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Soil CO_2 efflux in coffee agroforestry and full-sun coffee systems

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ABSTRACT. Agroforestry systems may show low CO_2 efflux, and CO_2 efflux contributes to sustainability. This work aimed to evaluate the soil CO_2 efflux in coffee plantations cultivated in agroforestry and full-sun systems during the winter in high-altitude tropical climate regions. The work was carried out at three family farms (RO, GI, and PA) in Minas Gerais, Brazil. Two treatments were established: coffee with and without trees, and 20 sampling spots for soil and gases. The air and soil temperatures in the agroforestry systems were lower than in the full-sun systems. The soil moisture content in agroforestry systems was higher than full-sun only on the GI. Except for the agroforestry systems in PA, all the other systems showed an increase in CO_2 efflux with increasing soil moisture. This increase was more pronounced in agroforestry systems (RO), followed by full sun (RO). On the GI farm, this correlation was lower in the agroforestry system. Soil CO_2 efflux was positively correlated with soil temperature and negatively correlated with total nitrogen, labile carbon and total organic carbon. Therefore, despite the microclimate stability promoted by the agroforestry systems in the winter, no decrease in the soil CO_2 efflux was observed when compared to full sun systems.

Keywords: CO_2 emissions; microclimate; shade-grown coffee; agroecological management; soil properties

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Introduction

Agroforestry systems have the potential to increase carbon sequestration (Jose & Bardhan, 2012). Soil CO_2 efflux is strongly related to higher soil temperature and moisture (Todd-Brown et al., 2013; Fekete et al., 2017; Jia et al., 2018). However, there is still a lack of information on how the removal or introduction of trees in agroecosystems can affect soil CO_2 efflux under different climate conditions.

Agriculture is considered an important source of greenhouse gas emissions but can also act as a sink of atmospheric CO_2, depending on land management. For instance, in agroforestry systems (AFs), trees allow greater sequestration of C, which is incorporated into their biomass and in the soil (Hergoualc'h, Blanchart, Skiba, Hénault, & Harmand, 2012). Although AF is associated with greater C sequestration, not much is known about what happens with the CO_2 efflux in these systems, which are regulated by air and soil temperatures and soil moisture.

Trees in AF regulate the microclimate by reducing air and soil temperatures (Araújo, Partelli, Oliosi, & Pezzopane, 2016; Oliosi Giles, Rodrigues, Ramalho, & Partelli, 2016) and they protect the soil against direct solar radiation. The greater the moisture content in the soil, the higher the levels of CO_2 efflux. Soil moisture influences the activity of microorganisms and the diffusion of gases in soil pores (Kochiieru, Lamorski, Feiza, Feizienė, & Volungevičius, 2018). Soil temperature and moisture influence the soil C cycle, fertility (Posada & Schuur, 2011), structure (Lenka & Lal, 2013) and rate of decomposition of soil organic matter.

Among the options of AF, those with coffee are widely used, since coffee tolerates shade. Trees provide appropriate microclimatic conditions for the ecophysiology of coffee, reducing the variation from biennial production and long lifespan of the coffee plant (Da Matta, Ronchi, Maestri, & Barros, 2007). In agroforestry coffee systems, Gomes et al. (2016) demonstrated that the CO_2 efflux is influenced by soil temperature in the summer. However, little is known about this influence in winter, especially in regions with high-altitude tropical climates, where winter coincides with a period of drought. Coffee is an important crop in the tropics, and quantifying soil CO_2 efflux will provide information on the C budget in agroforestry systems, and their importance in sustainable agriculture, especially under climate change scenarios.

This work aimed to (i) evaluate the influence of trees on the microclimate and CO_2 flux, (ii) quantify soil CO_2 emissions in agroforestry and full-sun coffee systems, and (iii) identify physical and chemical soil attributes that influence CO_2 efflux during the winter in a region with a high-altitude tropical climate.

Material and methods

Study area

The study was carried out in the municipalities of Araponga and Divino, both located in the *Zona da Mata* region of Minas Gerais State, in the Atlantic Forest biome, Brazil, during winter, the dry period of the region. This region has deep, well-drained and acidic soils with low nutrient availability. To carry out this study, three farms were selected, two located in the municipality of Araponga (RO and PA) and a third located in the municipality of Divino (GI). These farms cultivate coffee (*Coffea arabica* L. cv. Red Catuaí) under agroforestry (AF) and full-sun (FS) systems (Table 1). The studied sites have soil classified as Oxisol according to the US Soil Taxonomy (Soil Survey Staff, 2014).

Table 1. Environmental characteristics of agroforestry (AF) and full-sun (FS) coffee systems at the three family farms in the municipalities of Araponga and Divino, Minas Gerais State, Brazil.

