LUCAS DE CARVALHO GOMES

SOIL CO_2 EFFLUX IN AGROFORESTRY AND FULL-SUN COFFEE SYSTEMS

Dissertação apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Solos e Nutrição de Plantas, para obtenção do título de Magister Scientiae.

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GOMES, Lucas de Carvalho, M.Sc., Universidade Federal de Viçosa, outubro de 2014. **Efluxo de CO_2 do solo em áreas cultivadas com café sob manejo agroflorestal e a pleno sol**. Orientadora: Irene Maria Cardoso. Coorientadores: Eduardo de Sá Mendonça e Raphael Bragança Alves Fernandes.

A mudança climática global tem sido atribuída ao aumento da concentração de gases de efeito estufa na atmosfera, especialmente o dióxido de carbono (CO_2), como resultado das atividades humanas. Para atenuar esse efeito, existe um esforço global em reduzir as emissões de CO_2 e desenvolver tecnologias para remover parte desse gás da atmosfera. A maneira mais simples e natural para remover o CO_2 da atmosfera é realizada pelas plantas através da fotossíntese. Este processo remove o carbono da atmosfera formando biomassa vegetal, a qual mais tarde será depositada no solo, maior reservatório de carbono (2500 GtC) na biosfera terrestre. O balanço de carbono no solo é resultado da deposição de biomassa vegetal e perda de carbono, especialmente como CO_2. Portanto, o solo, no ciclo global do carbono, pode atuar como fonte ou dreno de carbono da atmosfera. Para melhor compreensão do papel do solo no ciclo do carbono não é suficiente conhecer apenas a quantidade de carbono que determinadas espécies de plantas depositam no solo, mas também como esse carbono é liberado de volta para a atmosfera. O CO_2 é liberado (efluxo de CO_2 do solo) a partir de respiração do solo, a maior fonte de CO_2 da biosfera terrestre. O efluxo de CO_2 do solo é um processo complexo que depende das características biológicas e físicas do solo, especialmente das condições de temperatura e umidade do solo. No entanto, o tipo de vegetação e as práticas agrícolas podem ser os principais componentes que controlam o efluxo de CO_2 do solo em agroecossistemas, porque influenciam as características biológicas e físicas do solo e regulam as condições de temperatura e umidade do solo. Nos sistemas agroflorestais as árvores aportam matéria orgânica no solo e o protegem contra a radiação solar direta, influenciando assim o efluxo de CO_2 do solo. O objetivo geral deste estudo foi compreender como a copa das árvores, em sistemas agroflorestais com café, afetam o efluxo de CO_2 do solo e quais os fatores controladores deste processo em comparação com café a pleno sol. Para isso avaliou-se o efluxo de CO_2 do solo (in situ), em sistemas agroflorestais com café e em sistemas com café a pleno sol em três propriedades de agricultores familiares na Zona da Mata de Minas Gerais, Brasil. O aumento nos níveis de cobertura da copa das árvores resultou no aumento da umidade do solo e na diminuição da temperatura do ar e do solo a 5 e 10 cm de profundidade. O efeito das árvores no microclima não afetou a média diária de efluxo de CO_2 do solo entre os sistemas agroflorestais e a pleno sol, mas contribuiu para que a dinâmica das emissões diárias fosse diferente entre os sistemas. No sistema agroflorestal o efluxo de CO_2 do solo foi mais estável durante o dia com menor variação entre o período de 08:00-10:00h e 12:00-14:00h e maior variação espacial do que no sistema a pleno sol. No sistema agroflorestal o efluxo de CO_2 foi explicado principalmente por variações na quantidade de nitrogênio total e carbono lábil e no sistema a pleno solo pela temperatura do solo, especialmente a 10 cm de profundidade. A análise de componetes principais mostrou que em geral o efluxo de CO_2 do solo correlacionou positivamente com a temperatura do solo a 5 e 10 cm de profundidade e negativamente com a umidade do solo. Em conclusão, as árvores em sistemas agroflorestais de café trouxeram maior estabilidade para o microclima e para o efluxo de CO_2 do solo comparado com sistemas a pleno sol.

ABSTRACT

GOMES, Lucas de Carvalho, M.Sc., Universidade Federal de Viçosa, October, 2014. **Soil CO_2 Efflux in Agroforestry and Full-Sun Coffee Systems**. Adviser: Irene Maria Cardoso. Co-Advisers: Eduardo de Sá Mendonça and Raphael Bragança Alves Fernandes.

