

Changes in Microclimate and Arabica Coffee Quality when Intercropped with Macadamia

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Editor: Samuel Pereira de Carvalho

Received in November 6, 2025 and approved in April 13, 2026

ABSTRACT

A series of studies has demonstrated that intercropping Arabica coffee with macadamia trees can increase coffee yield, land-use efficiency, and farmer income, but there is no information if it also improves coffee beverage quality by altering the microclimate of the crop canopy. This study aimed to assess the changes in the microclimate of an adult Arabica coffee crop (Obatã IAC 1669-20) when intercropped with the macadamia tree cultivar HAES 816, and to evaluate the coffee bean and beverage quality in intercropping with six macadamia cultivars (HAES 344, HAES 660, HAES 816, IAC 4-12B, IAC 4-20, and IAC 9-20) in southeastern Brazil. Five replicates were randomly selected from each treatment area. Macadamia intercropping reduced the extremes and mean air temperature (0.7 °C), incident solar radiation (24%), and the wind speed (39% maximum and 49% mean values) in the coffee canopy compared to monocropped coffee. The average relative air humidity was 1.9% higher in the intercrops than in the monocrops. The intercropping delayed coffee berry ripening and resulted in a larger bean size and higher hulled bean yield and beverage scores, but the coffee quality did not vary with the intercropped macadamia cultivar. Intercropping with macadamia trees provided a milder and more favorable environment for Arabica coffee plants than monocrops, which is a suitable strategy for higher-quality coffee beverage production.

Key words: *Coffea arabica*; *Macadamia integrifolia*; intercropping; beverage quality; agroforestry.

1 INTRODUCTION

Climate change is contributing to the increased vulnerability of agricultural systems worldwide (Shamshad et al., 2024). The AR6 SYR report indicates that the global average surface temperature will be 1.1 °C higher between 2011 and 2020, compared to the 1850–1900 period, and projected an increase of 1.5 °C in the first half of the 2030s and that will be very difficult to control the temperature increase within 2.0 °C by the end of the 21st century (IPCC, 2023; Poncet et al., 2024).

Coffee is one of the most consumed beverages worldwide, supporting a multimillion-dollar industry (ICO, 2024). Brazil has been the world's leading coffee producer and exporter for the last two centuries (Perdoná et al., 2021), and is currently responsible for one-third of global coffee production (FAOSTAT, 2024). However, considering the worst-case scenarios from the IPCC reports, Assad et al. (2004) predicted a reduction in the area suitable for Arabica coffee (*Coffea arabica* L.) cultivation by up to 95% in the main Brazilian regions, a scenario similar to several other regions of the world (Bunn et al., 2015). Coffee yield and quality are also expected to decline because of climate changes (Bunn et al., 2015; Poncet et al., 2024) and the fact that almost all coffee is grown in full-sun cultivation systems makes coffee crops in Brazil even more vulnerable (Assad et al., 2004; Poncet et al., 2024). Thus, seeking practices that make coffee cultivation

systems more sustainable and efficient in the face of adverse environmental conditions is imperative (Soratto et al., 2022; Moreira et al., 2024).

Tree planting can help protect coffee plantations from extreme temperatures and maintain plant gaseous exchange, maintain or improve soil fertility, improve water availability, reduce the biennial production pattern by reducing impoverishment (“die-back”), and increase the useful life of the plantation, reduce the incidence of some pests, diseases, and weeds, and be an extra source of income for the farmer (DaMatta & Rena, 2002; Pezzopane et al., 2010; Mancuso, Soratto & Perdoná, 2013; Silva et al., 2013; Perdoná & Soratto, 2015b; 2016). The sensory quality of coffee beverages can also be improved by intercropping coffee plants with tree species (Freitas et al., 2020). However, it may have disadvantages, such as higher costs of pruning to regulate shading, limitation of the production potential, and difficulty of mechanization, especially of the harvest (DaMatta & Rena, 2002; Mancuso, Soratto & Perdoná, 2013; Perdoná & Soratto, 2015b; 2016). Thus, efficient intercropping systems seek to meet sustainability interests while also aiming to maintain mechanization practices and ensure profitability for farmers (Perdoná & Soratto, 2020; Soratto et al., 2022; Luis-Olivas et al., 2023; Poncet et al., 2024).

Macadamia (*Macadamia integrifolia* Maiden and Betche) stands out among the trees that can be intercropped with coffee crops. The intercropping of Conilon coffee (*Coffea*

canephora Pierre) and macadamia reduced wind intensity by 72% and the average air temperature by 2.2 °C compared to coffee monoculture (Pezzopane et al., 2010). However, the intercropping of Arabica coffee and macadamia caused a decrease in coffee yield, especially when the shading was more intense (>87%) (Steiman et al., 2011).

In the state of São Paulo, Brazil, Hawaiian macadamia cultivars, especially HAES 816, have been more suitable for intercropping with Arabica coffee after crop planting (Perdoná et al., 2012; Perdoná & Soratto, 2016). Under rainfed conditions, intercropping with macadamia increased Arabica coffee yield by 10% and land-use efficiency 2.6-fold, whereas the combined use of intercropping and irrigation increased the land-use efficiency 5-fold (Perdoná & Soratto, 2015a; 2015b). Soratto et al. (2022) also found that Arabica coffee yield was 215% higher and gross income was 3.2-fold higher over 10 harvests in Arabica coffee–macadamia intercropping than in Arabica coffee monoculture under rainfed conditions, demonstrating the complementarity between crops. However, to date, the environmental changes caused by intercropping, which could explain the results obtained, have not been addressed, nor have the changes in coffee quality due to shading caused by macadamia trees.