Farms Characteristics	RO	PA	GI
Location	Araponga	Araponga	Divino
Latitude	20° 41´ 53.9´´ S	20° 39´ 28.9´´ S	20° 38´ 43.3´´ S
Longitude	42° 31´ 45.4´´ W	42° 33´ 18.9´´ W	42° 11´ 50´´ W
Altitude (m)	1040	800	650
Annual Mean Temperature (°C)	18	18	21
Annual Mean Precipitation (mm)	1345	1345	1282
Declivity (%)	12	3	5
Estimation of the mean tree heights (m)	12	5	5
Age of coffee plants (years)	20	9	25
Distance between coffee plants (m)	3 x 1	3 x 1	3 x 1
Year of implementation of AFs	1998	2006	2010
Main tree species present in AF	*Inga subnuda*	*Solanum* sp. and *Musa* sp.	*I. subnuda; Solanum* sp.; *Musa* sp.; *Toona ciliata*

In the GI property, the PS system is managed in a conventional way (weeding and chemical fertilization). In the other properties, both in AF and FS, the farmers use similar agroecological management practices, such as not using pesticides, using green soil cover, corn intercropped with coffee in full sun, and maintaining corn straw in the coffee plantation to add organic matter. However, the AF and FS coffee systems were implemented in different years (Table 1).

Experimental design

At each farm, a coffee area of approximately 300 m^2 was selected. In parts of this area, coffee was either intercropped with trees (AF) or not (full-sun - FS). Between coffee rows, ten spots of 1 m^2 each, 5 m apart from each other, were delimited in the AF and ten were delimited in the FS. In each of these spots, CO_2 efflux was analyzed, and soil samples were collected. Two treatments were established: coffee with and without trees. The ten spots were considered repetitions.

Level of shade

Hemispherical or "fish-eye" lens photographs were used to determine the canopy cover as indirect methods to evaluate the shade levels of the areas. The photos were taken with a Canon T2i 18-megapixel camera and a “fisheye” lens using a bubble-level tripod to keep the camera at the same level as the terrain.

The tripod with the camera was adjusted to 80 cm height above the soil surface in the center of the sampling areas. The camera was pointed to the north. As light intensity is important for the quality of the images, the photographs were taken in the morning, avoiding direct sunlight on the lens. A 6.3 M objective aperture was used to obtain all images (Pueschel, Buddenbaum, & Hill, 2012), and the photographs were saved as 16-bit. An image of each sampling area was taken and analyzed by the GLA (Gap Light Analyzer) program.

A blue band was used to achieve the ideal brightness (Leblanc, Chen, Fernandes, Deering, & Conley, 2005). A total of 60 images were taken.

Soil analysis

Randomized soil samples were collected at depths of 0 to 20 cm in AF and FS for particle-size and chemical analyses. For the other chemical and physical analyses, undisturbed and disturbed soil samples were taken in each 1 m^2 spot. Undisturbed samples were collected using volumetric rings and the samples were used to determine soil bulk density (BD) by the volumetric ring method and soil particle density (PD) was measured using the volumetric flask method (Embrapa, 1997). The disturbed samples were first ground and passed through a 0.2-mm-mesh sieve and the samples were then used to analyze the total organic carbon (TOC) (Yeomans & Bremner, 1988), labile carbon (LC) (Blair, Lefroy, & Lisle, 1995 modified by Shang & Tiessen, 1997) and total nitrogen (TN) (Bremner, 1996). Microporosity (Pmi) was calculated as the amount of water retained in undisturbed soil samples subjected to a pressure of -0.006 MPa (~60 cm H_2O). Total porosity (TP) was calculated using soil bulk density (BD) and particle density (PD), according to the equation TP = 1- BD/PD. Macroporosity (Pma) was calculated by the difference between total porosity (TP) and microporosity (Pmi).

Air and soil temperature and soil moisture

Air temperature (T_{air}) and soil temperature (T_{soil}) were measured, and soil moisture (S_{moi}) was determined at the same spot and time where CO_2 efflux was measured. T_{air} was measured using a Thermo-Hygrometer, Incoterm (Model 7666.02.0.00). To measure T_{soil}, a portable thermometer was inserted 5 cm deep into the soil. S_{moi} was considered the gravimetric water content. To determine S_{moi}, soil samples were collected at 0-5 cm and stored in aluminum cans. The cans were then sealed with plastic tape, preventing moisture loss. In the laboratory, soil samples were weighed and dried at 105°C for 48h.

Evaluation of soil CO_2 efflux and temperature sensitivity of soil

To evaluate the soil CO_2 efflux, a PVC ring (diameter of 10 cm and height of 7 cm) was placed in the center of each sampling spot. The rings were inserted 3 cm deep into the soil, with 4 cm of the PVC ring above the surface. Large branches and leaves were removed from the soil surface before installing the rings.

