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Growing *Coffea canephora* in agroforestry systems with Brazilian firetree, Brazil nut, and teak

Cultivo de cafeeiro *Coffea canephora* em sistemas agroflorestais com bandarra, castanheira-do-brasil e teca

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Highlights

Coffea canephora cultivation in agroforestry systems can be productive.
Bertholletia excelsa can be used in afforestation of *Coffea* canephora plantations.
Schizolobium parahyba is not suitable for intercropping with *Coffea canephora.*

Abstract

Planting coffee in agroforestry systems (AFSs) provides diverse advantages to farmers interested in producing environmental services, such as increased local biodiversity, reduction in soil erosion, improvement in water infiltration into the soil, and regulation of climate extremes. It can also be economically attractive due to the possibility of serving alternative markets that have higher and more stable prices for coffees integrated into alternative systems and the generation of products complementary to coffee. This study aimed to evaluate the effects of different planting densities of three forest species on the composition of AFSs with coffee plants under the conditions of the southwestern Amazon region. The study was conducted from November 2014 to June 2021 in the experimental field of Embrapa in Ouro Preto do Oeste, RO, Brazil. The coffee plants were intercropped with three forest species: i) Brazilian firetree (*Schizolobium parahyba* var. *amazonicum*), ii) Brazil nut (*Bertholletia excelsa*), and iii) teak (*Tectona grandis*). The treatments used in each experiment were four plant densities of plants: zero (coffee plants only, in full sun), 111 plants ha^{-1} (10 × 9 m), 222 plants ha^{-1} (10 × 4.5 m), and 444 plants ha^{-1} (5 × 4.5 m). The experiments were conducted in a split-plot arrangement, with plots consisting of

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plant densities and subplots consisting of harvest periods (crop seasons). The experimental design was completely randomized, with nine replications. The part of the plot used for data collection consisted of one planted row with 12 coffee plants. The average and accumulated productivities of coffe plants were evaluated over five harvests (2017-2021). Afforestation of the coffee field with Brazilian firetree plants reduces the mean yield and cumulative yield of *C. canephora* 'Conilon' in the first five commercial crop years. Brazil nut and teak planted at densities of up to 222 trees per hectare did not lead to a reduction in the mean and cumulative yield of coffee plants.
Key words: Amazon. Planting densities. Conilon. *Schizolobium parahyba. Bertholletia excelsa. Tectona grandis.*

Resumo

O plantio de cafeeiro em sistemas agroflorestais proporciona diversas vantagens aos agricultores interessados na produção de serviços ambientais, tais como; o aumento da biodiversidade local, redução da erosão do solo, melhoramento da infiltração de água no solo e regulação de extremos climáticos. Também pode ser economicamente atraente pela possibilidade de explorar mercados alternativos, que apresentam preços mais altos e estáveis para cafés implantados em sistemas alternativos e pela geração de produtos adicionais ao café. Objetivou-se, com este estudo, avaliar os efeitos de diferentes densidades de plantio de três espécies florestais na composição de SAF's com cafeeiros nas condições da Amazônia Sul Ocidental. O estudo foi conduzido no campo experimental da Embrapa em Ouro Preto do Oeste – RO, no período de novembro de 2014 a junho de 2021. Os cafeeiros foram consorciados com três espécies florestais: i) bandarra (*Schyzolobium paranyba* var. *amazonicum*); ii) castanheira-do-brasil (*Bertholletia excelsa*), e iii) teca (*Tectona grandis*). Em cada experimento, os tratamentos utilizados foram quatro densidades de árvores: zero (cafeeiros a pleno sol); 111 árvores ha^{-1} (10 m × 9 m); 222 árvores ha^{-1} (10 m × 4.5 m) e 444 árvores ha^{-1} (5 m x 4.5 m). Os experimentos foram conduzidos em esquema de parcelas subdivididas, com as densidades das árvores na parcela e as colheitas (safras) na subparcelas. O delineamento experimental utilizado foi o inteiramente casualizado com nove repetições (em faixa com informações dentro da parcela). A parcela útil foi constituída por uma linha de plantio de cafeeiros contendo 12 plantas. Foram avaliadas as produtividades médias e acumuladas dos cafeeiros durante cinco safras (2017-2021). A arborização do cafezal com plantas de bandarra reduz a produtividade média e acumulada dos cafeeiros *C. canephora* 'Conilon', nas primeiras cinco safras comerciais. A castanheira-do-brasil e a teca, plantadas em densidade de até 222 árvores por hectare, não promovem redução na produtividade média e acumulada dos cafeeiros.
Palavras-chave: Amazônia. Densidade de plantio. Conilon. *Schyzolobium paranyba. Bertholletia excelsa. Tectona grandis*.

Introduction

Commercially grown coffee plants originate from Africa, where they grew in understory conditions. Commercial growing came to be carried out mainly under full sun conditions with the domestication of the species, but there are benefits in using tree species intercropped with coffee plants for both the species *Coffea arabica* and *C. canephora.* The main benefits are related to environmental improvements (Arango, 2019; Henrique et al., 2020, 2022; Zaro et al., 2023), but there are also reports of increased yield (Freitas et al., 2020; Jácome et al., 2020) and improvement in beverage quality (Souza et al., 2019; Torrez et al., 2023).

In addition to benefits for the coffee crop, agroforestry systems (AFSs) can provide benefits for the rural worker, as they reduce the incidence of sunlight and air temperature (L. C. Gomes et al., 2020; Zaro et al., 2023), providing higher comfort for carrying out management operations necessary for the crop. Moreover, in economic terms, the tree component can be one more source of income for the farmer (Ehrenbergerová et al., 2019) whether through the use of fruits, such as the coconut *Cocos nucifera* (Pezzopane et al., 2011) and macadamia *Macadamia integrifolia* (Pezzopane et al., 2010), the latex *Hevea brasiliensis* (Zaro et al., 2020; Nunes et al., 2021), or even the use of wood, as in the case of AFS with the Australian red cedar *Toona ciliata* (Oliosi et al., 2016).