The global climate change has been attributed to increasing greenhouse gas concentration, especially Carbon Dioxide (CO_2) in atmosphere as result of human activities. To mitigate this effect, there is a global effort to reduce CO_2 emissions and develop technologies to remove part of this gas from the atmosphere. The most simple and natural way to remove CO_2 from atmosphere is carried out by plants through photosynthesis. This process removes carbon from atmosphere creating vegetal biomass, which later will be deposited in soil, the biggest reservoir of carbon in the terrestrial biosphere (2500 GtC). The balance of carbon in the soil is the result of input of vegetal biomass and the output of carbon, especially as CO_2. Therefore, the soil, in the Global Carbon Cycle, acts either as source or as a sink of carbon from the atmosphere. To better understand the role of soil in Carbon Cycle and to it become sink of CO_2 it is not enough to know the carbon that particular plant species can deposit in the soil, but also how this carbon is released back to atmosphere. The CO_2 is released from soil (also called soil CO_2 efflux) mainly from soil respiration, which is the biggest source of CO_2 from terrestrial biosphere. Soil CO_2 efflux is a complex process that depends on the soil biological and physical characteristics and especially on the soil temperature and moisture conditions. However, the vegetation type and the agricultural practices may be the main components to control the soil CO_2 efflux in agroecosystems, because they influence the soil biological and physical characteristics and control the soil temperature and moisture conditions. Agroforestry coffee management increases the amount of organic matter residue and the canopy's trees protect the soil against the directly solar radiation, thus, affecting the soil CO_2 efflux. The general objective of this study it was to understand how the canopy's trees in agroforestry and full-sun coffee systems affect the soil CO_2 efflux and which factors control it. To this end we evaluated the soil CO_2 efflux (in situ) in agroforestry and full-sun coffee systems in three different farms in Zona da Mata of Minas Gerais, Brazil. The increase in canopy cover levels from trees leads to increase soil moisture and decrease air and soil temperature at 5 and 10 cm depth. The effect of trees on microclimate did not affect the daily average of soil CO_2 efflux between agroforestry and full-sun coffee systems, but they showed different daily emission dynamics. In agroforestry system the soil CO_2 efflux was more stable during the day, presenting less variation from morning to midday and higher spatial variation than the full-sun system. In agroforestry system the variation of soil CO_2 efflux was explained mainly by total nitrogen and labile carbon and in full-sun system by soil temperature at 10 cm depth. The principal components analysis shows that in general the soil CO_2 efflux was positively correlated with soil temperature at 5 and 10 cm depths and negatively correlated with soil moisture. In conclusion, the trees in agroforestry coffee systems promoted stability to microclimate and soil CO_2 efflux compared to Full-Sun systems.

GENERAL INTRODUCTION

The greenhouse gases emissions by human activities, especially carbon dioxide (CO_2), has been identified as the cause of global climate change (Field et al., 2014). These emissions increased considerably during the past four decades, as a result mainly from burning of fossil fuels and the conversion of tropical forests for use in agricultural production (Rogner et al., 2007). The burning of fossil fuels is the main source of CO_2 emission in the developed countries, whereas, in Brazil, more than half of the total CO_2 emission is derived from agricultural practices and deforestation (BRASIL, 2013). Most of CO_2 emission due to agricultural activities is derived from soil. Nonetheless, our understanding about the release of CO_2 from soil is very limited, because many factors can differently influence this process in each ecosystem. In soil the production and diffusion of CO_2 result of a combination of abiotic and biotic soil processes such as, gas diffusion, roots and organisms respiration (Berisso et al., 2013; Hanson et al., 2000) and soil characteristics such as, temperature, moisture, texture and aggregation (Blagodatsky and Smith, 2012; Lloyd and Taylor, 1994; Wu et al., 2010). Therefore, it is necessary to adopt crop management, such as agroforestry systems, that increases carbon in the soil, the largest carbon reservoir in terrestrial biosphere (2500 GtC), and contribute to reduce the concentration of CO_2 in atmosphere. Agroforestry systems sequester carbon in plant biomass and increase the residue of organic matter in the soil (Duarte, 2007) which is responsible to improve the physical and chemical quality of soils. Moreover, the canopy cover from trees protect soil against directly solar radiation (Carvalho, 2011), which can significantly influence the soil CO_2 efflux to atmosphere.

The objective of this study aimed to understand how the canopy of the trees in agroforestry coffee systems affect the soil CO_2 efflux and which factors control this process. In Chapter 1, we reviewed how the main biotic and abiotic factors control soil CO_2 efflux and the importance of vegetation on this process. In Chapter 2 our specific objectives were to (i) evaluate how trees influence air and soil microclimate (soil temperature and moisture), (ii) quantify soil CO_2 efflux, and (iii) identify the main abiotic factors that control soil CO_2 efflux in agroforestry and full-sun coffee systems.

CHAPTER 1. THE MAIN FACTORS THAT CONTROL SOIL CO_2 EFFLUX

1. INTRODUCTION

From 2012 to 2013, the atmospheric Carbon Dioxide (CO_2) increased 2.9 ppm, the biggest increase since 1984 (WMO, 2014). The increase in the CO_2 emission was due to human activities and primarily from fossil fuel and land use change. These two source of emissions have been identified as the cause of global climate change (Field et al., 2014). To mitigate the problem of climate change, there is a global effort to reduce CO_2 emissions and develop technologies to remove part of this gas from the atmosphere.

To reduce CO_2 emissions worldwide it is necessary to reduce deforestation, to use biofuels instead fossil fuels, etc. Commercial technologies are available to remove CO_2 from atmosphere (Schuiling and de Boer, 2013), but the most simple and natural way to remove CO_2 from atmosphere is carried out by plants through photosynthesis. This process removes carbon from atmosphere creating vegetal biomass, which later will be deposited in the soil.