The rings were placed between rows of coffee plants 24 hours before each measurement to restore the CO_2 balance of the soil after disturbing the soil with the insertion of the ring (Heinemeyer et al., 2011). Total soil respiration was evaluated using a portable analyzer LI-8100 (Li-Cor, USA) coupled to a dynamic chamber (LI-8100), which was positioned on the same PVC ring previously installed. The chamber was coupled to an analysis system that quantified the concentration of CO_2 through infrared absorption spectroscopy. Each CO_2 efflux measurement took 1.5 min. The concentration of CO_2 inside the chamber was obtained every three seconds. Data were collected in the morning (8:00 am to 10:00 am) and in the afternoon (12:00 pm to 2:00 pm) for three consecutive days at each farm. The data from each day were averaged. The evaluation of CO_2 in the 20 rings was carried out as fast as possible to minimize the variation in soil temperature and moisture between the sampling areas (La Scala, Bolonhezi, & Pereira, 2006). From one farm to the other, there was an interval of seven days.

In total, 360 evaluations of soil CO_2 efflux were carried out in the three properties. However, at the GI farm, data from the third day were not considered because of unexpected rain that occurred in the early morning, which changed the soil moisture, temperature and soil CO_2 efflux. Consequently, the data obtained at the GI farm were calculated using the average from the first two days.

An exponential regression was applied to find the correlation between soil CO_2 efflux and soil temperature (Equation 1) (Van't Hoff, 1898).

$$FCO_2 = \alpha . e^{(\beta 1.T)} \quad (1)$$

where FCO_2 is the CO_2 efflux (μmol m^{-2} s^{-1}), T is the soil temperature, α is the soil CO_2 efflux interception when the temperature is zero and β1 is the regression coefficient obtained from the natural logarithm of the soil CO_2 efflux for soil temperature at 5 cm depth.

The parameter Q_{10} was calculated to compare the temperature sensitivity of soil in the AF and FS systems of each farm. This parameter describes the proportional change in soil respiration when the soil temperature is increased by 10°C (Giardina & Ryan, 2000). Q_{10} values were obtained based on the correlation between soil temperature at 5 cm depth and soil CO_2 efflux according to Equation 2.

$$Q_{10} = e^{10.\beta 1} \quad (2)$$

When calculating the Q_{10} values of each system at each farm, data from the two periods together (morning and afternoon) in each system were considered.

Statistical analysis

Soil CO_2 efflux and soil physical and chemical attributes were analyzed by descriptive statistics. The spatial variability of soil CO_2 efflux was characterized for each measurement by calculating the coefficient of variation using data from all the sampling areas of the two systems at the three farms. Scatter plots with Pearson correlations were used between canopy cover and air temperature, soil temperature and soil moisture. Scatter plots with Pearson correlations were also used between soil CO_2 efflux and soil temperature and soil moisture. Principal component analysis (PCA) was also used to reduce the complex dataset to a lower dimensionality to reveal simplified structures that explained the complex dataset. PCA was performed with all variables from the three farms combined to assess how the variables were correlated. R version 3.4.3 software was used to perform the Pearson correlations and PCA (R Core Team, 2017).

Results

Carbon, total nitrogen, and physical properties of the soil

The soil chemical attributes were similar between AF and FS at each farm, with more pronounced differences in the TOC and TN contents (Table 2). In both systems, the TOC values were lower at the GI farm than at the other farms. At the RO farm, TOC was 19% and TN was 24% higher in FS than in AF. At the PA farm, TOC was 14% and NT was 15% higher in FS than in AF. At the GI farm, TOC was 8.1% and TN was 7.2% higher in AF than in FS. The TOC contents at the RO and PA farms were approximately 33.8% higher than those at the GI farm.

Table 2. Average soil chemical (n = 10 per system) and physical (n = 30 per system) attributes in agroforestry (AF) and full-sun (FS) coffee systems at the three farms at a soil depth of 0-20 cm.