Most studies with coffee plants in AFSs have been carried out with the species *C. arabica* (Freitas et al., 2020; Martins et al., 2023; Olivas et al., 2023). Studies conducted in Brazil with *C. canephora* have been concentrated in the Atlantic Forest biome and with coffee plants of the Conilon botanical group (Oliosi et al., 2016; Correia et al., 2020; Trevisan et al., 2022).

Studies that describe the response of AFSs with coffee plants in the Amazon biome, especially in the State of Rondônia, where the mean temperatures remain high throughout the year and humidity and soil moisture reach critical levels for agriculture in the dry period (Alvares et al., 2013), are not yet conclusive regarding the agronomic performance of coffee plants. Most of these studies have concentrated attention on environmental gains (M. C. F. Costa et al., 2018; Henrique et al., 2020, 2022) and have not examined the response of coffee plants under AFS conditions.

Coffee plants in AFSs in the Amazon region, especially in Rondônia, can benefit from changes in microclimate, especially in the dry period, in which the maximum, mean, and minimum temperatures reach high values and relative humidity reaches the lowest values in the year (Alvares et al., 2013). For that reason, this study aimed to evaluate the agronomic performance of *C. canephora* 'Conilon' plants grown in AFSs with Brazilian firetree, Brazil nut, and teak under the conditions of the southwestern Brazilian Amazon region.

Materials and Methods

The study was conducted in the period from November 2014 to June 2021 at the experimental field of Embrapa in Ouro Preto do Oeste, Rondônia, Brazil (10°44'05''S, 62°15'20''W, and 250 m above sea level). The soil of the area was classified as an Argissolo Vermelho-Amarelo, and the chemical properties in the 0–20 and 20–40 cm layers before setting up the AFSs were: pH 6.3; P, 8.0 mg dm^{-3}; K, 0.25 cmol$_c$ dm^{-3}; Ca, 2.62 cmol$_c$ dm^{-3}; Mg, 0.81 cmol$_c$ dm^{-3}; H+Al, 2.5 cmol$_c$ dm^{-3}; Al, 0.0; CEC, 6.17 cmol$_c$ dm^{-3}; OM, 16.1 g kg^{-1}; and V, 58%.

Three experiments were conducted: 1) coffee plants intercropped with Brazilian firetree (*Schizolobium parahyba* var. *amazonicum*), 2) coffee plants intercropped with Brazil nut (*Bertholletia excelsa*), and 3) coffee plants intercropped with teak (*Tectona grandis*).

The treatments in each experiment consisted of four densities of plants: zero (coffee plants only, in full sun), 111 plants ha^{-1} (10 × 9 m), 222 plants ha^{-1} (10 × 4.5 m), and 444 plants ha^{-1} (5 × 4.5 m). The experiments were conducted in a split-plot arrangement, with plots consisting of plant densities and subplots consisting of harvest periods (crop seasons). The experimental design was completely randomized, with nine replications. The part of the plot used for data collection consisted of one planted row with 12 coffee plants.

The seedlings of forest species were produced from seeds obtained from trees in the mentioned experimental field. The coffee seedlings were produced from *C. canephora* seeds of the 'Conilon – BRS Ouro Preto' variety. The seedlings of forest species and coffee plants were planted at the same time, in November 2014. A spacing of 2.5 × 1.5 m (2667 plants ha^{-1}) was used for coffee plants. The forest species were planted following the spacings of each treatment, always in the plant row and the space between two coffee seedlings to maintain the density of coffee plants unchanged in the different treatments.

Soil tillage consisted of plowing and two harrowing operations, followed by opening furrows with a depth of 40 cm. In the furrows, 200 g of limestone, 30 g of FTE, and 200 g of single superphosphate were distributed per linear meter. Soil chemical analysis was carried out every two years to monitor soil chemical properties (Table 1).

Fertilization for production began in August 2016, culminating in the harvest of May 2017. Fertilizer applications from this period onwards were split monthly during the rainy period of each production cycle, October to May, using the fertilizer formulations 20–00–20 or 20–05–20 to supply the nutrients N, P_2O_5, and K_2O. Micronutrients were supplied by borax, zinc sulfate, magnesium sulfate, copper sulfate, and the MIB® complex fertilizer. Limestone and agricultural gypsum were also topdressed to supply calcium (Table 2).

Temperature and relative humidity data (maximum, mean, and minimum), as well as cumulative rainfall, during the period from November 2014 to June 2021, were obtained from the automatic weather station set up in the experimental field mentioned above (Figure 1). The plants received supplemental irrigation throughout the growing period and in the dry periods of 2016 and 2017.

Table 1

Chemical properties of an Argissolo Vermelho-Amarelo of the experimental area before setting up AFSs with Brazil nut, Brazilian firetree, and teak. Ouro Preto do Oeste, RO, Brazil, 2014

Depth	pH	P	K	Ca	Mg	H+Al	Al	CEC	m	V	OM
	Water	mg dm^{-3}		----------- cmol$_c$ dm^{-3}	-------------				---%---		g kg^{-1}
Brazil nut											
					August 2014						
00-20	5.9	3	0.13	1.64	0.81	2.4	0.0	4.96	0.0	52	15.5
20-40	5.9	3	0.08	1.26	0.50	1.6	0.0	3.48	0.0	53	9.3
					August 2016						
00-20	5.3	20	0.33	2.00	0.71	4.00	0.35	7.04	10.3	43	15
20-40	5.8	5	0.20	1.00	0.46	2.10	0.23	3.76	12.2	44	12
					August 2018						
00-20	4.5	60	0.58	0.94	0.53	6.41	0.49	8.47	20	25	13
20-40	5.2	5	0.30	0.82	0.51	2.52	0.19	4.15	10	39	7.2
August 2020											
00-20	5.2	33	0.33	3.40	0.88	4.11	0	8.72	0	53	11
20-40	5.8	24	0.22	3.77	0.66	2.85	0	7.51	0	62	6.1
Brazilian firetree											
					August 2014						
00-20	6.1	3	0.24	1.74	0.76	3.5	0.0	6.21	00	44	14
20-40	5.9	3	0.12	1.66	0.46	2.1	0.0	4.38	00	51	10
					August 2016						
00-20	5.5	18	0.32	2.30	0.78	5.20	0.31	8.6	8.36	40	14
20-40	5.6	3	0.17	1.10	0.52	2.47	0.17	4.2	8.81	42	11
					August 2018						
00-20	4.7	60	0.60	1.25	0.50	6.00	0.4	8.35	14.52	28	13
20-40	5.2	6	0.25	0.88	0.49	2.89	0.2	4.51	10.99	36	8
					August 2020						
00-20	5.4	38	0.39	3.30	0.98	4.41	0	9.08	0.00	51	10
20-40	5.8	21	0.19	2.77	0.63	2.78	0	6.37	0.00	56	7