Producers from several countries have used afforestation to produce high market-value specialty coffees (Vaast et al., 2006; Somporn et al., 2012; Mancuso, Soratto & Perdoná, 2013; Tolessa et al., 2017). However, controversy remains as ideal shade management practices are highly site-specific and require further studies to clearly indicate their influence on the quality of coffee produced (Freitas et al., 2020; Tolessa et al., 2017). Thus, it was hypothesized that intercropping Arabica coffee with macadamia could improve the microclimatic conditions in the plantation and, consequently, the bean and beverage qualities of the coffee.

This study aimed to evaluate changes in the microclimate, bean quality, and beverage quality of Arabica coffee intercropped with macadamia in an experiment planted 10 years before measurements in central part of São Paulo State, southeastern Brazil. In addition, we aimed to evaluate which macadamia cultivars provide the best-quality Arabica coffee beverage when intercropped.

2 MATERIAL AND METHODS

2.1 Site Description

This study was conducted on an experiment with monocropped Arabica coffee and coffee–macadamia intercropping located on a farm in Dois Córregos, São Paulo State, in southeastern Brazil (48°22' W; 22°21' S and 753 m asl). The experiment was started (planted) in February 2006 (Perdoná & Soratto, 2016), i.e., at the time of the evaluations

presented in this study (2016 and 2017), the plants were already in an advanced stage (adult plants).

2.2 Experimental Layout and Treatments

Briefly, the treatments consisted of monocropped Arabica coffee (continuously cropped coffee cultivar Obatã-IAC 1669-20 monoculture) and Arabica coffee (Obatã IAC 1669-20) intercropped with six macadamia cultivars (HAES 344, HAES 660, HAES 816, IAC 4–12B, IAC 4–20, and IAC 9–20). In the monocropped coffee treatment, Arabica coffee plants were arranged in a spacing of 3.5 by 0.7 m (4081 plants ha⁻¹). In the coffee–macadamia intercropping treatments, macadamia trees were arranged in a spacing of 10.5 by 4.9 m (194 plants ha⁻¹), and the coffee plants had the same arrangement as in monoculture; however, at a rate of 3887 plants ha⁻¹ due to the substitution of coffee plants for macadamia trees (Perdoná & Soratto, 2016).

Each treatment occupied a specified area of approximately 2,000 m² (comprising four rows of macadamia trees and/or 12 rows of coffee plants with a row length of approximately 50 m). Five replicates (sampling units) were randomly selected from each treatment area. Each sampling unit was 24.5 × 10.5 m (257.3 m²) and was composed of 105 coffee plants in the monocropped coffee treatment and of 70 coffee plants and five macadamia trees in the coffee–macadamia intercropping treatments. Details of plant management, experimental design, and sampling units are described in Perdoná and Soratto (2016, 2020).

2.3 Microclimatic Monitoring

Between 1st January 2016 and 31 December 2017, microclimatic measurements (air temperature, relative humidity, wind speed, and incident solar radiation) were taken. For this purpose, three portable weather stations were installed: one in the monocropped coffee treatment, second in a row of coffee plants intercropped with the macadamia cultivar HAES 816, which was considered the most suitable for intercropping (Perdoná & Soratto, 2016); and a third station located in an adjacent open field [a Bahiagrass (*Paspalum notatum* Flüggé) pasture].

The sensors were positioned approximately 2.7 m high (above the canopy of the coffee plants) and coupled to an automatic data acquisition system (model CR10X, Campbell Scientific, Logan, Utah, USA) programmed to take readings every 20 s, averages every 15 min and every hour, and to obtain daily values. In this study, the coffee plants had an average height of 2.8 m, whereas the HAES 816 macadamia cultivar had a height of 6.5 m (Perdoná & Soratto, 2020). The daily averages for each variable were presented.

2.4 Fruit Ripening, Hulled Bean Yield, Bean Size, and Beverage Quality

Between August and September of 2016 and 2017, coffee fruits from each sample unit were harvested using a mechanical coffee harvester (self-propelled coffee harvester Electron, TDI Máquinas Agrícolas, Araguari, Minas Gerais, Brazil). After harvest, a 1 kg sample of fruit from each treatment was drawn, from which the green, ripe (cherry), and dry fruits were counted (Table 1). The coffee berries harvested from each sampling unit were dried in a masonry patio in a hot house until they reached a moisture content of 11–12%. Subsequently, the fruits were processed (hull removal) to determine the hulled green-bean yield (as a percentage of the dried fruit). The hulled green-bean yields (in kg ha⁻¹) were presented by Perdoná and Soratto (2020). Coffee bean size was determined by passing a sample of 0.3 kg of hulled green beans through sieves with 15–18/64" (5.95–7.14 mm) diameter holes. We calculated the percentage of beans retained in each sieve (Table 1).

To evaluate the sensory quality of the coffee beverage, ripe berry samples were collected manually to avoid harvesting green or dry fruits. This was performed to separate the effects of a possible improvement in bean quality from the effect of uneven ripening of the beans. Sensory evaluation of the coffee beverages from each sampling unit was performed by a trained and certified Specialty Coffee Association (SCA) sensory expert (Q-grader). Each sample was tested in five cups (five

replicates, each corresponding statistically to 20% of the sample) in an air-conditioned room at 22 °C.