Systems	AF (RO)	FS (RO)	AF (PA)	FS (PA)	AF (GI)	FS (GI)
Soil chemical properties						
TOC (g kg^{-1})	37.80 (0.4)	46.90 (0.3)	30.60 (0.5)	35.60 (0.3)	26.00 (0.1)	23.90 (0.1)
TN (g kg^{-1})	3.40 (0.2)	4.45 (0.3)	2.89 (0.3)	3.40 (0.3)	2.90 (0.1)	2.69 (0.0)
LC (g kg^{-1})	2.70 (0.3)	2.40 (0.2)	2.20 (0.2)	2.40 (0.2)	2.30 (0.3)	1.89 (0.3)
Soil physical properties						
BD (g cm^{-3})	1.05 (0.02)	1.08 (0.02)	1.27 (0.05)	1.24 (0.07)	1.16 (0.04)	1.18 (0.02)
TP ($m^3 m^{-3}$)	0.56 (0.01)	0.54 (0.02)	0.44 (0.02)	0.40 (0.04)	0.49 (0.02)	0.49 (0.02)
Pma ($m^3 m^{-3}$)	0.18 (0.02)	0.13 (0.02)	0.90 (0.02)	0.10 (0.06)	0.14 (0.02)	0.14 (0.02)
Pmi ($m^3 m^{-3}$)	0.39 (0.01)	0.41 (0.00)	0.35 (0.01)	0.30 (0.02)	0.36 (0.01)	0.36 (0.01)
PD (g cm^{-3})	2.30		2.40		2.30	

*RO, PA, GI are three farms in the Zona da Mata region of Minas Gerais State, Brazil, two located in the municipality of Araponga (RO and PA), and a third located in the municipality of Divino (GI). The numbers in parentheses are (±) standard errors. TOC = total organic carbon, TN = total nitrogen, LC = labile carbon, BD = soil bulk density, TP = total porosity, Pma = macroporosity, Pmi = microporosity, PD = particle density.

The soil texture classes for farms RO, PA, and GI were 35.70, 60.20, and 37.00% sand; 10.00, 9.20, and 9.50% silt; and 53.50, 30.50, and 54.00% clay, respectively. The soils of the RO and GI farms were classified as clayey, and soils of the PA farm were classified as sandy. Within farms, the soils showed similar values for most of the physical attributes in AF and FS (Table 2). Macroporosity was the only physical property that showed great difference between the cultivation systems, but only at the PA farm, where macroporosity in AF was 90% higher than in FS.

Canopy cover, temperature and soil moisture

The AF_{RO} farm had the lowest (44.4%), and the AF_{PA} had the highest (76.2%) canopy cover. Regarding the areas under full sunlight (FS), the FS_{GI} farm had the lowest (6.9%), whereas the FS_{PA} farm had the highest (26%) canopy cover (Figure 1). When comparing the AF and FS systems within the three farms, the canopy cover was 48% higher in AF_{RO}, 66% in AF_{PA} and 88% in AF_{GI} than in the FS systems (Figure 1).

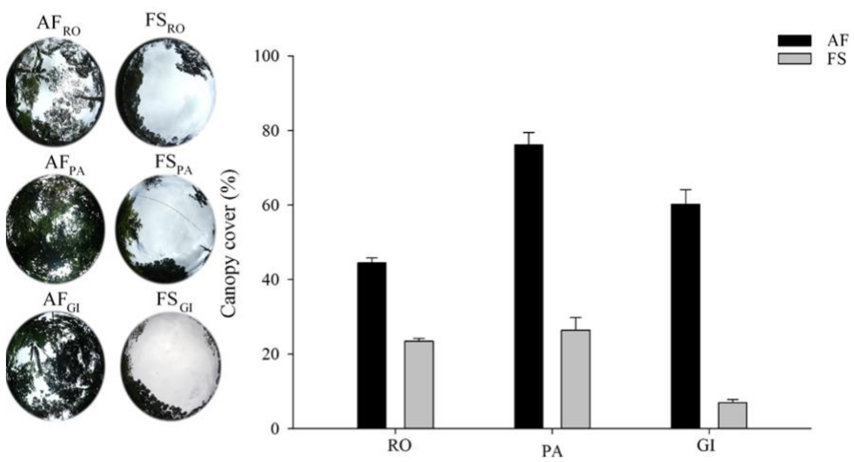

Figure 1. Canopy cover (%) in coffee plantations grown in agroforestry (AF) and in full-sun (FS) systems at different farms (RO, PA, and GI). The bars represent the standard errors (n = 10).

Air temperature (T_{air}) showed a negative correlation with canopy cover ($p < 0.05$) at the three farms (Figure 2). Soil temperature (T_{soil}) also showed a negative correlation ($p < 0.05$) with the canopy cover at the PA and GI farms. The GI farm was the only farm where soil moisture showed a positive correlation with canopy cover ($p < 0.05$), whereas at PA, no correlation was found. At RO, the correlation was negative ($p < 0.05$) (Figure 1).

