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Carbon sequestration in an agroforestry system of coffee and *Mimosa scabrella* (bracatinga) in southern Brazil

Paulo Henrique Caramori[1(*)], Heverly Morais[1], Alex Carneiro Leal[1], Armando Androcioli Filho[1], Daniel Campos Caramori[2], Geovanna Cristina Zaro[3] and Ângela Beatriz Ferreira da Costa[4]

[1] IAPAR. Rodovia Celso Garcia Cid, km 375, CEP 86047-902 Londrina, PR, Brazil. E-mails: pcaramori@gmail.com, heverlymorais@gmail.com, alexcarneiroleal@gmail.com and aandrociolifilho@gmail.com
[2] Graduate student at University of Montreal, Canada. Email: daniel.caramori@gmail.com
[3] Posdoctoral researcher at University of Guelph, Canada. Email: geoczaro@gmail.com
[4] Fellow of the Consórcio Pesquisa Café, IAPAR, Londrina, Brazil. Email: angelabcosta@gmail.com
[(*)]Corresponding author.

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ABSTRACT

Agroforestry systems (AFs) are an alternative to manage production in a sustainable manner and to adapt environments to climate change. Arabica coffee is sensitive to thermal extremes and could be one of the crops most affected by global warming. AFs can contribute to mitigate the effects of global warming through the sequestration of atmospheric carbon and its fixation in biomass and soil. This work assessed carbon sequestration and coffee yield in an AF of coffee with bracatinga (*Mimosa scabrella*), in a transitional climate region in southern Brazil. Two densities of bracatinga (555 and 139 trees ha^{-1}) compared to open-grown were evaluated. Carbon sequestration was significantly higher in the AF, but coffee production was reduced by competition with *M. scabrella*. Further studies are needed to adjust population density and management of *M. scabrella* to enable the commercial use of this system.

Introduction

The species *Coffea arabica* originated in the understory of montane rainforests of Ethiopia, where it adapted to low incident radiation and mild climates. When exposed to full sun, the coffee plant produces abundantly, as long as it has adequate supplement of water and nutrients. However, when the environment becomes unfavorable, damages to the plants are frequent, mainly caused by the excess of drain in years with high yield, resulting die-back and accentuating the biennial productive cycle (Da Matta, 2004).

Agroforestry Systems (AF) have been recommended as an alternative to improve the sustainability of production systems, including coffee cultivation (Mushler, 2016). The advantages of this system include the reduction of thermal extremes, maintenance of soil fertility, control of erosion, and reduction of the biennial production cycle of coffee. On the other hand, excessive shading can cause severe losses in coffee production and render the activity unfeasible (Beer, 1998). In Brazil, cultivation in full sun prevailed, partly due to the negative results of pioneering studies that detected yield losses under dense shading (Caramori et al., 1996). Other additional factors that justify the practicing of intensive cultivation in full sun include the extensive availability of areas in the country and the mechanization of coffee crops.

AFs are recommended as an alternative to protect coffee plantations from frosts in the south of Brazil (Baggio et al., 1997; Zaro et al., 2019). Experimental results indicated that a moderate shade could minimize frost damages and contribute to stable productions in areas with frequent frost occurrence (Caramori et al., 1996).

AFs have also become an excellent alternative to reducing high temperatures during the day. These systems may enhance agriculture in areas that would become unviable for coffee production in the coming decades due to global warming (Assad et al., 2004; IPCC, 2014).

Typically, underneath the AF canopy, temperatures are milder in the hottest hours of the day and tend to be equal to or slightly higher than the outside environment at night. The differences vary according to local conditions, species, population density and management (Valentini et al., 2010; Pezzopane et al., 2010; Pezzopane et al., 2011; Araújo et al., 2016; Zaro et al., 2019).

Agroforestry Systems are reported to increase atmospheric carbon sequestration in relation to annual monocropping. Tree species have greater carbon sequestration capacity for longer periods than annual species that rapidly decompose and recycle organic matter in tropical and subtropical conditions (Carvalho et al., 2010). The litter and root systems of the AF are important sources to increase soil carbon stocks, maintain a stable carbon pool, and increase soil conservation and fertility (Dignac et al., 2017). The large diversity of plant species adapted to tropical and subtropical conditions provides a wide variety of options of afforestation to help reestablish the broken equilibrium of natural systems (Noumi et al., 2018).