Soil is the biggest reservoir of carbon (2500 GtC; 1 GtC = 1 billion metric tons of carbon) in the terrestrial biosphere. The carbon in the soil is the result of the balance between the input of vegetal biomass and the output of carbon, especially as CO_2. Therefore, the soil, in the Global Carbon Cycle, acts either as source or as a sink of carbon from the atmosphere. The source of CO_2 released from soil (also called soil CO_2 efflux) is mainly from roots and microbial respiration, which has been estimated at 75 GtC year^{-1}, much higher than the amount of 6 GtC year^{-1} by burning fossil fuels (Schlesinger and Andrews, 2000). Soil temperature and moisture conditions, the main drivers of soil CO_2 efflux (Lloyd and Taylor, 1994; Wu et al., 2010) affect the production of CO_2, because they have great influence on roots respiration and microbial activity. The vegetation type, normally neglected in many studies, has also great influence on soil respiration, because it affects soil temperature and moisture. Nonetheless, our understanding about the soil respiration is very limited, because many factors can differently influence this process in each ecosystem.

The soil CO_2 efflux is the result of combination between production (mainly respiration) and diffusion of this gas to soil surface. Thus, soil characteristics that influence these process, will also affect the rates of soil CO_2 efflux (Figure 1). The diffusion of CO_2 to soil surface is affect by soil physical characteristics, such as aggregation and porosity, that influence the gas diffusivity and also by soil moisture that fill the soil pore space.

Therefore, it is not enough to know just the C that particular plant species can deposit in the soil, but also how the vegetation influences the soil CO_2 efflux. The balance of C in the soil, result of deposition of plant biomass and the soil CO_2 efflux, depends on the land use management. For instance, agroforestry coffee systems, when compared to the full-sun coffee cultivation, enhances the deposition of plant biomass, due to the trees intercropped with coffee, and the C content stored in the soil (Duarte, 2007; Hergoualc'h et al., 2012). The agroforestry also protects the soil against solar radiation, what may modify the soil biological and microclimates characteristics, especially temperature and moisture, therefore CO_2 efflux.

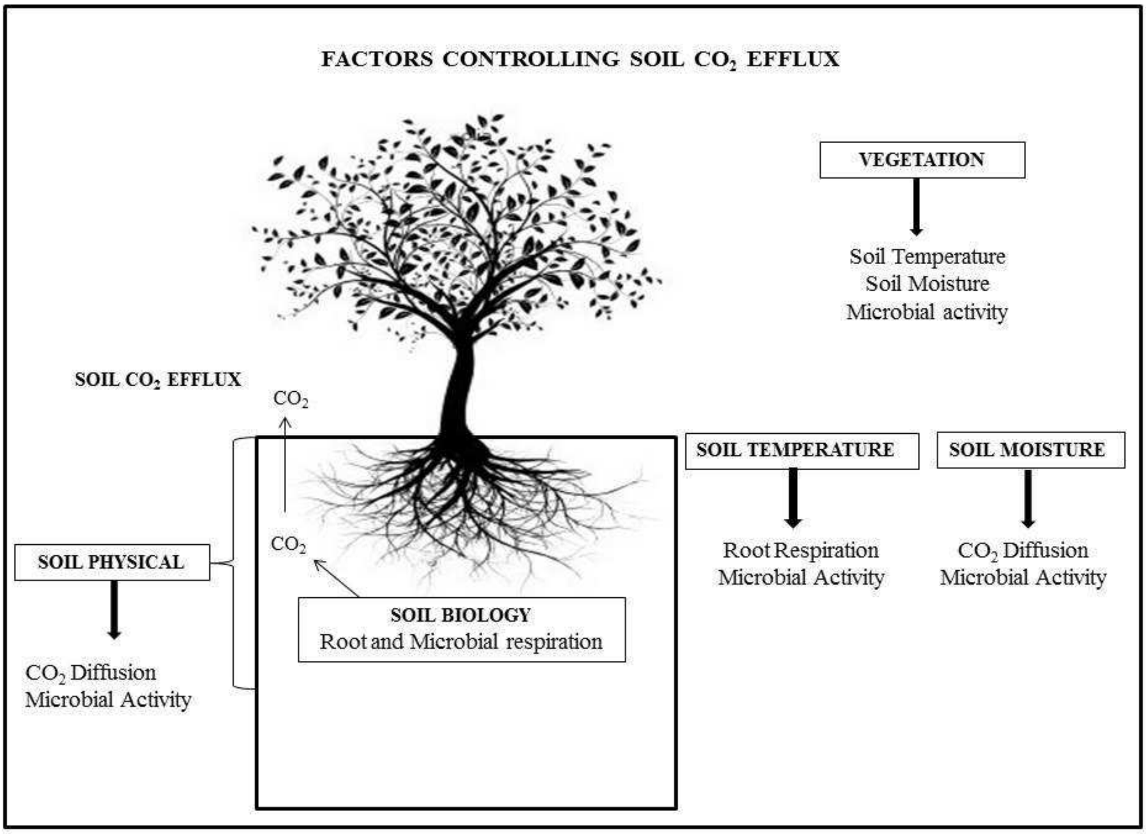

Figure 1: Vegetation, soil physical and environmental variables affecting the production (by Soil Biology) and the diffusion of CO_2 to soil surface.