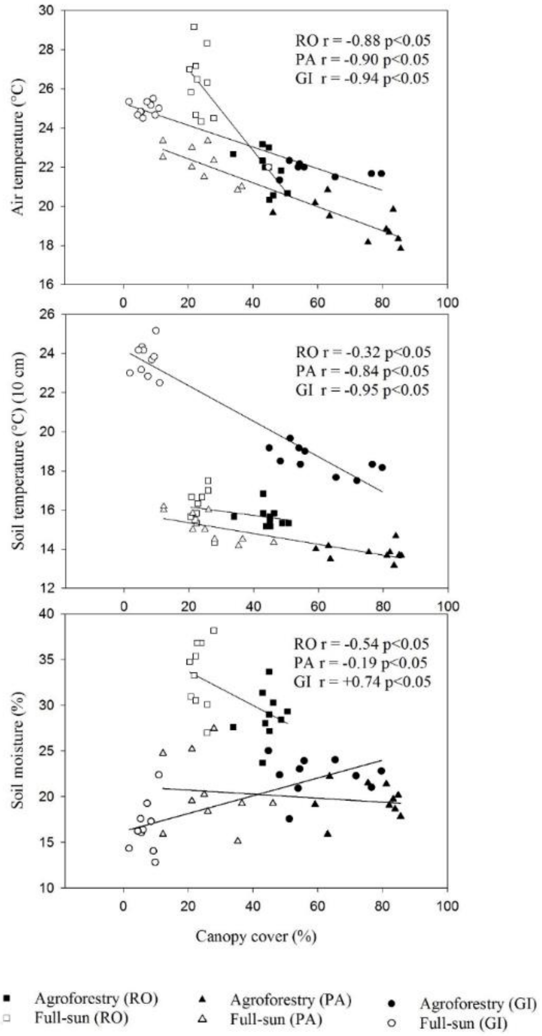

Figure 2. Correlation among canopy cover and climatic variables (air and soil temperatures and soil moisture) in agroforestry and full-sun coffee systems at three farms. RO, PA, and GI are three farms in the Zona da Mata region of Minas Gerais, two located in the municipality of Araponga (RO and PA), and a third located in the municipality of Divino (GI).

Soil CO_2 efflux

The average soil CO_2 efflux varied between 1.5 and 3.12 μmol m^{-2} s^{-1} in AF and FS at the three farms (Table 3). AF treatment on the GI farm (AF_{GI}) achieved the highest levels (3.12 μmol m^{-2} s^{-1}) of CO_2 efflux. Soil CO_2 efflux was lower in the FS treatment on the RO farm (FS_{RO}) (1.5 μmol m^{-2} s^{-1}). The spatial variation in the soil CO_2 efflux (expressed as the coefficient of variation – CV) was greater in the AF_{RO} (average of 40.38%) and lower in the AF_{GI} (average of 21.96%) (Table 3).

Table 3. Average values (n = 30) of soil CO_2 efflux (μmol m^{-2} s^{-1}), standard error (SE) and coefficient of variation (CV) at the three evaluated farms.

System	AF_{RO}	FS_{RO}	AF_{PA}	FS_{PA}	AF_{GI}	FS_{GI}
CO_2 efflux	1.75	1.50	1.56	1.65	3.12	2.09
SE	0.23	0.075	0.14	0.19	0.24	0.22
CV (%)	40.38	25.01	28.57	36.97	21.96	25.18

*AF (agroforestry) and FS (full-sun) coffee systems in the three farms. RO, PA, and GI are three farms in the Zona da Mata region of Minas Gerais, two located in the municipality of Araponga (RO and PA), and a third located in the municipality of Divino (GI).

The highest and lowest values of the Q10 parameter were observed in AF treatment on the PA farm (AF_{PA}) (2.01) and in FS treatment on the PA farm (FS_{PA}) (0.85; Figure 3). FS treatment on the GI farm (FS_{GI}) was the only system and farm that showed a correlation between CO_2 efflux and T_{soil} during the winter.