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Teak											
August 2014											
00-20	6.8	18	0.39	4.49	0.85	1.6	0.0	7.35	00	78	18
20-40	6.7	10	0.23	2.75	0.36	1.6	0.0	4.91	00	68	10
August 2016											
00-20	5.5	22	0.35	1.34	0.67	5.89	0.28	8.25	10.61	29	12
20-40	5.6	5	0.23	0.88	0.52	2.69	0.13	4.32	7.39	38	8
August 2018											
00-20	4.4	35	0.44	0.67	0.5	5.605	0.45	7.1	22	22	11
20-40	5.2	5	0.30	0.82	0.51	2.52	0.19	4.15	10	39	7
August 2020											
00-20	5.4	12	0.26	3.34	0.92	3.78	0	8.3	0	54	10
20-40	5.4	9	0.23	2.98	0.81	3.42	0	7.43	0	54	6

Fertilization for plant growth began at 40 days after seedling transplanting, with surface application of fertilizers. The plant growth period was from transplanting until the main flowering period, in August 2016. In that phase, 400 grams of the commercial formulation 20–00–20, distributed in four applications in the 2014/15 rainfall cycle and six applications in the 2015/16 cycle (October to May) was applied (Table 2).

Table 2
Production fertilization of agroforestry systems with Brazilian firetree, Brazil nut, and teak in the period from 2014 to 2021. Ouro Preto do Oeste, RO, Brazil, 2021

Input	Year					
	2014/15/16[1]	2016/17	2017/18	2018/19	2019/20	2020/21
	---------------------------- kg ha^{-1}------------------------------------					
Limestone	800	533	-----	1600	533	533
Nitrogen[2]	213	288	288	160	205	314
Phosphorus	160	27	27	40	36	100
Potassium	213	108	108	160	90	143
Gypsum	-----	----	----	100	----	100
Borax	-----	16	----	----	32	32
MIB®	30	---	30	-----	----	----
Zinc sulfate	-----	16	----	16	32	32
Magnesium sulfate	-----	53	----	53	80	80
Copper sulfate	-----	10	----	10	21	30

[1]Fertilization in the plant hole (planting) and fertilization for plant growth. [2]Amounts of N, P_2O_5, and K_2O per hectare per year.

The seedlings were pruned 90 days after transplanting for plant formation (Espindula et al., 2016) to be conducted with four stems per plant, totaling 10,668 stems per hectare. The forest species were managed to remain with a single stem. Additionally, branches were cut back annually, increasing air circulation and sunlight under their canopies.

Plant health management of the coffee field was carried out according to the technical recommendations for the crop under the edaphoclimatic conditions of the Amazon (Marcolan & Espindula, 2015). Weeds were controlled by cutting between the rows with a tractor-driven brush cutter and application of herbicide in the plant row. Every year as of 2016, the insecticide thiamethoxam Actara® was applied preventively at the time of the first rains, in October. No intervention was necessary to control diseases in the plants that composed the systems.

Coffee plant yield was determined by harvesting all fruits from the part of the plot used for data collection. A sample of 3 kg of fruits from each plot was dried on a drying patio with a mobile cover until it reached 12% moisture. After drying, the fruits were ground in a Carmomaq® dry coffee pod husking machine and the ratio between fresh fruits and dry coffee beans was used to estimate the plot yield. Yield was expressed as the number of 60 kg bags per hectare.

The data were plotted on scatter plots to evaluate the yield response of coffee plants over the years, and trend curves were obtained from a third-order polynomial model. Regression analysis was performed on the data to study the effects of planting densities of forest species on the yield of coffee plants in each year/crop season ($p \leq 0.05$). Analysis of variance was performed on the mean and cumulative yield data after five crop years ($p \leq 0.05$), and the means were compared by Tukey's test ($p \leq 0.05$).

