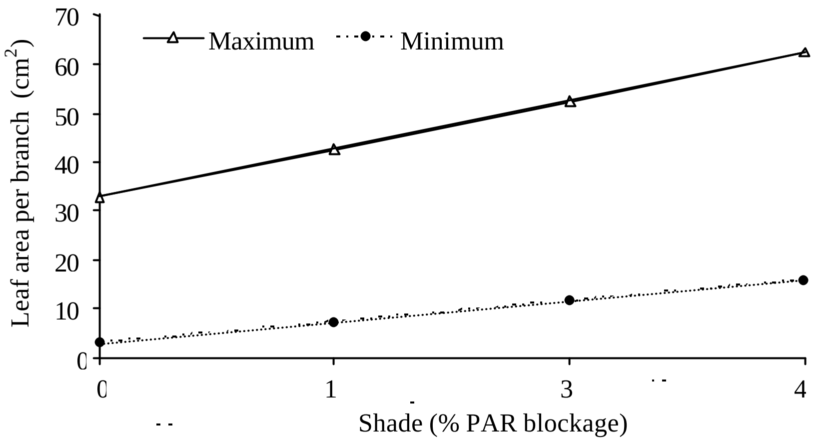

Fig. 1: Maximum (March) and minimum (September) leaf area per branch of coffee trees as a function of PAR blockage in 2005

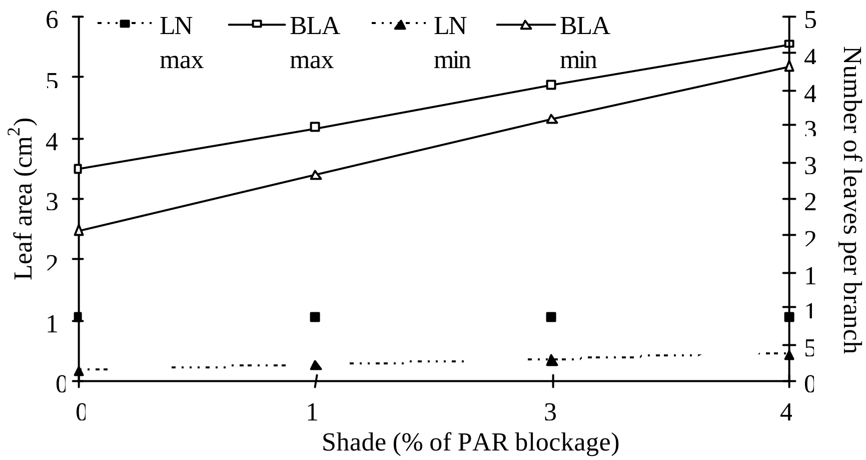

Fig. 2: Maximum (LN max) and minimum (LN min) number of leaves per branch, maximum (BLA max) and minimum (BLA min) leaf area per branch of coffee tree as a function of PAR blockage in 2005

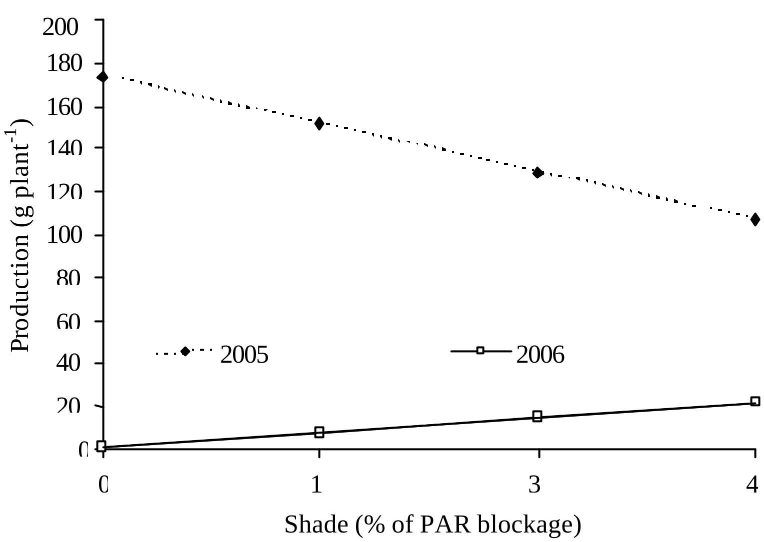

Fig. 3: Production of coffee tree as a function of PAR blockage in years 2005 and 2006