The classification system developed by the SCA was used with a decimal scale from zero to 100 points (SCA, 2016). It includes a standard list of attributes divided into broad and specific categories. For each cup, trained panelists scored the following sensory attributes: a) fragrance (from the dry powder) and aroma (after hydration and after breaking the crust); b) uniformity; c) absence of defects (undesirable fermentations, undesirable bitterness); d) sweetness (reference = 0.5% m/v); e) flavor; f) acidity (type of acidity, intensity, and quality); g) body (intensity and quality); h) finish; (persistence and residual quality); i) balance (interaction between flavor, body, and acidity); j) defects; and k) overall assessment (SCA, 2009, 2016).

2.5 Chemical Soil Attributes and Leaf Nutrient Concentrations

Topsoil (0–0.2 m) samples were collected in August 2016 and 2017 under coffee canopy projections. Three sub-samples were collected from each of the five sampling units and combined to form a composite sample for each treatment. Soil pH in 0.01-mol L⁻¹ CaCl₂ suspension (1:2.5 soil/solution), organic matter content, total acidity at pH 7.0 (H + Al), and concentrations of resin-extractable P, K⁺, Ca²⁺, and Mg²⁺ were determined (Raij et al. 2001). Cation exchange capacity (CEC) and base saturation (BS) values were calculated (Table 2).

Table 1: Percentage of green, ripe, and dry fruits at harvest and percentage of beans retained in sieves with hole diameters larger than 18/64", 17/64", 16/64", 15/64", and smaller than 15/64" of Arabica coffee intercropped with different macadamia cultivars or monocropped under drip-irrigated conditions, evaluated after ten years of planting in the 2016 and 2017 years, at Dois Córregos, state of São Paulo, Brazil.

Treatment	Fruit maturation stage (%)			Sieves (%)				
	Green	Ripe	Dry	18	17	16	15	<15
Year 2016								
Coffee-macadamia HAES 816	18.8	61.4	19.8	8	30	36	13	13
Coffee-macadamia HAES 344	19.1	64.7	16.2	13	31	30	14	12
Coffee-macadamia HAES 660	19.1	60.2	20.6	10	29	33	12	16
Coffee-macadamia IAC 9-20	20.1	58.7	21.2	34	40	9	9	8
Coffee-macadamia IAC 4-12B	13.9	64.6	21.5	20	30	25	15	10
Coffee-macadamia IAC 4-20	20.6	66.2	13.2	10	24	33	18	15
Monocropped coffee	18.3	51.0	30.7	5	19	38	24	14
Year 2017								
Coffee-macadamia HAES 816	22.3	64.4	13.3	16	26	29	13	16
Coffee-macadamia HAES 344	17.9	63.5	18.6	15	29	28	18	10
Coffee-macadamia HAES 660	20.1	63.6	16.2	13	21	35	21	10
Coffee-macadamia IAC 9-20	32.5	60.3	7.1	27	26	21	13	13
Coffee-macadamia IAC 4-12B	29.6	61.2	9.2	26	28	20	17	9
Coffee-macadamia IAC 4-20	16.1	68.1	15.8	2	31	31	15	21
Monocropped coffee	15.8	66.3	17.9	12	23	32	19	14

Table 2: Soil chemical characteristics in the tree canopy projection of Arabica coffee intercropped with different macadamia cultivars or monocropped under drip-irrigated conditions, evaluated after ten years of planting in the 2016 and 2017 years, at Dois Córregos, state of São Paulo, Brazil.

Treatment	pH(CaCl ₂)	OM (g dm ⁻³)	P _{resin} (mg dm ⁻³)	H+Al	K ⁺	Ca ²⁺	Mg ²⁺	CEC	BS (%)
				(mmol _c dm ⁻³)					
Year 2016									
Coffee-macadamia HAES 816	4.7	16	31	23	2.2	26	7	59	61
Coffee-macadamia HAES 344	4.4	17	43	21	1.8	25	7	56	62
Coffee-macadamia HAES 660	4.7	14	38	25	2.1	24	6	58	57
Coffee-macadamia IAC 9-20	4.7	13	32	28	1.8	19	6	56	50
Coffee-macadamia IAC 4-12B	4.3	11	34	28	1.9	19	5	55	49
Coffee-macadamia IAC 4-20	4.7	12	45	24	2.0	23	8	58	59
Monocropped coffee	4.5	14	37	20	2.2	22	7	52	62
Year 2017									
Coffee-macadamia HAES 816	4.6	16	43	23	2.0	24	7	57	60
Coffee-macadamia HAES 344	4.8	15	41	23	2.0	25	6	57	60
Coffee-macadamia HAES 660	4.6	18	35	27	2.2	24	7	61	56
Coffee-macadamia IAC 9-20	4.6	17	32	28	1.8	22	7	60	53
Coffee-macadamia IAC 4-12B	4.7	18	34	28	1.9	19	5	55	49
Coffee-macadamia IAC 4-20	4.6	16	49	24	2.1	23	8	58	59
Monocropped coffee	4.5	16	46	20	2.4	21	7	51	61

OM: organic matter, CEC: cation Exchange capacity, BS: base saturation.

In January each year (2016 and 2017), leaves from the third or fourth node of the plagiotropic branches of coffee plants (10 random leaves from the middle third of the plant per sampling unit) were collected (Raij, Cantarella & Quaggio, 1997). The leaves from the five replicates of each treatment were combined into a composite sample, dried in a forced-air oven at 65 °C for 72 h, ground (to pass through a 40-mesh stainless-steel screen), and subjected to nutrient macronutrient (N, P, K, Ca, Mg, and S) concentrations as described by Malavolta, Vitti and Oliveira (1997) (Table 3).