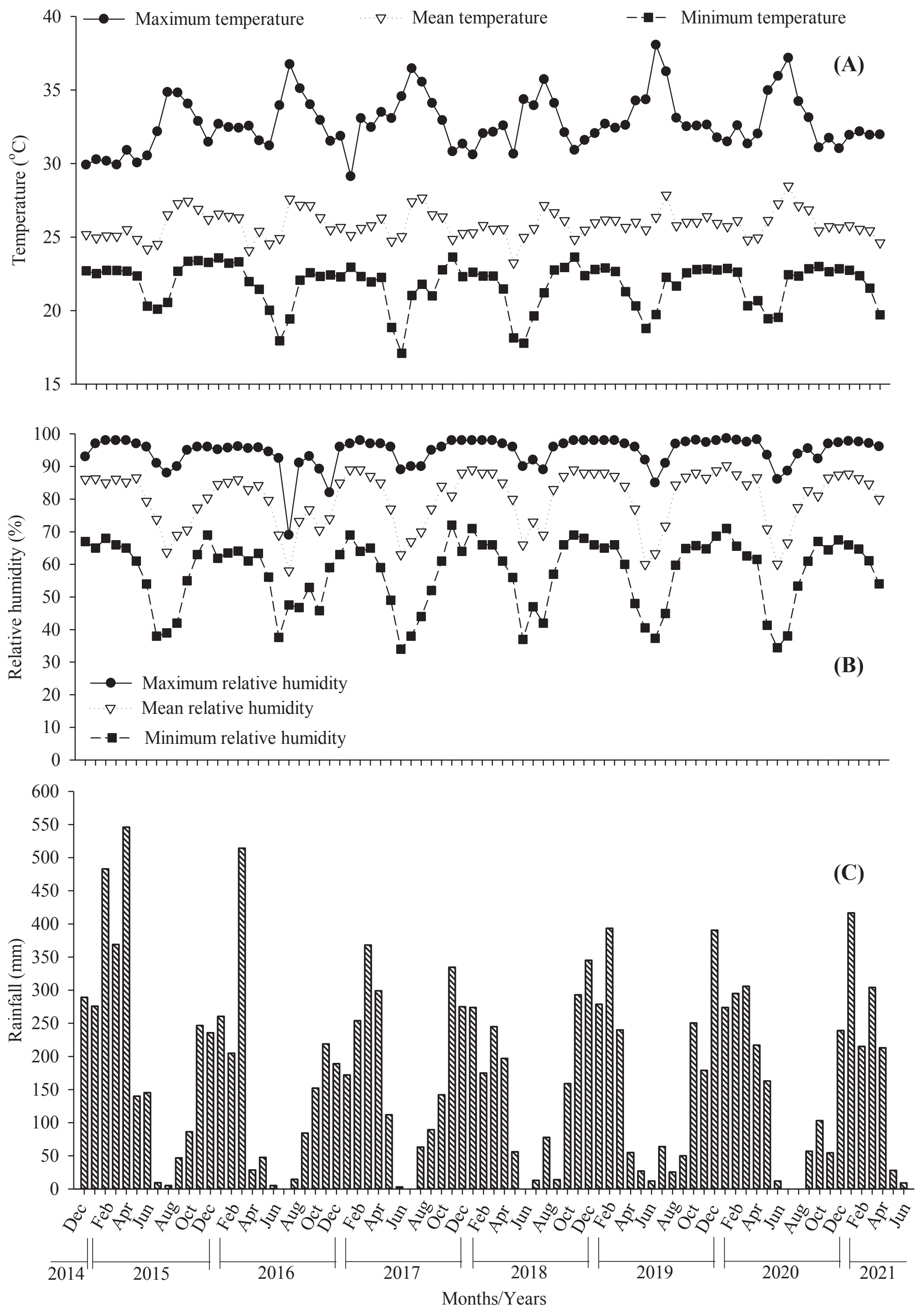

Figure 1. Maximum, mean, and minimum temperatures (A) and relative humidities (B) and cumulative monthly rainfall (C) from December 2014 to June 2021 in the experimental field of Embrapa in Ouro Preto do Oeste, RO, Brazil.

Results and Discussion

Brazilian firetree

There was a linear, although not very expressive, increase in fruit yield of coffee plants in the first crop year (2017) with an increase in plant density. An exponential decrease was verified in the second (2018), third (2019), and fifth (2021) crop years. In the fourth crop year (2020), the year of stem renewal, there was no effect of the forest component on the yield of coffee plants, and the mean value was 10 bags ha^{-1} (Figure 2A).

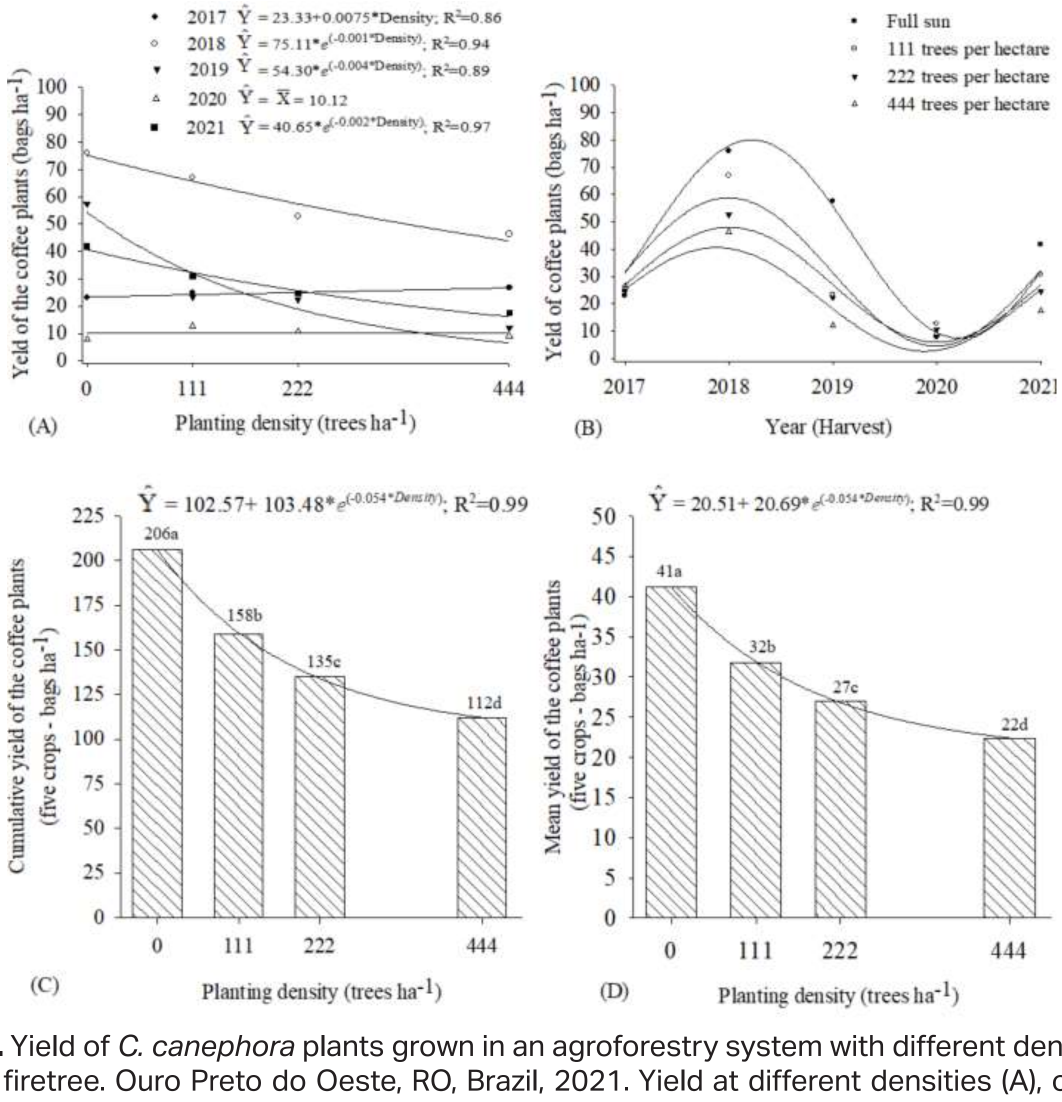

Figure 2. Yield of *C. canephora* plants grown in an agroforestry system with different densities of Brazilian firetree. Ouro Preto do Oeste, RO, Brazil, 2021. Yield at different densities (A), over five years (B), cumulative yield (C), and mean yield (D) of five harvests (2017, 2018, 2019, 2020, and 2021).