2. SOIL BIOLOGY

Soil respiration is the largest source of CO_2 from terrestrial ecosystems to the atmosphere (Metcalfe et al., 2011) and almost 10% of the atmosphere's CO_2 passes through soils each year (Raich and Potter, 1995). The CO_2 produced in soils is derived from respiration by roots (autotrophic respiration) and by soil organisms (heterotrophic respiration).

The autotrophic respiration is a combination of root activity and the activity of microorganism in the rhizosphere. Studies demonstrated that autotrophic respiration account for 45.8% in forest and 60% in non-forest vegetation from the total soil respiration (Hanson et al., 2000). In general, the root contribution to soil respiration ranges from 33-89% in forests, 17-40% in grasslands, 12-38% in croplands and 50-93% in arctic tundra (Raich and Tufekcioglu, 2000).

The heterotrophic respiration is result from soil faunal activity (Edwards et al., 1970). Fungi are the most active decomposers of plant residues in soils while bacteria are the secondary despite their high number (Struwe and Kjøller, 1994). The direct contribution of soil macrofauna to total soil respiration account for < 3% of total CO_2 respired (Holt et al., 1990), but the macro and mesofauna can greatly increase soil CO_2 production (Ke et al., 2005; Lubbers et al., 2013) stimulating microbial activity, probably through fragmentation of plant residues.

The distinguishing between autotrophic and heterotrophic respiration is important to identify the source of CO_2 and predict how the climatic variables will influence each component leading us to better understand the carbon cycle in soil. Wang et al. (2014) carried out a meta-analysis from 202 soil respiration datasets from 50 different ecosystems warming experiments and identified that a warming of 2 °C affect differently the two components of soil respiration. The autotrophic respiration did not change significantly, but the heterotrophic respiration increases 21% in average.

To identify the contribution of autotrophic and heterotrophic respiration to the total soil respiration is not easy, because of the complexity of soil environment, but there are some available methods. Hanson et al. (2000) reviewed the main methods to separate the total soil respiration: (1) root exclusion, (2) integration of respiratory components (e.g. litter and roots) and (3) isotope methods.

The root exclusion method estimates root contribution for total soil CO_2 by measuring soil respiration with and without the presence of roots. The roots exclusion techniques can be categorized into three areas: (1) root removal – the soil is removed and the roots presents are collect, then the soil is placed back in reverse order of removal. Further barriers are installed to prevent root growth. (2) Trenching – presents roots are cut by trenching at a sampling plot limit but not removed, and a barrier is installed to prevent future root growth, and (3) gap analysis – the vegetation above ground is removed from relatively large areas (e.g. opening gaps in forests) and the soil CO_2 efflux measurements in the gap are compared to CO_2 data for a forested area (Hanson et al., 2000).

The integration of respiratory components is done by separating from soil the components that contribute to soil CO_2 efflux (i.e. roots, sieved soil, and litter) followed by measurements of the specific rates of CO_2 efflux from each component. Then, rates of CO_2 efflux from all component parts are multiplied by their respective masses and summed to obtain an integrated total soil CO_2 rate. The potential limitation of this approach is that root specific respiration rates are measured in vitro (Hanson et al., 2000).

The isotope methods allow partitioning total soil CO_2 efflux between root respiration and soil organic matter decomposition in situ, which is an advantage to root exclusion and integration of respiratory components methods. The disadvantage of isotope methods is the complexity of experimental setup and cost of analytical measurements for radioactive or stable C isotopes. Isotopes methods can be broadly classified as: (1) pulse labelling, (2) repeated pulse labelling, and (3) continuous labelling.

Pulse labelling is the addition of ^{14}C- or ^{13}C-labelled CO_2 to small plants in closed laboratory chambers, for the purpose of quantifies the distribution of labelled C within a plant and the amount of labelled carbon respired above and belowground plant parts during a determined period of time. Repeated pulse labelling is a variant of pulse labelling where isotopically labelled CO_2 is added to plants at different times during the growing season. Continuous labelling is carried out by the assimilation of uniquely labelled carbon by plants under laboratory (chamber) or field conditions over periods that are comparable to the life span of a plant (Hanson et al., 2000).

3. SOIL PHYSICAL

Soil physical characteristics, especially soil density, aggregation and porosity, strongly influence soil CO_2 efflux in well-drained soils, such as Oxisols, the most common soil in Brazil. These characteristics influence the physical conditions for roots and microorganisms activity and also for diffusion of CO_2 to soil surface and can be considered passive in the process of soil CO_2 efflux because they not vary in short space of time.

The increase in soil bulk density due to soil compaction reduces air permeability, effective pore diameter, gas diffusivity, number of effective pores per unit area, and increase tortuosity in vertical and horizontal directions. All these consequences reduce the soils capacity to conduct gases (Berisso et al., 2013). An increase in soil bulk density also decreases microbial activity (Torbert and Wood, 1992).