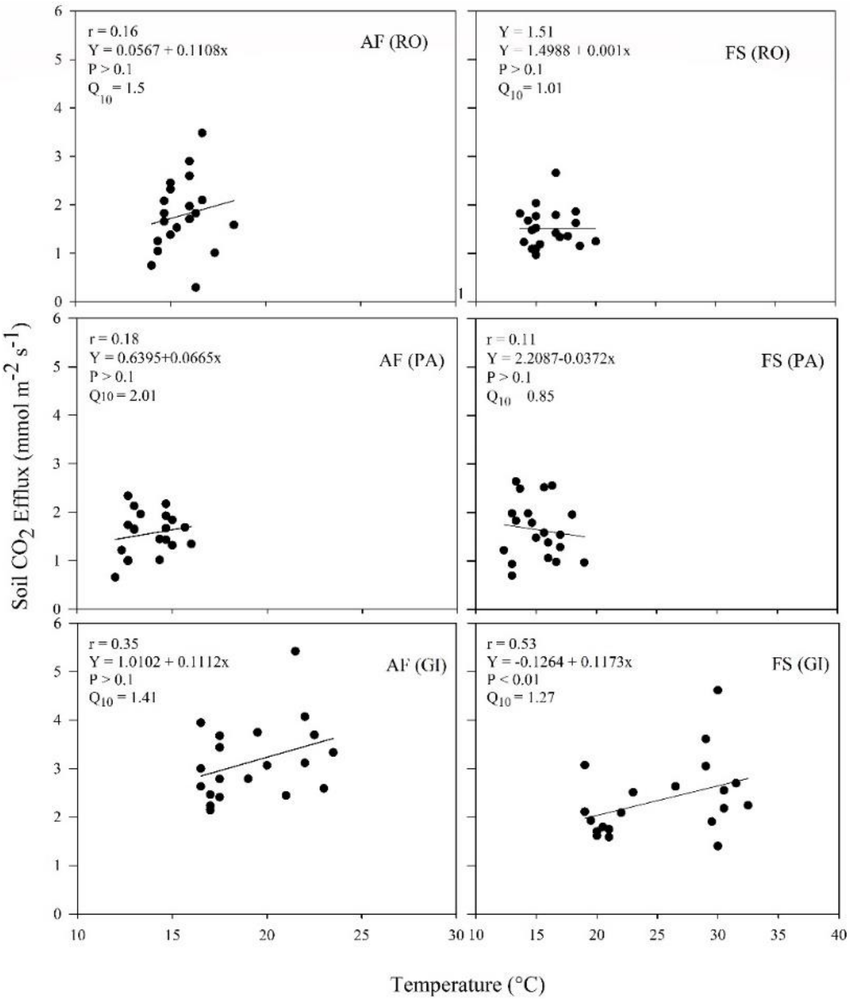

Figure 3. Q10 values and the correlation between soil temperature (T_{soil}) and soil CO_2 efflux in agroforestry (AF) and full-sun (FS) systems at three farms. RO, PA, and GI are three farms in the Zona da Mata region of Minas Gerais, two located in the municipality of Araponga (RO and PA), and a third located in the municipality of Divino (GI).

Except for AF_{PA}, all the other systems showed an increase in CO_2 efflux with increasing soil moisture (Figure 4). This increase was more pronounced in AF treatment in the RO farm (AF_{RO}) (r = 0.62), followed by FS_{RO} (r = 0.51). At the GI farm, this correlation was lower in AF (r = 0.44) and FS (r = 0.38).

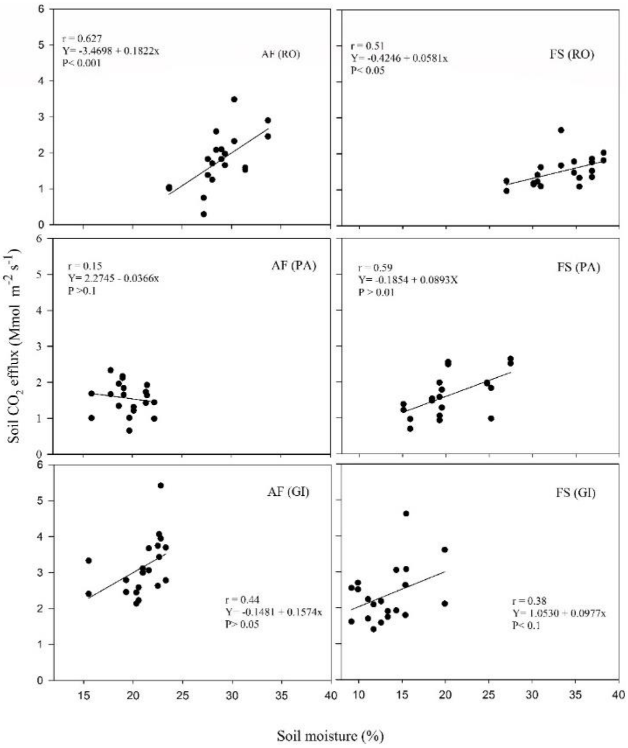

Figure 4. Correlation between soil moisture and the soil CO_2 efflux in agroforestry (AF) and full-sun (FS) systems at three farms. RO, PA, and GI are three farms in the Zona da Mata region of Minas Gerais, two located in the municipality of Araponga (RO and PA), and a third located in the municipality of Divino (GI).

Influence of soil attributes on CO_2 efflux

The PCA of the total data indicated the correlation between the variables and which variables were responsible for the variation in soil CO_2 efflux among all systems (Figure 5). In general, soil CO_2 efflux was positively correlated with soil temperature and negatively correlated with TN, LC, and TOC.