Bracatinga (*Mimosa scabrella*, Benth), is a tree native to the coldest regions of southern Brazil, and is used for firewood, charcoal, construction, and furniture. It is a perennial tree, 4 to 18 m high and 20 to 30 cm DBH, reaching up to 30 m in height and 0.50 m or more DBH in adult phase. This species has been reported to demonstrate satisfactory behavior in shading coffee plantations in Central America and Mexico (Picado, 1985). In higher elevation and colder areas of southern Brazil, forest fragments of *M. scabrella* with nine years old sequestrated about 147 Mg ha^{-1} of carbon (Ferreira et al., 2016). Bracatinga has a great potential to compose AF with coffee plantations in southern Brazil.

The objective of this work was to determine the carbon sequestration and coffee production in a SAF of coffee with bracatinga in a transitional climate from tropical to subtropical in Londrina, PR, southern Brazil.

Material and Methods

The experiment was carried out at the Experimental Station of the Agronomic Institute of Parana in Londrina (23° 36' S, 51° 16' W), during the period from 2000 to 2007. The local soil is a Dystropheric Red Latosol. The climate is subtropical, classified according to Koeppen as Cfa, with annual mean temperature of 21 °C (16.9 °C in the coldest month and 23.9 °C in the hottest month) and precipitation of 1641 mm (Nitsche et al., 2019).

Coffee seedlings were implanted in January 1998, with a spacing of 1.50 m between rows and 0.80 m between plants in the row, with one plant per hole. The cultivar used was IAPAR 59. This study used all the latest technical recommendations from that period to manage the coffee crop. After the severe frosts that occurred in July 2000, the plants were pruned at a height of 40 cm. In October 2001, bracatinga seedlings were planted in an area between coffee plants in the rows at a spacing of 4.0 m x 4.5 m (555 trees ha^{-1}). In December 2002, part of the population of *M. scabrella* was eliminated to correspond to a density of 139 trees ha^{-1} and spacing of 8.0 m x 9.0 m. Thereafter the study was conducted with three treatments (open-grown, 139 trees ha^{-1} and 555 trees ha^{-1}), in a randomized block design with three replications. Each experimental plot occupied an area of 756 m^2 (31.5 m x 24.0 m), with a total experimental area of approximately 6804 m^2. The area of each plot used to evaluate coffee production was 72 m^2.

The production of processed coffee per plant was calculated by using the average of the plants present in the plot, including those that did not produce during the year. Mean coffee yield per treatment from 2002 to 2006 was estimated in kg ha^{-1} of processed coffee.

In August 2007, the study collected four bracatinga trees from the treatment with 139 trees ha^{-1}; ten coffee plants from this AF; and ten coffee plants in full sun, in order to measure biomass and carbon stocks above and below the surface.

The biomass of coffee and bracatinga was measured separately and split into four components: root, litter, branches and leaves. The fresh mass weight of each component was taken in the experimental field, and samples were collected to determine the weight of the dry mass in oven with forced circulation at 65 °C, from which the total biomass was estimated.

Soil sampling was done in August 2007 at depths 0-0.1, 0.1-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8 and 0.8-1.0 m, in four replications, making a composite sample representative of each treatment.

All samples were sent for carbon determination by the Walkley-Black method.

To calculate the carbon stock in biomass, the carbon content was assumed as 45% based on previous studies (Mello et al., 2012; Zaro et al., 2019).

The carbon stock in the soil was measured by fixed layers using the equivalent layer method, as described by Silva et al. (2013):

$$Ec = (DshTOC) / 10$$

where Ec = carbon stock, Mg ha^{-1}; Ds = soil bulk density, kg dm^{-3}; h = layer thickness, cm; TOC = Total organic C content, g kg^{-1}. Ds was assumed to be 1.15 kg dm^{-3}, based on determinations by Faria and Caramori (1987) in the same area. Zaro et al. (2019) obtained mean Ds measured up to 0.7m of 1.12 kg dm^{-3} ± 0.10, after 16 years of an AF of coffee with rubber trees in an area contiguous to this experiment.

The results were analyzed by the F test and compared with the Tukey test at a significance level of 5%.

Results and discussion

The bracatinga trees had rapid and vigorous growth, reaching 4.5 m in the first year and 6.5 m in the second year at the density of 555 trees ha^{-1} (Leal et al., 2005). At the end of the experiment in 2007, the plants reached heights of 12 to 15 m (data not shown).

Table 1 shows the biomass values of open-grown and AF coffee plants. The coffee plants in AF presented less biomass production, due to the competition with *M. scabrella*. The largest accumulations of biomass are evident in the dry mass of branches which resulted from long-term effect. The leaf mass is more related to the conditions prevailed in the previous one or two years (Table 1).