The soil texture establishes the conditions of aeration that affect the diffusion of CO_2 to soil surface, because the gas diffusivity depends on the soil particle size. Soil texture also affects the concentration of oxygen influencing the soil microbial activity. C mineralization was higher in silt loam soils compared with clay loam soils. The clay particle may protect the soil organic matter (Harrison-Kirk et al., 2013). However, in Oxisols, the structure is more important than texture for soil aeration. Structure depends on the soil aggregation, which affects strongly the gas transport in soils (Horn and Smucker, 2005).

The soil aggregation, product of combination of soil particles, plant and microbial residue, humic materials or polysaccharide polymers, is important for the accessibility of soil organic matter by microorganisms. The soil aggregation influences the decomposition rate of organic matter in the soil (Jastrow et al., 2007), consequently the CO_2 efflux in the soil. Microaggregates (< 250 mm diameter), protect soil organic matter against decomposition more than do macroaggregates (> 250 mm diameter) (Denef et al., 2001). Soil CO_2 efflux was significantly affected by increasing the concentration of C and nitrogen (N) within macroaggregates, but was not influenced by the concentration of C and N in the microaggregates (Lenka and Lal, 2013). Soil with aggregates of 0–2 mm diameter in the subsurface showed lower emission of CO_2 than soil with aggregates > 2 mm (Kimura et al., 2012), probably because of less access of organic matter by microorganism.

4. SOIL TEMPERATURE AND MOISTURE

Soil temperature and moisture are active drivers of soil CO_2 efflux in different ecosystems (Fenn et al., 2010; Guntiñas et al., 2013; Kim et al., 2010; Lloyd and Taylor, 1994; Wu et al., 2010), because they influence directly soil biology activity and the diffusion of gases in soils.

Soil temperature affects the production of CO_2 in soils influencing the rates of roots respiration and microbial activity. The rapidly increasing in soil temperature increases roots respiration (Atkin et al., 2000) and microorganism metabolic activity, which reduces carbon use efficiency (Schindlbacher et al., 2011).

Soil moisture affects the production and also the diffusion of CO_2 to soil surface. Soil moisture influences the production of CO_2 in soil because it is the main driver of microbial activity in many ecosystems (Liu et al., 2009), ensuring adequate water supply for microbes. Excessive soil moisture affect the gas exchange in soil because fill the pore space, lowering the oxygen available for development of aerobic microorganisms (Melling et al., 2013) and the diffusion of CO_2 to soil surface (Melling et al., 2005).

5. VEGETATION

The vegetation type and agricultural practices may be the main factors that control the rates of soil respiration, since they control the abiotic and biotic factors that are important for the production and diffusion of CO_2 to soil surface. They influence the soil microclimate (soil temperature and moisture), the soil physical characteristics and the quantity and quality of biomass deposited on the soil.

The effects of vegetation on the important factors to soil CO_2 efflux will differ according to the vegetation types. Soil respiration rates were approximately 20% higher in grassland than in forest growing under similar conditions, suggesting that forest conversion to grassland would stimulate soil CO_2 emission to the atmosphere (Raich and Tufekcioglu, 2000). In grassland the soil temperature was higher than in soil under forest, since the grass does not intercept the solar radiation as the trees.

The management practices of the vegetation in agroecosystems interfere in soil characteristics and may have great impact on soil CO_2 efflux. The agroforestry coffee systems are widely used in Central and South America (Bacon, 2005), except in Brazil. However, to overcome problems of land degradation, in the Zona da Mata of Minas Gerais state, Brazil, a group of coffee growers implanted in 1993 experiments with agroforestry coffee systems in cooperation with local Non-Governmental Organizations and researches (Cardoso et al., 2001). Later, the results indicated improvement of soil quality (Souza et al., 2010). The canopy of the trees decreased 5.4 °C the mean daily maximum temperature in the agroforestry systems (Souza et al., 2012) and reduced the rates of moisture loss from soil surface (Carvalho, 2011) compared to full-sun coffee systems. Therefore, it is expected that agroforestry systems may change the dynamics of soil CO_2 efflux compared with management of full-sun coffee.

6. CONSIDERATIONS

The soil CO_2 efflux is a complex process that depends on the soil biological and physical characteristics and especially on the soil temperature and moisture conditions. However, the land use and vegetation type may be the main components to control the soil CO_2 efflux in agroecosystems, since they influence the soil biological and physical characteristics and control the soil temperature and moisture.