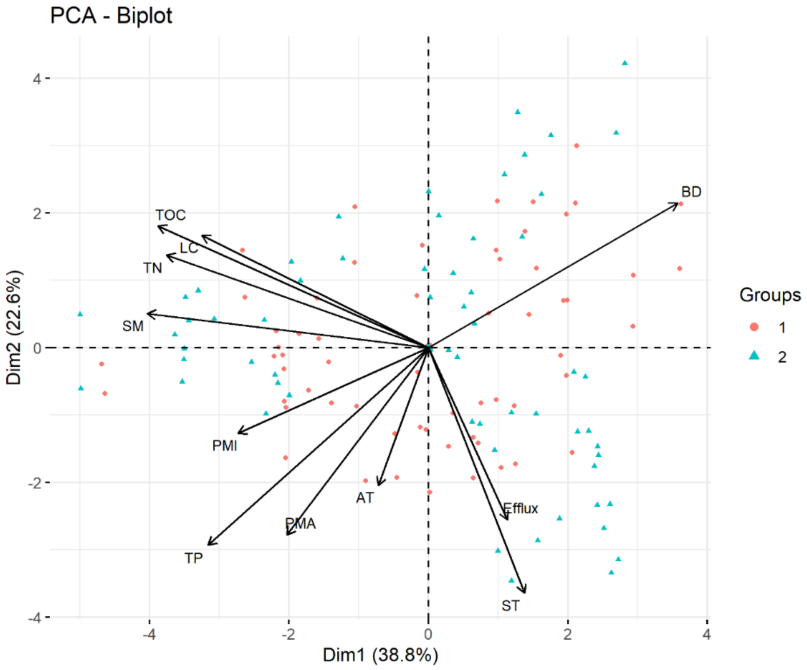

Figure 5. Principal component analysis of all data obtained in the agroforestry (Group 1) and full-sun coffee systems (Group 2) at the three farms (RO, PA, and GI). The plot shows the soil properties and environmental factors that influence soil CO_2 efflux. RO, PA, and GI are farms in the Zona da Mata region of Minas Gerais, two located in the municipality of Araponga (RO and PA), and a third located in the municipality of Divino (GI). ST = soil temperature at 5 cm depth; Pma = macroporosity; Pmi = microporosity; TP = total porosity; TOC = total organic carbon; TN = total nitrogen; LC = labile carbon; SM = soil moisture; and BD = soil bulk density.

Discussion

Relationship between shading and soil properties

Agroforestry coffee systems (AF) provided greater shade when compared to full-sun coffee systems. At the three farms, the densities and characteristics (crown dimensions, phenology, and leaf density) of the trees in the AF resulted from different canopy cover provided by the shade of the trees (Gomes et al., 2016), as well as the amount of litter and its quality.

The agroforestry coffee system has commonly higher soil organic carbon when compared to full-sun crops (Thomazini, Mendonça, Cardoso, & Garbin, 2015; Tumwebaze & Byakagaba, 2016; Zaro et al., 2020); however, at the RO and PA farms, the amount of organic carbon in AF was lower than that in FS. The straw of corn intercropped with full-sun coffee supplied carbon to the soil. In the FS_{PA}, the farmer mainly chose a variety of corn that produces more straw to add more organic matter to the soil. However, both the AF and FS in the RO and PA properties had high levels of carbon in the soil compared to forest soils (Assunção, Pereira, Rosset, Berbara, & García, 2019). This indicated that agroecological coffee management, even in full sun, is important for recovering soil quality (Barrios et al., 2016).

The amounts of C and N in the soil are related not only to the quality and quantity of the litter produced by plants intercropped with coffee plants (Li et al., 2020) but also to the implementation of the system. The AF and FS systems in GI were implemented more recently, so less carbon was found in the soil. Although less when compared to RO and PA, at the GI farm, the soil was in the recovery process, and the trees were contributing to increasing the soil organic carbon content. At GI, the TOC content was approximately 50% higher than that in soils under tillage planting and similar to that in soils with no-tillage planting (Assunção et al., 2019).

The similarity in the physical properties of the soil observed in agroforestry and full-sun systems has been reported in previous studies (Carmo et al., 2014; Guimarães, Mendonça, Passos, & Andrade, 2014; Jácome, Mendonça, Passos, & Andrade, 2020) due to the more conservative practices adopted in perennial crops, such as coffee. For instance, the soil in coffee systems is not turned. In the case of the studied farms, this is also because of the agroecological practices employed in both AF and FS (Gomes et al., 2016). The higher macroporosity observed at the PA farm may be related to its higher sand content when compared to the other properties evaluated and not to the management.