Table 1. Biomass of leaves and branches (Mg ha^{-1}) of open-grown coffee and coffee in AF with M. scabrella in Londrina, Parana, Brazil.

Component	Open-grown	AF
Leaves	4.49 a*	4.74 a
Orthotropic Branches	16.19 a	10.57 b
Plagiotropic Branches	8.00 a	5.54 a

* Means followed by the same letter in the row do not differ at 5% of significance according to Tukey´s test.

Table 2 shows the biomass values and the corresponding carbon sequestration of open-grown coffee and the sum of coffee and bracatinga in the AF. It is observed that the total number of leaves, branches and roots was higher in the AF. In the sum of all components the difference was significant, showing the advantage of the AF.

The carbon stock in the soil was higher in the AF, due to the greater accumulation of organic matter up to 0.4 m in depth (Table 3). These results are explained by the greater volume of decomposing material on the surface (liter) and the greater root volume of coffee and *M. scabrella* in the profile. The AFs have lower rates of decomposition and soil respiration when compared to open-grown systems, due to the milder environment that forms beneath the shade trees crowns (Ontl; Schulte, 2012). Perennial crops usually have higher accumulations of carbon in the upper soil layers compared to arable crops with incorporation of surface manure (Ferchaud et al., 2016). Agroforestry has the potential to increase the carbon stock by 25 to 40% in the first 1 m soil layer in comparison to annual crops (De Estefano; Jacobson, 2018). The carbon reservoir in the AF conditions is more stable and cumulative, a fact that leads to an improved soil profile in the medium and long terms (Dignac et al., 2017). It is estimated that an increase of 0.4% of soil carbon could help maintaining global temperature increases below 1.5/2 °C by 2050 (Minasny et al., 2017; Paustian et al., 2016; Chambers et al., 2016). This led France to launch the 4 per 1000-carbon sequestration in soils for food security and climate initiative at the COP 21 in Paris (Dignac et al., 2017). In this context, the AF may be an important technique to help achieving these goals.

Table 2. Biomass of leaves, branches, roots and liter and carbon sequestration (Mg ha^{-1}) from open-grown coffee and AF of coffee with *M. scabrella*. Londrina, Parana, Brazil.

Component	Open-grown	AF
Leaves	4.49 b*	7.35 a
Branches	24.19 b	69.10 a
Roots	16.67 a	22.01 a
Liter	9.35 a	11.21 a
Total biomass	54.71 b	109.67 a
Carbon sequestration	24,62 b	49,35 a

* Means followed by the same letter in the row do not differ at 5% of significance according to Tukey´s test.

Table 3. Carbon stock (Mg ha^{-1}) in the soil, in different depths (m), in the AF of coffee with *Mimosa scabrella* and open-grown coffee. Londrina, Parana, Brazil.

Depth (m)	AF	Open-grown
0-0.1	28.21	24.37
0.1-0.2	16.09	17.23
0.2-0.4	23.83	21.71
0.4-0.6	14.44	15.13
0.6-0.8	14.74	14.26
0.8-1.0	16.15	14.54
Total	113.46	107.24

The accumulated production of processed coffee in five harvests showed that bracatinga trees had severe competition with coffee plants (Table 4).

The treatments with bracatinga had significantly lower

Table 4. Production of processed coffee accumulated in the harvests of 2002 to 2006. Londrina, Parana, Brazil.

Treatment	Kg ha^{-1}
Open-grown	11,490 a*
139 trees ha^{-1}	6,490 b
555 trees ha^{-1}	3,010 c

* Means followed by different letters indicate significance at 5% according to the Tukey test.

production than open-grown cultivation. In the average of the five harvests analyzed, the AF treatments with 139 and 555 trees ha^{-1} produced 63% and 26% of the open-grown. Leal et al. (2005) reported that, from May to August 2003, the photosynthetically active radiation that reached the coffee trees in this area consisted of 23% and 55% of the total incident in densities of 555 trees ha^{-1} and 139 trees ha^{-1}, respectively. It should be noted that no management was carried out with thinning of lower branches of *M. scabrella*, which undoubtedly increased the competition for light with coffee plants.

The first two years of coffee plants are characterized by the prevalence of vegetative growth. During this period, dense shade of coffee trees can be advantageous by reducing stress and providing better conditions for photosynthesis. In Lavras, MG, Brazil, field experiments using artificial shading on coffee during the first two years, with interception of radiation of 35, 50 and 65% resulted in higher photosynthetic rates during the rainy season. During the dry season the interception of 50% showed better results (Balisa et al., 2012). However, during the reproductive phase the excess of shading inhibits the differentiation process of the floral buds. As a consequence, there is a decrease in the number of productive branches and fruits per branch, leading to an overall decrease in coffee yield (Morais et al., 2006).