Fruit yield in the second crop year (2018) was higher than that in the first (2017) and third (2019) crop years, indicating the biennial effect of production. It was accentuated with an increase in the density of plants in the system. The peak yield in the second crop year (2018) was found in coffee plants in full sun, with a yield of more than 88 bags per hectare. In contrast, the lowest yield (24.47 bags per hectare) was observed for the treatment with the highest density of Brazilian firetree plants (444). The fourth crop year (2020) showed lower fruit yield of coffee plants at all plant densities, a reflection of the management practice of stem renewal. In addition, the fifth crop year (2021) had a resumption of fruit production, with the beginning of the new production cycle (Figure 2B).

The increase in the density of Brazilian firetree plants led to a reduction in the mean and cumulative yield of coffee plants (Figures 2C and D). The highest cumulative yields and mean yields were found in coffee plants in full sun, with 206 and 41 bags per hectare, respectively (Figures 2C and D).

This reduction may be associated with excessive shading brought about by Brazilian firetree plants on coffee plants. According to Baliza et al. (2012), the amount of sunlight on the surface of coffee plant leaves can affect the internal structure and photosynthetic functions. These authors, upon studying the effect of different levels of artificial shading on coffee plants of the *C. arabica* species, found that coffee plants can reduce the photosynthetic rate and have lesser thickness of the mesophyll and palisade parenchyma with 90% shading.

In addition, for afforestation with species of the genus *Schizolobium,* the reduction in coffee yield may be related not only to competition for sunlight but also to competition for water and soil nutrients during the juvenile phase of these tree species. It occurs because species of this genus have initial growth rates that may correspond to an increase of more than 1.6 meters in height per year (J. M. Gomes et al., 2019). These growth rates are related to the intense production of auxins and gibberellins, which drive plant growth, mainly height (Cordeiro et al., 2016), and the increase in fine and absorbent roots, which allow the maintenance of high growth rates (A. K. L. Silva et al., 2011).

Absorbent roots need to extract large amounts of water and soil nutrients to maintain these high growth rates. This rapid growth can be enhanced by favorable climate conditions, especially under Amazonian conditions. In this case, the mean annual temperature in the Brazilian southwestern Amazon is approximately 25 °C (Alvares et al., 2013), which allows growth throughout the year, as long as there is water available in the soil and the deficit of vapor pressure is not an impediment.

The growth of Brazilian firetree plants continues after the juvenile phase although more slowly. At that time, three-year-old Brazilian firetree plants already had a mean height of approximately 6.64 meters, a diameter at breast height of 7.74 cm (A. K. L. Silva et al., 2011; Cordeiro et al., 2016), and a well-developed root system. It probably gives this species an advantage in capturing available environmental resources.

The effect of competition of Brazilian firetree with coffee plants could already be verified in the second year of production (2018), a crop year in which the treatment with 444 Brazilian firetree plants per hectare brought about a lower yield of coffee plants than the other plant densities (Figures 2A and B). In that crop year, an expressive increase in yield was expected compared to the first year, when coffee plants were grown in full sun (Espindula et al., 2021).

Regarding the proposal of offering shade to coffee plants in the hottest periods, the Brazilian firetree is a deciduous tree and loses its leaves in the dry period, between July and August, when the mean air temperature reaches the highest values, and the relative humidity reaches the lowest levels (Figure 1). Thus, the Brazilian firetree does not fulfill the function of making the microclimate favorable for the development of coffee plants precisely during the period when this species needs it most.

Furthermore, the Brazilian firetree had an additional problem in the composition of AFS with coffee plants. The branches of this species break easily especially under wind conditions due to the reduced density of its wood, which is around 0.3 g cm^{-3} (Vidaurre et al., 2018), and the low C/N ratio, which ranges from 1.5 to 1.8 g in the petioles (Carvalho et al., 2013). Therefore, there may be mechanical damage to the coffee plants, such as breakage of stems or productive branches, when it occurs.

Brazil nut

The increase in the density of Brazil nut trees led to an exponential increase in the fruit yield of coffee plants in the first crop year (2017). In contrast, a linear decrease was observed in fruit yield in the other crop years (2018, 2019, and 2021) with an increase in plant density in the system. In 2020, there was no effect of the forest component on the yield of coffee plants because it was a year of steam renewal and the mean yield of all the densities was 13.7 bags ha^{-1} (Figure 3A).