2.6 Statistical Analysis

The microclimatic measurement data were plotted in graphs, and the results were interpreted. The data of hulled green-bean yield and coffee beverage quality (evaluated in five repetitions) were subjected to analysis of variance (ANOVA) using the SISVAR statistical software package (Ferreira, 2011), separately by year. To complete these analyses, we considered each sampling unit as a replicate and assumed that the lack of randomization of treatments did not bias the analyses because the experimental area was uniform, as reported by Perdoná and Soratto (2016, 2020). Data were analyzed using a complete randomized design with seven treatments and five replicates. Means were separated using Tukey's test at a probability level of 0.05.

3 RESULTS

3.1 Microclimatic Measurements

The extremes in daily air temperature were considerably reduced by the presence of macadamia trees intercropped with coffee compared to the other conditions (Figures 1a–d). In 2016, the mean air temperature in the intercrop was on average 0.6 °C lower than in the monocropped coffee and 1.4 °C lower than in the open field condition (Table 4). In 2017, the intercrop also reduced the mean air temperature by an average of 0.8 °C compared to the monocropped coffee; however, there was practically no variation between this treatment and the open field. Slight reductions in average maximum temperatures and increases in average minimum temperatures were also recorded in the intercrop compared with the other conditions in both years (Table 4).

The intercrop maintained a higher relative air humidity than the other conditions during the two years (Figures 1c,d). The relative humidity was, on average, 2.1% and 1.7% higher in the intercrop than in the monocrop in 2016 and 2017, respectively (Table 4).

Wind speed was reduced in the intercropping system (Figures 2a–d). The mean wind speed was generally lower and varied much less in the intercropping system than in the other conditions (Figures 2a,b). In 2016, the maximum wind speed was 14.6 m s⁻¹ in the monocropped coffee and, on the same day,

Table 3: Concentration of nutrients (N, P, K, Ca, Mg, and S) in the leaves of Arabica coffee intercropped with different macadamia cultivars or monocropped under drip-irrigated conditions, evaluated after ten years of planting in the 2016 and 2017 years, at Dois Córregos, state of São Paulo, Brazil.

Treatment	N	P	K	Ca	Mg	S
	(g kg ⁻¹)					
Year 2016						
Coffee-macadamia HAES 816	29	2.1	18	12	4.7	1.1
Coffee-macadamia HAES 344	28	1.9	21	10	4.1	1.1
Coffee-macadamia HAES 660	27	1.7	23	10	3.6	1.0
Coffee-macadamia IAC 9-20	28	1.8	20	7	4.0	1.0
Coffee-macadamia IAC 4-12B	27	2.0	19	9	4.1	1.1
Coffee-macadamia IAC 4-20	27	2.0	25	7	3.6	1.0
Monocropped coffee	28	2.0	20	8	2.8	1.0
Year 2017						
Coffee-macadamia HAES 816	29	2.0	24	9	3.6	1.0
Coffee-macadamia HAES 344	28	1.8	23	11	3.8	1.0
Coffee-macadamia HAES 660	29	2.0	19	8	4.1	1.2
Coffee-macadamia IAC 9-20	26	1.7	21	8	3.6	1.2
Coffee-macadamia IAC 4-12B	26	1.6	20	8	3.3	1.0
Coffee-macadamia IAC 4-20	27	2.0	22	8	3.4	1.2
Monocropped coffee	27	1.9	25	8	3.2	1.0

it was 6.6 m s⁻¹ in the intercrop, i.e., 55% lower (Figure 2c). In 2017, the maximum wind speed recorded in the monocrop was 9.8 m s⁻¹, being 49% lower in the intercrop (5.0 m s⁻¹) (Figure 2d). On average, for both years, the maximum daily and mean wind speeds were reduced by 39.2% and 48.5%, respectively, in the intercrop compared to those in the monocrop (Table 4). The maximum wind speed was, on average, 63.7% lower under intercrop conditions than under open-field conditions.

Intercropping with macadamia resulted in lower average incident solar radiation on the coffee canopy (Figures 2e,f). In 2016, the average incident solar radiation was 13.4 MJ m⁻²d⁻¹ in monocropped coffee and 10.5 MJ m⁻² d⁻¹in intercrop (Table 4). In 2017, 13.0 MJ m⁻² d⁻¹ was recorded in monocrop, while 9.6 MJ m⁻² d⁻¹was found in intercrop.

3.2 Coffee Hulled Bean Yield and Beverage Quality

In 2016, a year of high production in coffee plants (Perdoná & Soratto, 2020), intercropping with the macadamia cultivar HAES 344 provided a higher hulled bean yield than monocropped coffee and coffee intercropped with macadamia IAC 9-20 (Table 5). In 2017, there was a difference in the hulled bean yield of coffee between the treatments in which the coffee plants were intercropped with the macadamia cultivars IAC 4-20 and IAC 4-12B. In general, the differences between treatments were not large in any year, and no significant differences were observed across years.

In 2016, only coffee beverages produced by intercropping with macadamia cultivars HAES 816, HAES 344, and IAC 4-12B were significantly higher than those from the monocropped coffee (Table 5). In 2017, there were no differences in beverage scores. Despite that, all intercrop treatments received numerically higher scores than monocropped coffee in both years. On average over the two years, coffees harvested from intercropping with HAES 816, HAES 344, IAC 9-20, and IAC 4-12 B obtained higher beverage scores than monocropped coffee.