Microclimate created by tree shading in coffee plantations

The trees in agroecosystems regulate the microclimate by reducing air and soil temperatures (Araújo et al., 2016; Oliosi et al., 2016), as observed in our study.

The trees' shade and soil organic matter favor a higher moisture content due to lower soil evaporation (Gomes et al., 2016) and water retention in the soil, which is especially important in winter, when the precipitation is low in the region. At GI, with lower organic carbon in the soil, there was a positive correlation between soil moisture and shade level. The RO farm showed a negative correlation, and PA showed no correlation between soil moisture and shade levels. Soils at these two farms had higher organic matter contents, which, in the dry season, probably had more influence on soil moisture than the shade. Gusli et al. (2020) found that an increase of 1 g kg^{-1} of soil organic carbon in agroforestry systems increased the available soil water capacity by 6% (vol/vol). Moreover, coffee plants are responsible for higher water consumption in AF systems than intercropped trees. In AF, the use of water is more efficient than in FS because the water dynamics are different (Padovan et al., 2018; Carvalho et al., 2021).

Interaction between CO_2 efflux and cultivation systems

The lower CO_2 efflux obtained in the winter compared to the values found by Gomes et al. (2016) in the same areas in the summer is probably due to the lower rainfall (Vitória et al., 2019) and temperature during the winter. The low precipitation and temperature in the winter season influence the CO_2 efflux since the microbial processes are reduced, which affects the soil's carbon stock and efflux (Schindlbacher, Schnecker, Takriti, Borken, & Wanek, 2015; Thomazini et al., 2015; Carvalho et al., 2021).

Commonly, soil CO_2 efflux varies in space and time (Kim et al., 2017; Han, Shi, & Jin, 2018; Parker et al., 2020). In winter, less microbial activity and more stabilization of organic matter, due to the years of implementation of the systems, may explain the lower CO_2 efflux on PA and RO and the similarity between the AF and FS systems at both farms. In summer, Gomes et al. (2016), studying the same systems, found higher

CO_2 efflux in the FS system than in the AF system. This suggests that the soil CO_2 efflux was mainly due to heterotrophic respiration, which is carried out only by soil microorganisms (Valente et al., 2020).

CO_2 efflux varies according to the quantity and quality of organic matter, temperature and moisture, which determine microbial activity (Vitória et al., 2019; Araújo et al., 2016; Oliosi et al., 2016; Padovan et al., 2018; Carvalho et al., 2021). The higher CO_2 efflux in AF_{GI} (less mature system) than in FS_{GI} and the other studied systems is probably due to the association of higher organic matter content and higher soil moisture content, leading to greater CO_2 efflux, even in winter, indicating more respiratory activity of the microorganisms.

Our results indicate that in winter, the presence (AF) or absence (FS) of trees in mature agroecological systems, in which the soil is properly managed, does not influence the efflux of CO_2, unlike in summer, when trees in AF lowered the CO_2 efflux (Gomes et al., 2016). In mature systems, the organic matter is more stabilized, as seen from Q10.

Sensitivity of CO_2 efflux to microclimate conditions and soil properties

In the present study, Q10 only showed significant coefficients of determination in FS_{GI}. The other systems showed lower variations in soil temperature and soil CO_2 efflux during the winter. Therefore, in FS_{GI}, instead of having CO_2 incorporated into the soil, a large proportion of the C of the microbial biomass was lost. This could be caused by the increase in soil temperature (Thomazini et al., 2015). It is worth noting that even with no correlation between soil temperature and CO_2 efflux at the PA farm, Q10 showed higher levels than at the RO and GI farms, which may be explained by the large area of shade at this farm. In environments that have higher Q10, a greater stability of soil organic matter is usually observed, with a decrease in the temperature sensitivity of soil, hence not affecting the mineralization and release of C into the atmosphere (Thomazini et al., 2015). The RO and GI properties showed a correlation between soil moisture and CO_2 efflux, with the highest correlation coefficients found in the properties AF_{RO} and FS_{RO}.

Temperature showed a positive correlation with CO_2 efflux only in the systems at GI (Pearson's correlation). In addition to winter, the systems at GI are located at a lower altitude, and air temperatures were higher compared to the other systems. TN, LC and TOC showed a negative correlation with CO_2 efflux. These factors are linked to the quality of the residue deposited in the areas and depend on the decomposition and release of organic compounds and nutrients from the litter (Duxbury, Smith, & Doran, 1989; Vezzani et al., 2018).

Conclusion

The CO_2 efflux is similar in the Agroforestry and Full Sun mature coffee systems during the winter season. In young, less mature systems, the shade provided by the trees in AF does not decrease the soil CO_2 efflux and can increase it due to higher soil moisture than in Full Sun systems.

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