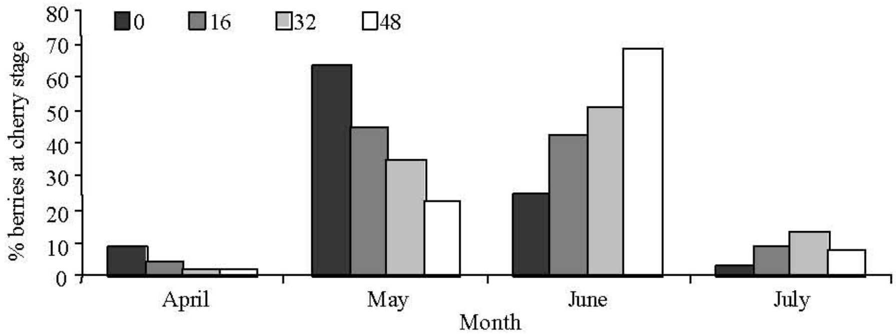

Fig. 4: Maturation of berries during harvest months in year 2005 in coffee trees under 0, 16, 32 or 48% of PAR blockage

Table 3: Adjusted regression equations of the effect of the percentage of PAR blockage (S) on the variables: Production per tree (g hulled coffee per tree), Mass of one dry berry (g), number of berries per tree and berry size (% sieve = 17/18), in coffee trees (*Coffea arabica*)

Variable	Year	Adjusted Equation	R^2/r^2
Production per tree	2005	Y = 1739.63 – 13.97* S	0.78
	2006	Y = 5.64 + 4.53* S	0.64
Berry mass	2005	Y = 0.44 + 0.001* S	0.59
	2006	Y = 0.021 + 0.003* S	0.83
Berries per tree	2005	Y = 7789.75 – 73.10* S	0.83
	2006	Y = 67.97 + 50.63* S	0.58
Berry size	2005	Y = 47.6 + 0.42* S	0.91

* $P<0.05$

Table 4: Adjusted regression equations of the effect of the percentage of PAR blockage (S) on the percentage of berries in cherry stage in April, May, June and July in coffee trees (*Coffea arabica*) in 2005

Month	Adjusted Equation	R^2/r^2
April	$Y = 9.82 - 0.45\,S + 0.0058^*\,S^2$	0.59
May	Y = 60.32 – 0.77* S	0.67
June	Y = 25.82 + 0.84* S	0.74
July	Y = 7.84	-

* $P<0.05$

In 2005, the number of leaves at the end of the period of greater growth was not affected by the levels of shading, while the leaf area increased with the increase of shading (Table 2). At the end of the period of smaller growth, the leaf area increased, from 21.6 to 42.7 cm^2 with the increase of shading (Figure 2).

The leaf area per berry increased with shading (Table 2), varying between 10.1 cm^2 per berry in the trees under full sun and 16.0 cm^2 per berry in the trees under 48% of shading. With the increase of shading, it was also observed the increase of the specific leaf area (Table 2). In 2006, the more shaded trees presented fewer dry branches than the trees under full sun (Table 2).s

In 2005, the production and the number of berries per tree decreased with the increase of shading (Table 3). The trees under full sun presented a production of 1.74 kg of hulled coffee, while the trees under 48% of shading presented 1.07 kg, which represents a reduction of 38.5% in production. However, the mass and the size of the berries increased with shading (Table 3).

The production in 2006 presented an opposite trend to what had been observed in 2005 (Figure 3). In 2006, the production of the trees under 48% of shading was 223.25 g $tree^{-1}$ and that of the trees under full sun was 5.64 g $tree^{-1}$ of hulled coffee, which represents a reduction of 97.5% in production (Figure 3).