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CHAPTER 2. TREES MODIFY THE DYNAMICS OF SOIL CO_2 EFFLUX IN COFFEE AGROFORESTRY SYSTEMS

Highlights

- Soil CO_2 efflux dynamics were analysed in two coffee cultivation management systems
- Tree canopy in the Agroforestry System (AF) reduced soil temperature and increased soil moisture
- Daytime soil CO_2 efflux was more stable in AF system than in Full-Sun (FS) system
- Soil temperature is the main factor regulating soil CO_2 efflux in the FS system

ABSTRACT

Agroforestry systems (AF) can help significantly reduce atmospheric carbon levels over the next years through photosynthesis and regulation of soil CO_2 efflux. The objective was to characterise the soil CO_2 efflux dynamics of coffee plants cultivated under AF and Full-Sun (FS) systems and identify the factors that regulate this process. The study was carried out in AF and FS systems, in three family farms (identified as RO, PA, and GI), Minas Gerais, the Atlantic Forest Biome, Brazil. Twenty 1-m^2 sampling points (ten in AF and 10 in FS), each separated by a distance of 5 × 5 m, located between coffee plant rows on each farm were selected. Soil physical and chemical attributes, soil temperature, air temperature and soil moisture, the percentage of canopy cover, and soil CO_2 efflux were measured at each sampling point under the two systems. Tree canopy in the AF systems reduced air and soil temperature and increase soil moisture. The average daily soil CO_2 efflux values did not differ in the two systems, but different daily emission dynamics were observed. Daytime soil CO_2 efflux was more stable (i.e. from morning to midday) in the AF system (increasing in average 15%) compared to the FS system (increasing 49.1%). Soil CO_2 efflux was regulated by labile carbon and total nitrogen in the AF system and by soil temperature variation at 10 cm depth in the FS system. In general, the principal components analysis shows that soil CO_2 efflux was positively correlated with soil temperature at 5 and 10 cm depths and negatively correlated with soil moisture. In conclusion, AF systems promoted stability to microclimate and soil CO_2 efflux and enhances the capture of CO_2 through photosynthesis compared to FS systems.

Keywords: soil carbon, soil respiration, tree canopy, field experiment, Atlantic Rainforest Biome

1. INTRODUCTION

Greenhouse gas emissions resulting from human activities, especially carbon dioxide (CO_2), have been identified as the cause of global climate change (Field et al., 2014). Over the last four decades, greenhouse gas emissions into the atmosphere have increased considerably, primarily due to the burning of fossil fuels, cement production, and the conversion of tropical forests into agricultural land (Rogner et al., 2007). From 2002 to 2011, on average, the global CO_2 emissions from the burning of fossil fuels and cement production was 8.3 GtC $year^{-1}$ and due to changes in land use management was 0.9 GtC $year^{-1}$ (Stocker et al., 2013). The land use management (agricultural practices and deforestation) in Brazil, from 1990 to 2010, was the main source of CO_2, which account for about 57% of CO_2 emissions (716.389 $GgCO_2$/year) (BRASIL, 2013).

Most CO_2 emissions due to agricultural activity originates from the soil, which is the largest C reservoir (2500 GtC) in the terrestrial biosphere. The production and diffusion of CO_2 in the soil originate from several biotic soil processes such as, roots and organisms respiration (Berisso et al., 2013; Hanson et al., 2000) that are related to soil characteristics such as, temperature, moisture, texture and aggregation (Blagodatsky and Smith, 2012; Lloyd and Taylor, 1994; Wu et al., 2010).

Soil temperature and soil moisture are the main factors involved in the regulation of soil CO_2 efflux (Wu et al., 2010). An increase in soil temperature causes an increase in soil CO_2 efflux because of changes in roots respiration and the decomposition rates of organic matter (Peng et al., 2009). Soil moisture is the main driver of soil microbiotic activity (Liu et al., 2009) and interferes with gas diffusion in the soil because water replaces the air in the soil pore space (Melling et al., 2005). Texture and aggregation interferes in the production process of CO_2 and in its transport to soil surface (Harrison-Kirk et al., 2013; Lenka and Lal, 2013). Soil texture and aggregation affect soil porosity and interferes in the process of gas diffusion and the accessibility of soil organic matter to microbial decomposition (Jastrow et al., 2007).

Soil characteristics are influenced by soil management. For instance, the trees in agroforestry (AF) systems sequester C in plant biomass and increase the amount of organic matter residue present in the soil (Montagnini and Nair, 2004), which is important for improving the physical and chemical quality of soils. The canopy cover of trees also protects the soil against direct solar radiation (Breshears and Ludwig, 2010). Therefore, AF systems may positively influence soil CO_2 efflux to the atmosphere.

Understanding this efflux would provide support for the adoption of AF systems, by quantifying the extent to which they help reduce CO_2 levels in the atmosphere. At several locations worldwide, carbon stock analyses have shown that significant quantities of carbon (1.1–2.2 PgC) could be removed from the atmosphere over the next 50 years, if AF systems were globally implemented (Albrecht and Kandji, 2003). AF coffee systems are widely used in Central and South America (Bacon, 2005). However, Brazilian coffee plants are adapted to full-sun cultivation conditions. Full-sun (FS) systems lose the benefits provided by trees, resulting in high soil temperatures and larger fluctuations in moisture conditions (Lin, 2007a).

Although the benefits of AFs are recognised worldwide, there are not so many in situ investigation of soil CO_2 efflux dynamics in AF coffee systems. To understand these dynamics, it is necessary to quantify soil CO_2 efflux and identify the biotic and abiotic factors that regulate this variation. By identifying the responsible factors, appropriate strategies can be adopted to control and decrease atmospheric CO_2 levels.