Previous studies have shown that a shading that intercepts up to 30 to 40% of photosynthetic radiation in well-managed crops does not cause reduction of coffee production in an AF with *Grevillea robusta* (Baggio et al., 1997). The situation can change in sites with a high frequency of frosts, where a denser shading can offer greater protection and compensate for the competition for light (Caramori et al., 1996). Another factor that can influence the results is the competition between shade trees and coffee plants for water and nutrients. More suitable species consist of trees with deep pivoting roots that compete less for water and nutrients in the upper layers of the soil. Zaro et al. (2019) concluded that in an AF of coffee and double rows of rubber trees spaced 16 m apart, coffee production was similar to cultivation in full sun, based on the average of seven harvests in an area adjacent to the present experiment. Thus, the need for further studies is evident in order to verify the interactions of this system and to adapt the *M. scabella* population and its management to enable the commercial cultivation of this AF.

The contribution of the trees to the total carbon sequestered was evident. The largest contributions are from trunks and roots. *Mimosa scabrella* is a species of subtropical climate that, under our experimental conditions, would be in a marginal situation from the climatic point of view. However, the species showed excellent growth in isolated planting in the conditions of Londrina, PR (Leal et al., 2005). As it is a honey-producing species with excellent calorific value, it has the potential to diversify activities within the property and add value. In the native areas to the south, bracatinga is widely used for the production of firewood, in logging systems with removal of wood and controlled burning for planting and regeneration (Grodzki et al., 2004).

The results presented in this work show that there is a great potential to increase carbon sequestration in coffee crops with the use of AFs. Further studies are still necessary, especially those that can approach the quantitative aspects of competition between trees and coffee plants, with an emphasis on different species, densities, and management of trees with pruning. Most studies on AF with coffee are qualitative and restricted to limited sites, due to the operational difficulties of conducting long-term experiments and the large areas required to operationalize them. In order to make these systems feasible for farmers, research should focus on the development of models that allow to quantify these relationships to identify the balance points between the system's productivity and coffee production (Van Oijen et al., 2010).

Conclusion

The AF of coffee with *M. scabrella* showed a higher carbon stock in biomass and in the soil when compared to open-grown. However, the population density of bracatinga caused a significant drop in coffee yield, suggesting the need for further studies to adapt the *M. scabrella* population and its management in this system.

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Paulo Henrique Caramori[1(*)], Heverly Morais[1], Alex Carneiro Leal[1], Armando Androcioli Filho[1], Daniel Campos Caramori[2], Geovanna Cristina Zaro[3] e Ângela Beatriz Ferreira da Costa[4]

1 IAPAR. Rodovia Celso Garcia Cid, km, CEP 375 86047-902 Londrina, PR.
E-mails: pcaramori@gmail.com, heverlymorais@gmail.com, alexcarneiroleal@gmail.com e aandrociolifilho@gmail.com
2 Graduate student at University of Montreal, Canada. Email: daniel.caramori@gmail.com
3 Posdoctoral researcher at University of Guelph, Canada. Email: geoczaro@gmail.com
4 Bolsista do Consórcio Pesquisa Café, IAPAR, Londrina, Brazil. Email: angelabcosta@gmail.com
(*)Autor para correspondência.

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RESUMO

Os sistemas agroflorestais (SAF) são uma alternativa para o manejo sustentável da produção e para a adaptação de ambientes às mudanças climáticas. O café arábica é uma planta sensível a extremos térmicos e poderá ser uma das culturas mais afetadas pelo aquecimento global. Os SAF podem contribuir para mitigar os efeitos do aquecimento global por meio do sequestro do carbono atmosférico e sua fixação na biomassa e no solo. Neste trabalho avaliaram-se o sequestro de carbono e a produção de um SAF de café com bracatinga (*Mimosa scabrella*) em uma região de transição para clima subtropical no sul do Brasil. Foram avaliadas duas densidades de bracatinga (555 e 139 árvores ha^{-1}) comparadas com o cultivo a pleno sol. O sequestro de carbono foi significativamente superior no SAF, mas a produção de café foi reduzida pela competição com a *M. scabrella*. São necessários novos estudos para ajustar densidade populacional e manejo da bracatinga para viabilizar o uso comercial desse sistema.

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