In 2005, the maturation of berries occurred later in the trees under 48% of shading. Most berries of the trees under full sun reached the cherry stage in May (63%), while the berries of the trees under 48% of shading presented more berries in cherry stage in June (68%) (Table 4). There was not ripening uniformity in the trees under16 and 32% of shading (Figure 4).

The berries were larger in the trees under 48% of shading, which presented 67.8% of the berries matching sieve 17/18 or higher, while the unshaded trees presented 47.6% of berries in this sieve size (Table 3).

DISCUSSION

The absence of fertilization application effects on the variables evaluated may be explained, in part, by the greatest answer variability observed in the coffee trees when in field conditions [13]. Another possible cause for the absence of the effect of fertilization in the experiment could be the presence of nutrient reserves in the soil of the trees that presented a small berry load. This fact was observed after the harvest in 2005 (high yield year), when the K average content was 62 mg dm^{-3} in the soil of the plots under full sun, while in the plots under 48% of shading the K average content was 94 mg dm^{-3}. The presence of nutrient reserves in the soil, mainly K, may indicate that the recommendation of fertilization for coffee trees under full sun conditions exceeds the necessary dose for the shaded trees.

The greatest internodes length and the greatest number of total nodes observed in the shaded trees in 2005 indicate that these trees reached greater size than the trees under full sun. Nevertheless, it does not necessarily mean greater accumulation of mass [10] but just a result of branch etiolation.

In 2005, the leaf area per branch at the end of the greater growth period was influenced by the size of the leaves, while the leaf area per branch in the end of the cold and dry periods was influenced by both the leaf area and the number of leaves. It indicates a greater retention of leaves in the shaded trees, in comparison to the trees under full sun during the cold and dry season of the year under similar weather conditions [5]. The smallest loss of leaves in the shaded trees during the dry and cold period may indicate less water stress in these trees. The fall of leaves during the cold and dry season of the year is attributed to the increment in the production of ethylene and the reduction in the concentration of auxins, as an answer to the water stress [10].

In 2005, it was observed that the leaves present in the shaded trees were thinner than those in the trees under full sun, as indicated by the values of specific leaf area. The etiolation, together with the formation of larger and thinner leaves, is one of the mechanisms of adaptation to the lowest solar radiation conditions, which allow the greatest capture of the radiation available [14]. Large leaves, with thin palisade and lacunar parenchymas and abundant intercellular spaces, facilitate the absorption of radiation and increase the changes that this solar radiation is absorbed by chloroplasts. Coffee trees that grow under full sun present small and thick leaves, with more stomata than the shaded trees [6]. However, the trees under full sun may present a greater accumulation of dry mass in the leaves, since the high load of berries stimulates the photosynthesis and the formation of photoassimilates [15], although the total branch and leaf growth is smaller in the years of a high berry load. In coffee trees with great load of berries there is four times more allocation of carbohydrate in the berries than in the branches [16]. In the experiment, the high load of berries in 2005 probably reduced the availability of carbohydrates reserved for the formation and growth of branches and of leaf area in the subsequent cycle, which, by its turn, caused low production of berries in 2006.

The productive response of the coffee trees to shading depends in great part on the berry load capacity, which is influenced by the weather and soil conditions and the handling procedures of each site. In years with high yields as in 2005, the increase of shading results in drop in production, as already reported in Brazil by Morais et al [17] and Colombia by Farfan and Mestre [18], who relate that in coffee trees with the increase in the number of intercropped trees from 70 to 278 trees per hectare, the production per tree decreased from 1.033kg to 0.047 kg of hulled coffee. On the other hand, in coffee trees with low production levels, it can be seen an increase in production with the increase in shading, as observed in Mexico by Soto-Pinto et al [19]. They report that production rose from 0.375 kg of hulled coffee per tree to 0.750 kg when shade increased to 48%. In production systems with low intensity of intervention, the productive capacity of the coffee trees under full sun may not be completely explored, reaching production values similar or even lower than those of the shaded coffee trees. The variation of production of the shaded coffee trees is more influenced by factors such as handling procedures, the objective of the farmer or the intensity of inputs applied than the solar radiation available for the trees [20].