This study aimed to understand how the tree canopy affects the soil CO_2 efflux in AF coffee systems versus FS coffee systems and to identify which factors control this process in each system. Our specific objectives were to (i) evaluate how trees influence soil microclimate (soil temperature and moisture), (ii) quantify soil CO_2 efflux, and (iii) identify the main abiotic factors that control soil CO_2 efflux in AF and FS coffee systems.

2. MATERIAL AND METHODS

2.1. Study areas

This study was carried out in Zona da Mata of Minas Gerais State, Brazil, located in the Atlantic Rainforest Brazilian biome, which is one of the five biodiversity hotspots in the world (Myers et al., 2000). Three family farms were selected (referred to as RO, PA, and GI), which were cultivate with coffee (Coffea arabica) under AF and FS systems. All three farms used similar agroecological management practices, e.g. skimming of weeds, no use of pesticides, cultivating maize among coffee rows leaving the straw in the field, which contributes to keep the soil covered and to add organic matter to the soil. In PS_{PA} the famer even chose a maize variety that produce more straw in order to have more organic matter added to the soil. The soils in this region are generally acidic and present low natural fertility, with organic matter input and nutrient cycling being required for natural quality maintenance. Table 1 provides more information about the location, environmental characteristics and historic of each farm.

Table 1: Location, environmental characteristics and historic of Agroforestry (AF) and Full-sun (FS) coffee systems studied in three farms (RO, PA, GI), Minas Gerais, Brazil.

Site code	RO	PA	GI
Location	Araponga	Araponga	Divino
Latitude	-20° 41' 53.9"	-20° 39' 28.9"	-20° 38' 43.3"
Longitude	-42° 31' 45.4"	-42° 33' 18.9"	-42° 11' 50"
Altitude (m)	1040	800	650
Average annual temperature (°C)	18	18	21
Average annual rainfall (mm)	1345	1345	1282
Soil type	Oxisol	Oxisol	Oxisol
Slope (%)	12	3	5
Estimated average trees height (m)	12	5	5
Coffee age (years)	20	9	25
Land use before Coffee	Pasture and rice	Coffee yard	Pasture
Coffee spacing (m × m)	3 × 1	3 × 1	3 × 1
Year of AF Implementation	1998	2006	2010
Main plant species present	Inga subnuda	Solanum sp and Musa sp.	I. subnuda, Solanum sp, Musa sp, and Toona ciliata

2.2. Study design

At each farm, we selected a coffee field of approximately 300 m^2. In field, we selected 20 sampling points with 1-m^2 each, which were located between the rows of coffee plant. Among the 20 points, 10 points were located in the AF system and 10 points in the FS system. The distance between sampling points was about 5 × 5 m. AF and FS systems were considered treatments, whereas the 10 points in each treatment were considered replicates. In total, 60 points were sampled across the three farms. For soil CO_2 efflux analyses, we placed a Poly Vinyl Chloride (PVC) ring (10 cm diameter and 7 cm height) on the soil at the centre of each sampling point. The rings were inserted 3 cm deep into the soil, leaving 4 cm above the soil surface to avoid changes in soil temperature, moisture, and radiation balance that affect the soil surface inside the ring. Large branches and leaves were removed from the soil surface for optimum ring installation. The rings were installed 24 hours before the evaluation of soil CO_2 efflux, which is the time required to recover soil CO_2 equilibrium after the soil disturbance due to ring insertion (Heinemeyer et al., 2011).

2.3. Soil sampling and analysis

After three days of evaluation of soil CO_2 efflux, disturbed soil samples from inside the PVC rings were collected from 0–10 cm soil depth at each sampling point. Outside each PVC ring, three undisturbed soil samples were collected, using volumetric rings that were approximately 5.3 cm in height and 4.8 cm in diameter. In total, we collected 60 disturbed and 180 undisturbed soil samples from the three farms.

We analysed the total organic carbon (TOC) of the disturbed samples by the wet oxidation of organic matter, using a potassium dichromate solution in acidic medium and an external heat source (Yeomans and Bremner, 1988). Labile carbon (LC) was quantified by oxidation with $KMnO_4$ (33 $mmol.L^{-1}$), as proposed by Blair et al. (1995) and modified by Shang and Tiessen (1997). Total nitrogen (TN) was quantified by sulphuric acid digestion (Bremner, 1996).

Soil bulk density (BD) was analysed by the volumetric ring method (EMBRAPA, 2011) using the undisturbed soil samples. Soil particle density (PD) was analysed by the balloon volumetric method with ethanol as the liquid penetrant (EMBRAPA, 2011). Total porosity (TP) was calculated from the relationship between BD and the particle density (PD), according to equation 1.

$$\mathrm{TP} = 1 - \frac{\mathrm{BD}}{\mathrm{PD}} \qquad \text{(Eq. 1)}$$

Microporosity (PMi) was calculated as the amount of water retained in undisturbed soil samples subjected to pressure -0.0006 Mpa (60 cm H_2O). Macroporosity (PMa) was calculated as the difference between TP and PMi. All of these physical characteristics were analysed according to EMBRAPA (2011). Soil texture was also analysed according to EMBRAPA (2011) and adjusted based on Ruiz (2005a, 2005b). We used equation 2 to calculate the Water Filled Pore Space (WFPS) from the BD, TP and gravimetric moisture results of each point:

$$WFPS = \frac{(SM*BD)}{(TP*100)} \qquad \text{(Eq.2)}$$

where SM is gravimetric soil moisture in (%), BD is soil bulk density (g cm^{-3}), and TP is total porosity (%).