4 DISCUSSION

The average daily solar radiation incident on the coffee plant canopy was reduced by an average of 24% by intercropping with macadamia trees compared to monocropped coffee (Table 4). Reductions in radiation input caused by shading can reduce photooxidative damage, which is frequently observed in Arabica coffee grown in full sun and can increase the life expectancy of plants (DaMatta et al., 2007; Mancuso, Soratto & Perdoná, 2013). High levels of solar radiation, combined with high temperatures, can lead to a rapid decrease in photosynthesis in Arabica coffee plants (Moraes et al., 2003). This is because the saturation irradiance is relatively low in coffee plants, ranging from to 600-700 $\mu\text{mol photon m}^{-2} \text{s}^{-1}$ (DaMatta et al., 2007), and it

is not uncommon for days to reach values above 1000 $\mu\text{mol photon m}^{-2} \text{s}^{-1}$ in coffee-growing regions, with photoinhibition of photosynthesis occurring under this condition, reducing the accumulation of photoassimilates. According to Gomes et al. (2020), agroforestry systems with 50% shade can mitigate the impacts of climate change by maintaining 75% of the area suitable for Arabica coffee production.

The decrease in incident solar radiation may have been the main cause of the decrease in air temperature observed in the intercropping system in the present study (Table 4). These results corroborate those of previous studies, albeit to a lesser extent. Pezzopane et al. (2010) observed a decrease of up to 2.5 °C in the Conilon coffee-macadamia intercropping in the state of Espírito Santo, Brazil, which may have been

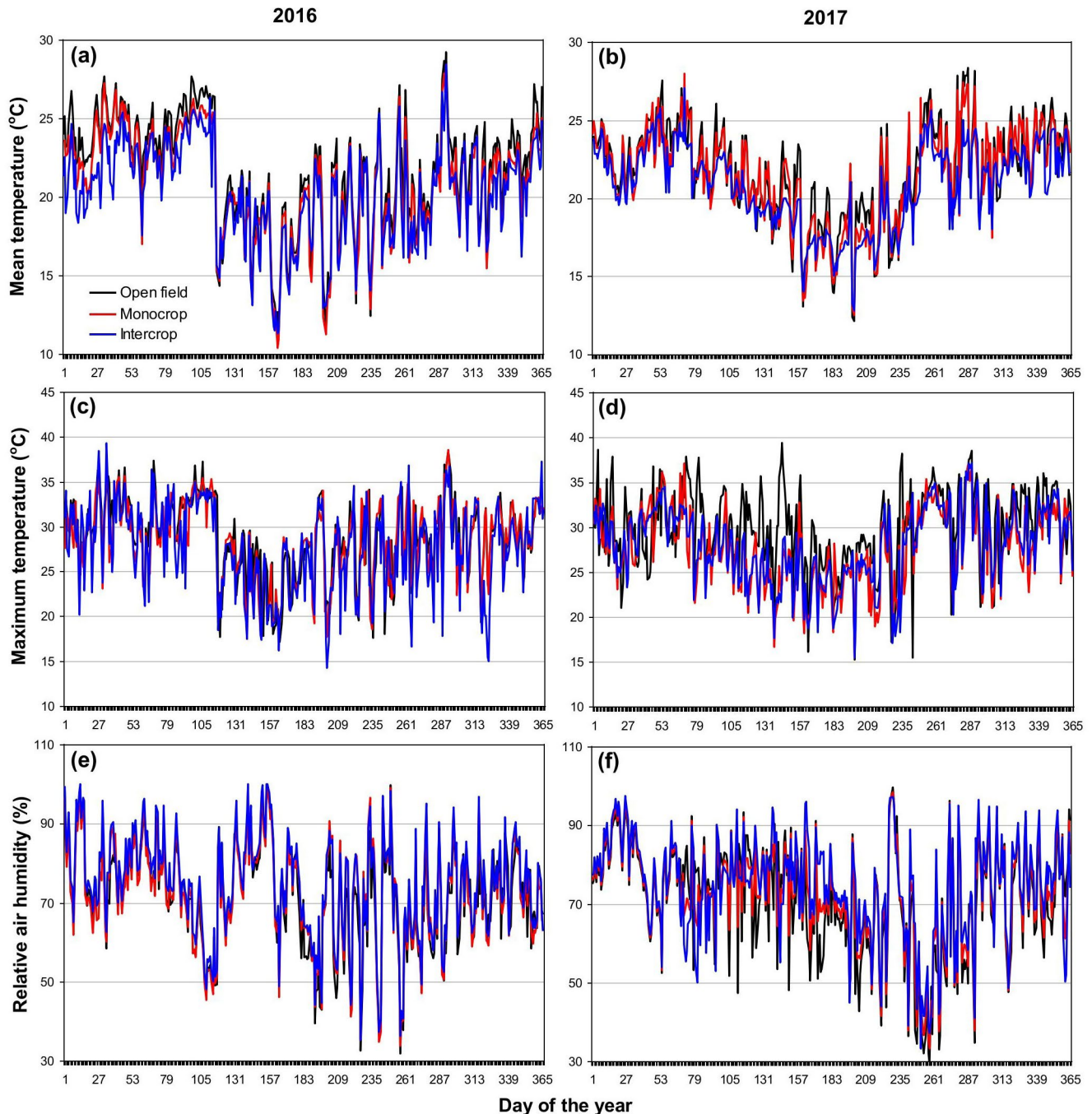


Figure 1: Mean daily air temperature (a, b), maximum daily air temperature (c, d), and relative air humidity (e, f) in open field (Bahia grass pasture, black line), Arabica coffee monoculture (monocropped coffee, red line), and Arabica coffee intercropped with macadamia cultivar HAES 816 (coffee-macadamia intercrop, blue line), evaluated after ten years of planting during 2016 (a, c, e) and 2017 (b, d, f) years, at Dois Córregos, state of São Paulo, Brazil.