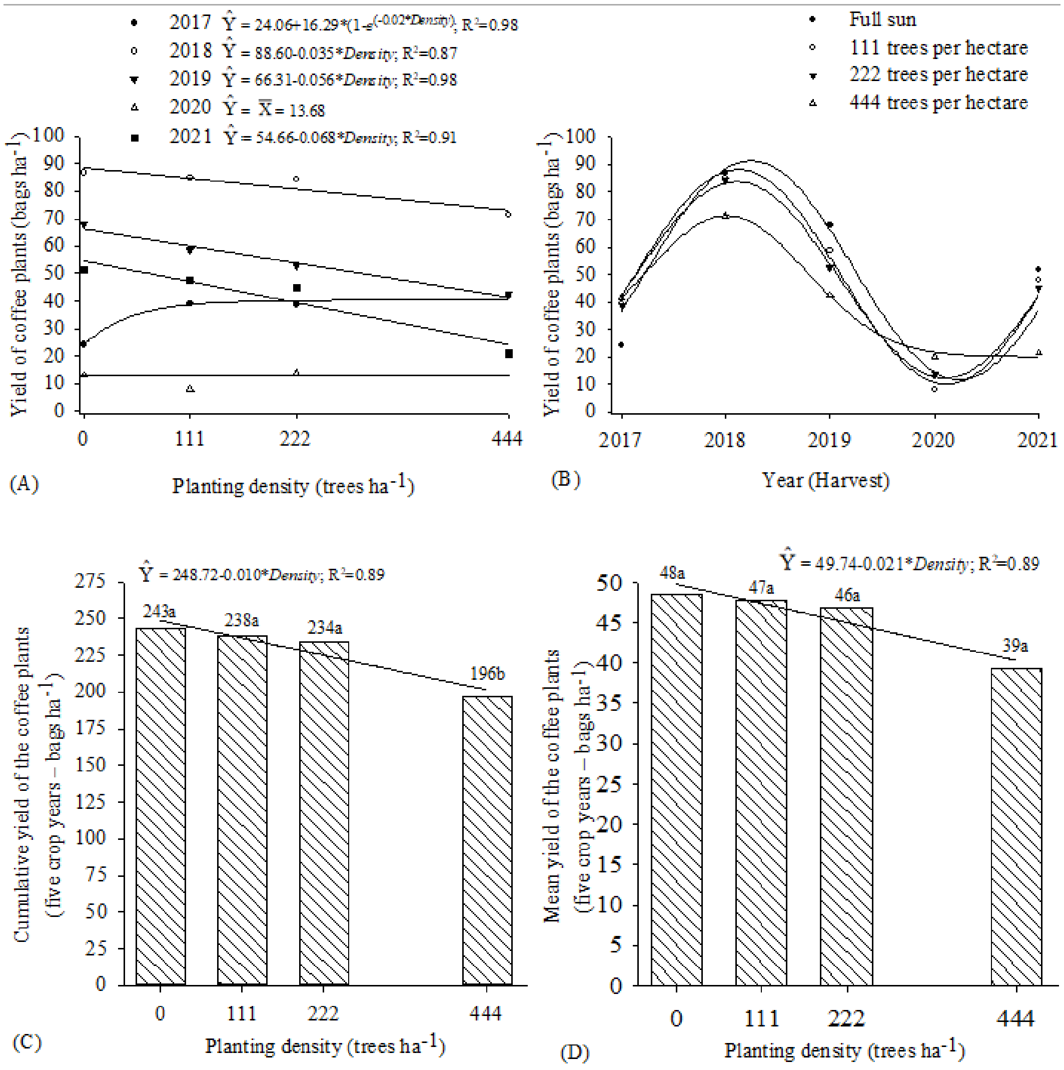

Figure 3. Yield of *C. canephora* plants grown in an agroforestry system with different densities of Brazil nut trees. Ouro Preto do Oeste, RO, Brazil, 2021. Yield at different densities (A), over five years (B), cumulative production (C), and mean yield (D) of five harvests (2017, 2018, 2019, 2020, and 2021).

Tree density did not change the biennial effect of fruit production of coffee plants, except at the highest density, that is, 444 Brazil nut trees per hectare, in which the biennial effect on production was attenuated. The yield response over the years was marked by an increase in production from the first to the second year, a decrease in the two subsequent years, and an increase from the fourth to the fifth year (Figure 3B).

The results imply that afforestation with Brazil nut up to the density of 222 trees per hectare did not compromise the yield of coffee plants up to seven years of the system, which may be related to the growth response of Brazil nut trees during the first years of cultivation. In this sense, a study with Brazil nut grown in full sun under the climate conditions of the Amazon showed that the mean increase in height in two years was 204 ± 115.5 cm [n = 39] (Scoles et al., 2011), which indicates not only a small increase in height but also high variability of growth among the individuals.

The similar yields of coffee plants at densities of 0, 111, and 222 plants per hectare also indicate that Brazil nut trees did not show significant competition for water and soil nutrients. It is due to the capacity of adaptation in soils with low nutrient availability, as the Brazil nut tree develops and produces in soils with low pH, total organic carbon, and the sum of bases and high Al saturation contents (C. S. Silva et al., 2021).

Furthermore, Brazil nut is a semi-deciduous species, that is, leaf abscission occurs throughout the year, but the trees do not become completely leafless. It may contribute to reducing the incidence of sunlight and, consequently, reducing the environmental stress of the coffee tree components of the system.

The presence of Brazil nut trees did not affect the yield response of coffee plants over time (years/crop seasons), except in the treatment with 444 plants per hectare, in which a smaller biennial yield effect was found (Figure 3 B). The maximum (2018) and minimum (2020) yield extremes at this density were less expressive than in the other treatments. Nevertheless, because the yields of all the crop years were negatively affected by the presence of Brazil nut trees, the cumulative and mean yields at the end of the five crop years were lower than those of the other treatments despite the lower biennial yield effect at this plant density.

The biennial yield effect was marked by a maximum peak in the second crop year and a minimum peak in the fourth crop year (Figure 3B). The biennial yield effect, a phenomenon characterized by alternation of yield between subsequent crop years, is common in *C. canephora* (Espindula et al., 2021; Torres et al., 2022). In years with high yield, the fruit becomes the main drain and competes with the roots and vegetative shoots in the requirement for nutrients and photoassimilates, reducing the formation of shoots and roots directed to sustaining the subsequent crop year. In contrast, vegetative shoots are formed in years with smaller harvests, sustaining larger harvests in the following yield cycle.

This alternation is very common when coffee plants are managed with traditional production pruning, in which the sustaining stems are renewed annually. Nevertheless, the use of Cyclical Programmed Pruning (Poda Programada de Ciclo) (Verdin et al., 2014, 2016) led to management marked by yield cycles in which the stems are renewed every three or four crop years, a period in which there is a drastic reduction in fruit production (Espindula et al., 2022).