The fact that the shaded trees have the same number of productive nodes as the trees under full sun and fewer berries per tree demonstrates that the difference in the production was also due to the formation of fewer berries per productive node. In Paraná state, Brazil, the 50% shading during floral bud development (April to October) did not affect berry growth and development or yield [21]. In our experiment, the coffee trees were shaded during all year around, for six years and the results suggest the reduction of the stimulus for flower bud differentiation, caused by the low incidence of solar radiation [10], although an opposite effect in different coffee cultivar in Mexico is reported by Lin [22].

There is a great argument about the shading effect on the reduction of the photosynthetic rate of shaded coffee trees. Experiments carried out in isolated leaves report a lower liquid photosynthesis rate in the shaded leaves than in the leaves under full sun [6]. However, there is no information about the photosynthetic behavior of the whole tree or the behavior of the photosynthesis over the day in different seasons and, the shaded trees may present twice the value of the photosynthetic rate of the trees under full sun, in rainy and cloudy days [10]. This is very important under the conditions of the experiment, since the greatest demand for nutrients from the berries, in the stage of its fast filling, occurs during the hot and rainy season of the year. On the other hand, in the winter season, a sharp decline is observed in the photosynthetic rate in the trees under full sun conditions [23]. The canopy of the tree in the agroforestry system generates microclimatic conditions that reduce the extremes in temperature [24]. This could reduce the drop of temperature in the system during the cold and dry season of the year. From this point of view, during the winter, the shaded trees would have an advantage in terms of photosynthesis, in comparison to the trees under full sun. The reduction of the photosynthetic rate of the shaded trees may be related to the lowest formation of berries, which demand less photoassimilates [25].

Another characteristic frequently observed in the shaded coffee trees is the late and non-uniform ripening, which increases the costs or reduces the quality of the harvest. In the experiment, although late ripening was observed in the trees under 48%, it was uniform and the highest percentage of ripe berries was observed one month after the same occurrence in trees under full sun. The main cause for the lack of uniformity in the ripening of the berries of coffee is the rotation of short drought periods and rain, as frequently observed in regions with equatorial weather, where the flowering season may vary from 12 to 15 weeks [26]. In the present work, shading may have reduced the effect of water stress on the trees, limiting the synchrony in the opening of the flower buds. On the other hand, the slow ripening of the berries in the trees under a higher level of shade may have compensated this effect, allowing most berries to be found in the cherry stage in June. Other study was carried out in Costa Rica, it was also observed a late flowering and larger berries in the shaded trees [27]. The late ripening of the berries of the coffees trees under 48% of shading may also indicate the delay of the phonological cycle, as a consequence of the drop in the temperature of the leaves in the shaded trees.

The berries of the trees under full sun that ripens more quickly may have incomplete ripening and low beverage quality. The incomplete maturation in berries with fast ripening presents high content of chlorogenic acid and trigonelline, which increase the beverage astringency [28]. The highest content of saccharose, present in the berries of trees that are under shading conditions, or planted in places of higher altitude, is responsible for the improvement in the quality of the berries of *C. arabica* var. Catuaí [29].

In the trees under full sun, the competition for carbohydrates among the berries may have affected the size of the berries [17, 6]. In 2005, there was a low leaf area x berry relation in all the trees. The trees under full sun present 10.12 cm^2 of leaf area per berry and the trees under 48% of shade, 15.82 cm^2 per berry. It has been reported that 20 cm^2 of leaf are necessary to support a berry without harming the vegetative growth [15]. This explains the death of branches observed in 2006, which was lower in trees at 48% of shading. The death of branches is usually a consequence of the overload of berries in the trees due to the formation of insufficient photoassimilates to support the branches [15]. The death of branches in 2006 also caused the formation of a smaller number of berries, which were lighter than those obtained in 2005 in all the treatments.

CONCLUSIONS

- The coffee trees that grow under full sun conditions present shorter branches, with a smaller leaf area per branch and smaller and thicker leaves.
- Shading favors the formation of fewer berries per tree and consequently, smaller production. However, the berries are bigger and heavier.
- Coffee trees under high levels of shading present later ripening than the unshaded ones. In both cases, the coffee trees present a uniform ripening.

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