Table 4: Annual average for the microclimate measurements recorded in the 2016 and 2017 years and their percentage in relation to the open field condition.

Year	Microclimate measurement	Treatment	Annual average	Percentage in relation to the open field
2016	Daily air temperature (°C)	Open field	28.7	100.0
		Maximum Monocrop	28.4	98.8
		Intercrop	27.6	96.2
		Open field	21.6	100.0
		Mean Monocrop	20.8	96.3
		Intercrop	20.2	97.1
		Open field	15.2	100.0
		Minimum Monocrop	15.5	102.4
		Intercrop	15.8	104.1
	Relative air humidity (%)	Open field	71.6	100.0
		Monocrop	72.5	101.2
		Intercrop	74.6	104.1
	Wind speed (m s ⁻¹)	Open field	8.2	100.0
		Maximum Monocrop	4.5	54.1
		Intercrop	2.8	33.8
		Open field	2.4	100.0
		Mean Monocrop	1.1	43.2
		Intercrop	0.4	16.5
	Solar radiation (MJ m ⁻² day ⁻¹)	Open field	16.8	100.0
		Monocrop	13.4	79.6
		Intercrop	10.5	62.4
2017	Daily air temperature (°C)	Open field	29.8	100.0
		Maximum Monocrop	27.7	93.1
		Intercrop	27.9	96.9
		Open field	21.7	100.0
		Mean Monocrop	21.5	99.0
		Intercrop	20.7	95.5
		Open field	16.0	100.0
		Minimum Monocrop	15.9	99.4
		Intercrop	16.2	101.4
	Relative air humidity (%)	Open field	71.0	100.0
		Monocrop	72.6	102.3
		Intercrop	74.3	104.6
	Wind speed (m s ⁻¹)	Open field	6.5	100.0
		Maximum Monocrop	4.2	64.0
		Intercrop	2.5	38.0
		Open field	2.4	100.0
		Mean Monocrop	0.9	36.3
		Intercrop	0.6	25.3
	Solar radiation (MJ m ⁻² day ⁻¹)	Open field	16.4	100.0
		Monocrop	13.0	79.2
		Intercrop	9.6	57.7

due to the climatic characteristics of the region or the spacing between plants used in the intercrop. The minimum valleys and, mainly, the maximum peaks of daily temperature were also reduced in the intercropping system, demonstrating that this is an efficient way to protect coffee plants from extreme temperatures. For this reason, intercropping coffee plants with shade trees is considered a climate-smart agricultural practice (Pezzopane et al., 2010; Ortiz-Gonzalo et al., 2018; Selbonne et al., 2022). This improves coffee yield and quality, as milder temperatures slower the ripening and drying of fruits on the plant (Pinard, Boffa & Rwakagara, 2014; Tolessa et al., 2017), as observed in the present study (Table 1).

Intercropping with macadamia trees maintained relative humidity in the canopy of coffee plants than the monocrops. Arabica coffee plants have a strong stomatal sensitivity to increased vapor pressure deficits, which largely restricts the influx of CO₂ into the leaves, thus limiting photosynthesis, particularly in the afternoon (DaMatta et al., 2007), even with soil water availability. This favored CO₂ assimilation, photosynthesis, and sugar accumulation, and consequently provided greater production and better quality of the coffee beverage, even under irrigated conditions, since sugar content is positively correlated with flavor (Borém et al., 2016; Pereira et al., 2021).

Reductions of 48.5% in the average and predominantly peak wind speeds were found, proving the efficiency of the intercropping of macadamia trees as a windbreak in coffee plantations as a climate smart agriculture practice (Ortiz-Gonzalo et al., 2018; Selbonne et al., 2022). Pezzopane et al. (2010) also found, on average, reductions of 72% and 54% in average and maximum wind speeds, respectively, in Conilon coffee–macadamia intercropping.

Although coffee intercropped with the macadamia cultivars HAES 344 and IAC 4-20 stood out in terms of hulled bean yield in 2016 and 2017, the differences were not consistent in both years, and there were no differences on average across the years. Intercropping resulted in a higher percentage of green and ripe fruits and a lower percentage of dry fruits than in monocropped coffee (Table 1), indicating slower ripening, probably because of the lower temperatures observed. Larger coffee beans (i.e., a higher percentage of beans retained on the 18/64” and 17/64” sieves) were also observed in the intercrop than in the monocrop. Coffee beans produced in medium or dense shade are typically heavier than those from full sun crops (Vaast et al., 2006; Bosselman et al., 2009; Tolessa et al., 2017). Shaded coffee plants have a lower fruit load (Vaast et al., 2006; Alemu, 2015; Perdoná & Soratto, 2020) and their fruits ripen more slowly because shading reduces the temperature around the coffee fruit, which is harvested 2–4 w later than the fruit of plants grown in full sun (Vaast et al., 2006; Bosselman et al., 2009). Furthermore, the greater partitioning of photoassimilates to individual fruits, and even

from the husk (mainly the mesocarp) to the bean (endosperm), increases the weight of coffee beans under shade conditions (Tolessa et al., 2017). Despite this, the small influence of intercropping on hulled bean yield can be explained by the small reduction in the fruit load of coffee plants, which was on average 12% compared to those grown in full sun (Perdoná & Soratto, 2020).