The lower yield observed in the fourth crop year (2020) is related to the transition from the first to the second yield cycle, a period in which coffee plants had only one stem. However, the yield reduction observed between the second and the third crop years was beyond expectations. This reduction may be related to the absence of irrigation during the drought period of 2018 (July to October), a fact that may also have affected the crop year of 2020, as there was also no irrigation in 2019. In addition, the conditions of lower pH and base saturation, as well as high aluminum saturation, observed in the soil analysis of 2018 (Table 1), may have contributed to a reduction in the 2019 crop year, with consequences extending to the 2020 crop year.

Brazil nut tree densities did not affect the cumulative yields and mean yields of coffee plants, except at the highest density, in which yields were lower than in the other treatments (Figures 3C and D).

The lower cumulative and mean yield of fruits found at the density of 444 Brazil nut trees per hectare (Figures 3C and D) indicate that, at that density, the trees affected the agronomic performance of coffee plants, possibly due to light interception. Upon evaluating the long-term effects of spacing between plants on the growth and morphometry of *B. excelsa,* researchers have found that the canopies of Brazil nut trees tend to be wider and longer at intermediate (5 × 5 m) and greater spacings (Oliveira et al., 2021). Thus, Brazil nut trees possibly reduced light interception by coffee plants and compromised the processes related to photosynthesis at the spacing of 5 × 4.5 meters (444 trees per hectare).

Soil amendment, as well as planting and topdressing fertilization, was conducted (Table 2). Brazil nut contributes to soil acidification during the nutrient uptake process through its demanding characteristic of a higher need for removal of exchangeable bases (M. G. Costa et al., 2017) and may have led to a less favorable environment for the development of coffee plants, especially through the absence of calcium in the areas of higher density.

Teak

The increase in the density of teak trees led to an exponential increase in the yield of coffee plants in the first crop year (2017) (Figure 4A). A quadratic response was observed in the second crop year (2018), with a maximum yield at the density of 222 trees ha^{-1}. The third (2019) and fifth (2021) crop years showed linear reductions in yield with an increase in tree density, and no effect of density was observed on yield in the fourth crop year (2020). The mean yield in that crop year was 8.3 bags ha^{-1}.

Increased yield was also observed in coffee plants of the species *C. arabica* grown with teak at the density of 82 trees per hectare (spacing of 13.6 × 9 meters) in the south of the State of Minas Gerais, Brazil (Jácome et al., 2020), which has a tropical mesothermal climate (Cwa). The results indicate a beneficial effect of this tree species on the agronomic performance of coffee plants in the first years after setting up the system.

The beneficial effects of teak at low densities may be related to the level of shading produced by the canopy of this species during its initial growth. A study with artificial shading of *C. Arabica* showed that a 35% reduction in sunlight is most recommended for growing coffee plants in a shaded environment because there is an improvement in the internal structure of the leaves, which may favor physiological characteristics of interest for optimizing the development of this crop (Baliza et al., 2012). Similar to these results, a study performed with Robusta coffee in agroforestry systems in a region of the equatorial Amazon with a tropical forest climate (Af) confirmed that a moderate shading of up to 25% provided yields similar to that when growing coffee in full sun, and the vegetative growth stimulated by the shade of trees did not compromise the yield of coffee plants (Piato et al., 2022).

The benefits of the presence of teak can also be associated with improvements in environmental conditions, such as a reduction in temperature extremes and an improvement in soil conditions. In this context, the potential for an increase in moisture, improvement in biological activities, and reduction in erosive processes that occur when tree species are inserted into crops stand out (Moreira et al., 2018; Nunes et al., 2021). Nevertheless, despite the positive effects on the microclimate, teak is a species with deciduous characteristics belonging to the family Lamiaceae (Midgley et al., 2015) and, therefore, it loses its leaves during periods of drought, leaving coffee plants vulnerable to high temperatures in the periods in which shading is most important.