Intercropping with macadamia had a positive effect on coffee beverage quality, with a substantial increase in the score in 2016 and the average of the years. Coffee quality is a complex characteristic that can be assessed at different levels, including the chemical composition and integrity of beans, their physical classification, and sensory analysis of the beverage itself (Pereira et al., 2021). Many factors are involved

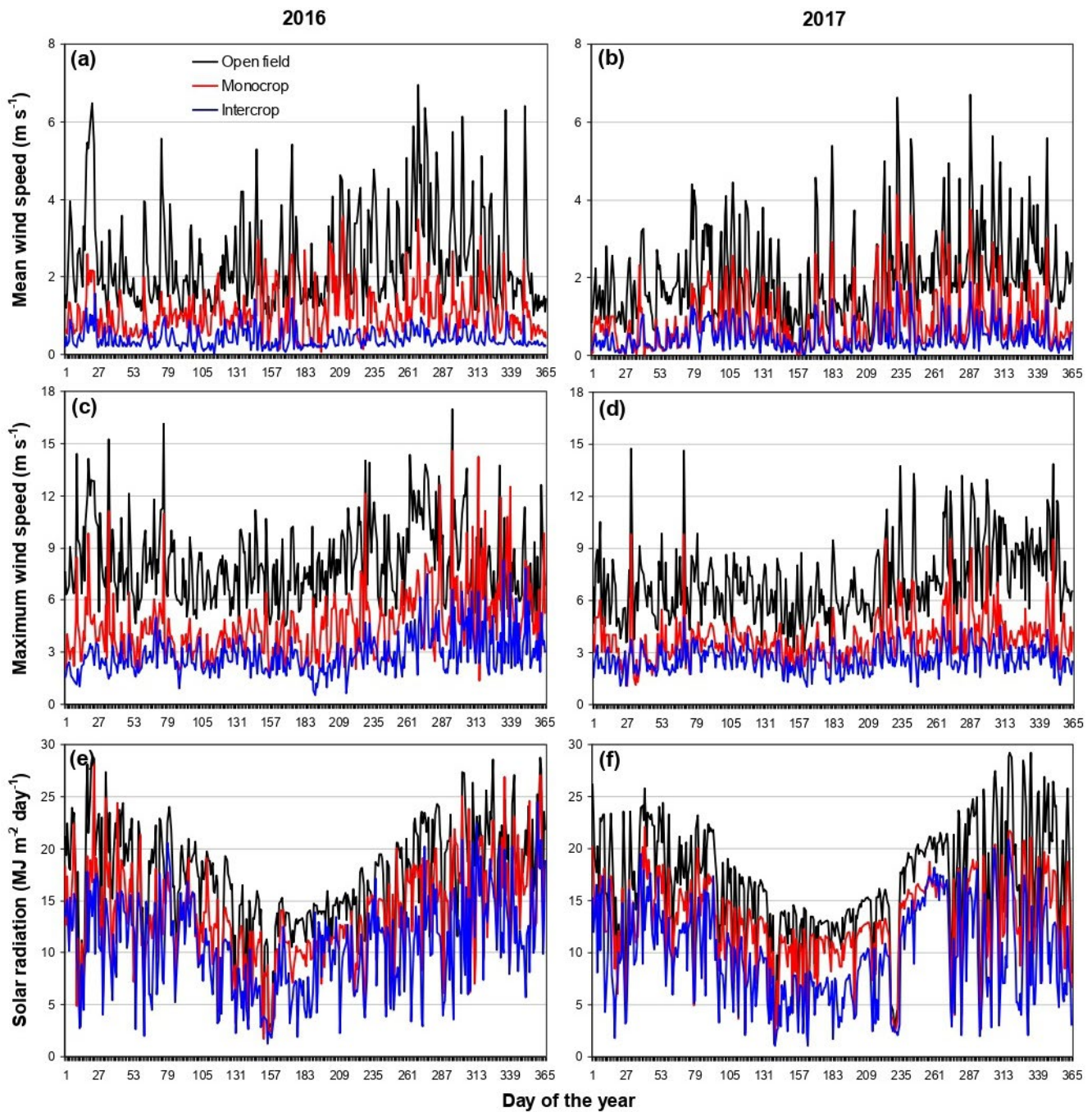


Figure 2: Mean daily wind speed (a, b), maximum daily wind speed (c, d), and daily solar radiation (e, f) in open field (Bahia grass pasture, black line), Arabica coffee monoculture (monocropped coffee, red line), and Arabica coffee intercropped with macadamia cultivar HAES 816 (Coffee-macadamia intercrop, blue line), evaluated after ten years of planting during 2016 (a, c, e) and 2017 (b, d, f) years, at Dois Córregos, state of São Paulo, Brazil.

Table 5: Hulled green-bean yield and cup quality of Arabica coffee intercropped with different macadamia cultivars or monocropped under drip-irrigated conditions, evaluated after ten years of planting in the 2016 and 2017 years, at Dois Córregos, state of São Paulo, Brazil.