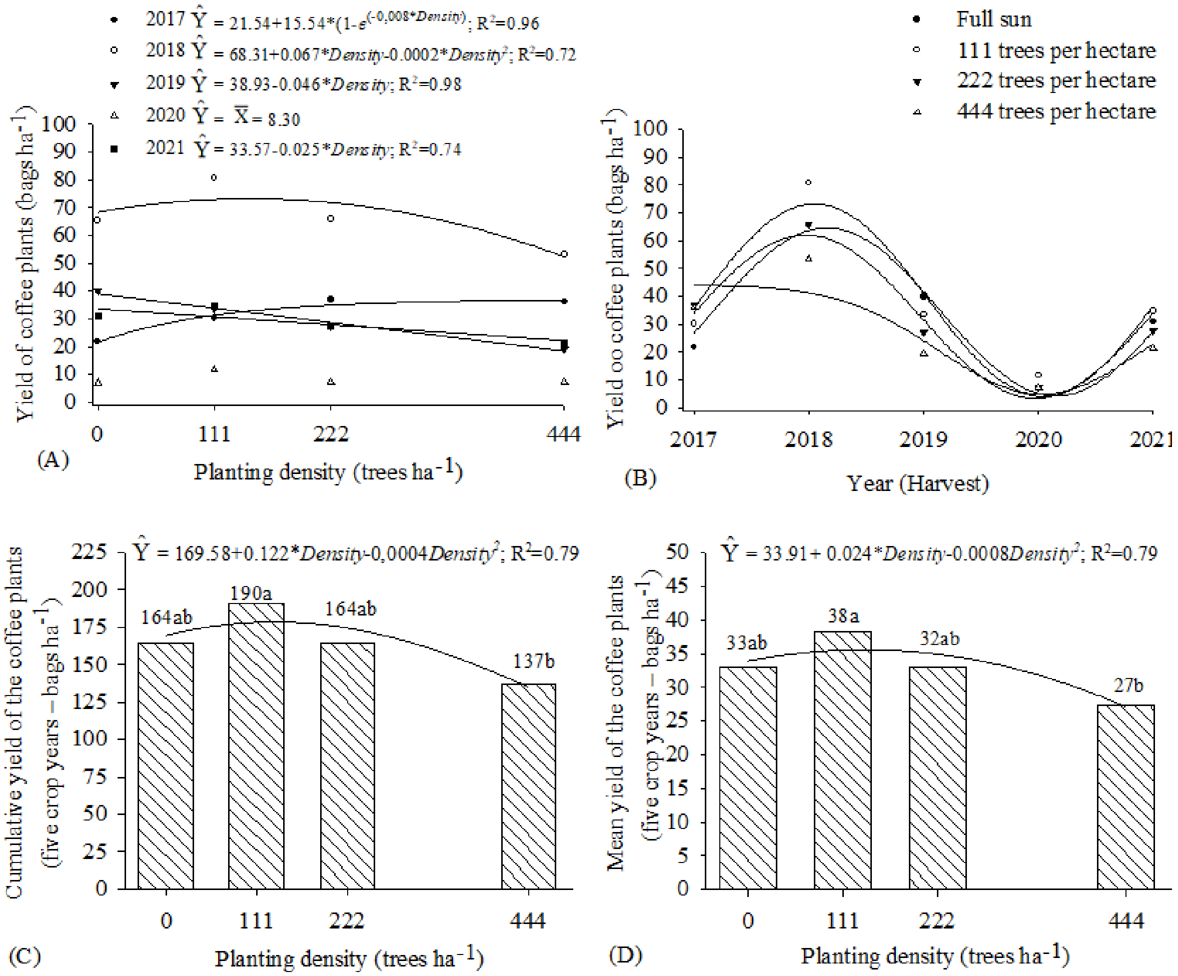

Figure 4. Yield of *C. canephora* plants grown in an agroforestry system with different densities of teak trees. Ouro Preto do Oeste, RO, Brazil, 2021. Yield at different densities (A), over five years (B), cumulative yield (C), and mean yield (D) of five harvests (2017, 2018, 2019, 2020, and 2021).

The effects of teak on soil properties potentially include soil acidification (Jácome et al., 2020), but its root system also makes a favorable contribution through its capacity for association with mycorrhizal fungi and nitrogen-fixing bacteria (Chaiya et al., 2021), which mobilize nutrients in the soil, facilitating uptake by plants.

A biennial effect was observed on fruit production of coffee plants regardless of the tree density in the system (Figure 4B). The yield curves were characterized by two production peaks, one maximum in the second crop year and the other minimum in the fourth crop year, the year of stem renewal. The density of 444 trees per hectare led to a lower biennial effect on yield, as this density had no peak of maximum yield in the second crop year (2018). Thus, the biennial yield effect of coffee plants is more related to stem management and supply of water and nutrients than to the shading level, as observed in the systems with Brazilian firetree and Brazil nut.

Cumulative and mean yields showed a difference only between the densities of 111 and 444 trees per hectare, with the highest values being found at the density of 111 trees (Figures 4C and D). The absence of differences among the densities of 0, 111, and 222 plants per hectare (Figures 4C and D) indicate that there was no negative effect of afforestation on coffee yield up to the fifth crop year. However, the yields obtained in this study are below those obtained for the crop under sole coffee cropping conditions (Teixeira et al., 2020; Espindula et al., 2021). This lower yield may have occurred as a result of other production factors, such as the genetic potential of coffee plants and crop management. Together, these factors may have limited the expression of crop yield potential.

Superior clones and crop densification can increase coffee field yield in AFSs

The yields of coffee plants obtained in the three experiments are below the yield potential of *C. canephora* plants under Amazonian conditions, regardless of the tree density of the system. The lower yields observed in this study are mainly related to the genetic potential of coffee plants and the spacing adopted for this system component.

Regarding genetic potential, the fact that seedlings produced from seeds were used in this study is noteworthy. The species *C. canephora* reproduces by mandatory cross-pollination and crops formed by seeds are heterogeneous and express high genetic variability for vegetative and reproductive traits (Rocha et al., 2013). For that reason, the use of clonal plantlets, produced from superior parent plants, could result in yields superior to those found in this study.

A mean yield higher than 80 bags per hectare was found over three crop years in a study in which the yield performance and ten hybrids of *C. canephora* (Conilon × Robusta) were evaluated in four environments in the State of Rondônia (Teixeira et al., 2020). In that same study, the maximum yield in the year of high yield was higher than 130 bags per hectare. Similarly, a mean yield of 82 bags per hectare was obtained in another study also conducted in the State of Rondônia in a clonal crop field composed of 15 genotypes, with the maximum yield of stems in the second crop year reaching 115 bags per hectare (Torres et al., 2022).

The study by Teixeira et al. (2020) resulted in the recommendation of ten clonal coffee tree genotypes for Amazonian conditions. These genotypes (cultivars) are already being studied regarding their leaf anatomical characteristics (Araújo et al., 2021), which are especially affected by shading conditions, and should form part of new trials for cultivation under SAF conditions in the Amazon.

Regarding the spacing between coffee plants, which was 2.5 × 1.5 meters in this study, resulting in a density of 2667 plants per hectare, increasing plant density tends to reduce the individual plant yield, but it increases the overall yield in the area (Espindula et al., 2021). These authors studied densities of 1666, 1904, 2222, 2666, and 3333 coffee plants per hectare, as the sole crop, and found higher yields in the treatment with the highest density (3333 plants). Moreover, the highest yields for Conilon coffee plants under the growing conditions of the Atlantic Forest in the State of Espírito Santo were achieved at spacings that resulted in 5000 coffee plants per hectare (2 × 1 meters) (Verdin et al., 2014).

Thus, given the evidence regarding the yield potential of clonal crops with superior genotypes and the increase in yield with denser plant populations, these factors should be considered in new studies so that the maximum agronomic performance of coffee plants can be achieved. However, the number of stems per plant and, consequently, per hectare should also be considered in addition to spacing, as the increase in the number of stems results in a smaller stem diameter (Espindula et al., 2021). It may result in a higher propensity for the plant to topple and break, and this possibility increases in afforested crops due to the etiolation of stems grown under shaded conditions.

Conclusions

The afforestation of the coffee field with Brazilian firewood trees leads to a reduction in the yield of *C. canephora* 'Conilon'.

In the first five commercial crop years, Brazil nut and teak, planted at a density of up to 222 trees per hectare, do not lead to a reduction in the yield of *C. canephora* 'Conilon.'

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