Treatment	Hulled green-bean yield (%)			Beverage score (SCA)		
	2016	2017	Mean	2016	2017	Mean
Coffee-macadamia HAES 816	51.8ab	51.8ab	51.8a	83.4a	82.3a	82.8a
Coffee-macadamia HAES 344	54.0a	51.0ab	52.5a	83.0a	83.0a	83.0a
Coffee-macadamia HAES 660	53.3ab	50.3ab	51.8a	81.7ab	82.8a	82.2ab
Coffee-macadamia IAC 9-20	51.3b	51.3ab	51.3a	82.5ab	83.2a	82.9a
Coffee-macadamia IAC 4-12B	53.0ab	49.8b	51.4a	83.3a	82.6a	83.0a
Coffee-macadamia IAC 4-20	52.5ab	52.5a	52.5a	82.0ab	82.1a	82.0ab
Monocropped coffee	51.3b	51.8ab	51.6a	80.0b	81.0a	80.5b
F probability	0.019	0.041	0.414	0.005	0.325	0.002

Means followed by the same letter in the column are not significantly different at $P < 0.05$ according to Tukey's test.

in the production, harvesting, postharvest, storage, and preparation processes of the beverage, which interact, alter the final perception, and define the quality of the coffee beverage (Echeverria-Beirute et al., 2018). The overall quality of coffee and its specific quality attributes (e.g., overall assessment, acidity, and flavor) increase with increasing altitude and shade level of shade (Tolessa et al., 2017; Freitas et al., 2020). Coffee beans grown in cooler environments accumulate sufficient sugars and lipids, both of which are key compounds that are positively correlated with coffee quality (Vaast et al., 2006). Somporn et al. (2012) reported that Arabica coffee grown under lychee (*Litchi chinensis* Sonn.) shade had superior bean weight, total sugar, total phenolic and chlorogenic acid content, and antioxidant activity; however, lower concentrations of vanillic and caffeic acids were observed. Läderach et al. (2011) observed that coffee quality scores increased as the level of shading increased. Bosselmann et al. (2009) reported that shade has no significant effect on coffee beverage quality at higher altitudes.

It is important to note that the coffees subjected to beverage quality evaluation in this study were harvested manually, avoiding the harvesting of green or dry fruits. Thus, we separated the effects of the possible improvement in bean quality from those of uneven fruit ripening. This is because producers who seek high-quality coffee have the possibility of selective harvesting or even use methods for separating fruit post-harvest. Even at higher costs, these processes are worthwhile because the demand for high-quality coffee has increased more intensely worldwide than the general demand for coffee (Borém et al., 2016; Pereira et al., 2021). Furthermore, specialty-coffee producers develop loyal relationships with trading companies and better position their coffee in the market (Branco & Santos, 2018). In addition, afforestation makes climatic conditions more favorable for high-quality coffee production, this is because shading causes slower fruit

ripening and greater partitioning of substances in the grains, mainly because of the lower temperature of the plant canopy (Vaast et al., 2006; Somporn et al., 2012; Tolessa et al., 2017), as corroborated by the results of this study. In Ethiopia, which is recognized as the origin of exotic and high-quality coffee, Arabica coffee trees are grown under trees at different levels, and shade management is among the predominant agronomic practices (Tolessa et al., 2017). It is evident that the changes in coffee quality are due to changes in the microclimate, as no marked changes were observed in soil fertility attributes or nutrient concentrations in coffee leaves as a result of intercropping with macadamia (Tables 2; 3), corroborating the results of Pinard, Boffa and Rwakagara (2014).

Although environmental preservation is imperative for an agricultural system to be considered truly sustainable, it must also balance economic viability and social fairness (Gitari et al., 2024; Poncet et al., 2024). For this reason, coffee farmers in Vietnam have already converted their conventional full-sun farms into organic shade farms, while implementing regenerative agriculture techniques (Le et al., 2021). In this way, the Arabica coffee-macadamia intercropping has been shown to meet the needs of environmental preservation, as well as contributing to the resilience of small producers, improving food security, and reducing vulnerability to market volatility (Renard & Tilman, 2019; Pedoná & Soratto, 2015b; 2016; 2020; Soratto et al., 2022).

Agroforestry, or the intercropping of trees with agricultural crops, promotes biodiversity, improves soil quality, and contributes to carbon sequestration, thus mitigating the effects of climate change (Luis-Olivas et al., 2023; Gitari et al., 2024; Chappa et al., 2024). It has been demonstrated that intercropping coffee and macadamia can be a viable option to make cropping systems more stable and efficient. This system improves the microclimate, enhances coffee production (Pedoná & Soratto, 2015b; 2016; 2020; Soratto et al., 2022) and quality,

strengthens food security through better resource use, intensifies food production, and provides additional economic resources for farmers, while also delivering important ecosystem services. These benefits are consistent with the emerging concept of climate-smart agriculture, which aims to sustainably increase the productivity of agricultural systems while enhancing resilience to climate change and reducing carbon footprints (Lipper et al., 2014, Selbonne et al., 2022).

5 CONCLUSIONS

This study demonstrated that intercropping with macadamia trees reduced the air temperature and wind speed (maximum and mean values) in the canopy, providing a milder and more favorable environment for Arabica coffee plants than monocrops. This milder microclimatic condition in the intercrop resulted in slower ripening of coffee berries and the production of larger coffee beans, which is a proper strategy to provide a higher quality coffee beverage. However, the coffee quality did not vary with the intercropped macadamia cultivar.

6 AUTHOR CONTRIBUTIONS

Conceptual Idea: Perdoná, M.P.; Soratto, R.P.; Methodology design: Perdoná, M.P.; Data collection: Perdoná, M.P., Data analysis and interpretation: Perdoná, M.P.; Soratto, R.P.; Parecido, R.J., and Writing and editing: Perdoná, M.P.; Soratto, R.P.; Parecido, R.J.

7 ACKNOWLEDGMENTS

This study was funded by the São Paulo Research Foundation (FAPESP, Proc. 2015/16790-6). We thank the National Council for Scientific and Technological Development (CNPq) for providing an award for excellence in research to the second author.

8 DATA AVAILABILITY STATEMENT

Data available upon request to authors.

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