2.4. Canopy cover

To estimate the canopy cover level (%) Hemispheric Photographs (HPs) were taken of each sampling point (Figure 1), with a Canon T2i 18 megapixel camera and a fisheye lens. The camera was attached to a tripod with a spirit level. The tripod with camera was set at 80 cm high above the soil surface in the centre of all sampling plots, aiming to ensure real brightness of the soil surface. The camera was pointed to the magnetic North. Light intensity is important for image quality; thus, images were taken at sunrise, preventing the direct entry of sunlight into the lens and avoiding excess light in the images. We used a lens aperture of F 6.3 for all images (Pueschel et al., 2012), which were saved as 16-bit. Five images were taken at each sampling point, and the best image was analysed by the program GLA (Gap Light Analyzer) in the blue band, seeking to achieve the optimum brightness value (thresholding) of the sky (Leblanc et al., 2005).

The images were obtained with a Zenithal angle of 0–90º resulting in a view of 180º from the soil surface; however, pixels become mixed when the Zenithal angle has high values (Jonckheere et al., 2004; Leblanc et al., 2005). To avoid this problem, a mask that limited Zenithal angle values of 0–70º (Macfarlane et al., 2007) and 9 segments azimuth was created before analysis in the GLA program; thus, the analysed images represented a view of 140º from 80 cm high above the soil surface. In total, 60 images were analysed.

2.5. Air and soil microclimate

When measuring soil CO_2 efflux, we also measured air temperature, humidity and soil temperature, in addition to collecting soil samples to analyse moisture content. Air temperature and humidity were measured at 80 cm height using a Thermohygrometer (Incoterm, model 7666.02.0.00). Soil temperature was evaluated using a soil thermometer type dipstick placed at 5 cm and 10 cm soil depths, 3 cm from the outside of the ring. To evaluate gravimetric soil moisture, soil samples were collected at 0–5 cm depth and stored in aluminium cans, which were capped and sealed with plastic tape after collection to prevent any moisture loss. In the laboratory, the soil samples were weighed and dried in an oven at 105 ºC for 48 h, after which moisture was measured.

2.6. Soil CO_2 efflux and soil temperature sensitivity

To evaluate soil CO_2, we used the IRGA LI-8100 with a bell of 10 cm in diameter (model 8100-102). Soil CO_2 efflux was evaluated for 90 s in each ring. We tried to complete the evaluation of all 20 rings in the 20 sampling points at each farm as quickly as possible to minimise variation in soil temperature and moisture between the sampling points (Scala et al., 2005). The data were collected in the morning (8:00 to 10:00 h) and at midday (12:00 to 14:00 h) over 3 consecutive days at each farm during spring 2013 (October and November). In total, we carried out 360 evaluations of soil CO_2 efflux at the three farms.

To compare the temperature sensitivity of the soil in the AF and FS systems of each farm, the proportional change in soil respiration when soil temperature increased by 10 °C (Q_{10}) was calculated, based on the relationship between soil temperature at 5 cm depth and soil CO_2 efflux. The exponential regression was applied to find the relationship between soil CO_2 efflux and soil temperature (Eq. 3). Thus, the Q_{10} values were obtained according to Eq. 4 (Van't Hoff, 1898).

$$CO_{2ef} = \alpha.e^{(\beta 1.T)} \quad \text{(Eq. 3)}$$

where CO_{2ef} is the soil CO_2 efflux (μmolm^{-2} s^{-1}), T is the soil temperature, α is the intercept of soil CO_2 efflux when the temperature is zero and $\beta 1$ is the regression coefficient obtained from the natural logarithm of the CO_2 efflux and soil temperature at 5 cm depth.

$$Q_{10} = e^{10.\beta 1} \quad \text{(Eq. 4)}$$

To calculate the Q_{10} of the two systems in each farm, the data for the two daytime measurements (morning and midday) were grouped for each system.

The three farms are located in different altitudes (Table 1). Moreover, soil CO_2 efflux was measured on different dates, and each site had different soil temperatures at 5 cm depth. Therefore, to compare soil CO_2 efflux between the three farms, the efflux at each system was normalised to a temperature of 25 ºC, generating new soil CO_2 efflux (R_{25}) values at each sampling point. The R_{25} was calculated according to the following equation (Acosta et al., 2013):

$$R_{25} = CO_{2ef} * Q10^{\frac{(25-T)}{(25)}} \quad \text{(Eq. 5)}$$

where CO_{2ef} is the soil CO_2 efflux (μmolm^{-2} s^{-1}) measured at each point, and T is the soil temperature at 5 cm depth, measured at the time of soil CO_2 efflux evaluation.

2.7. Statistical analysis

The relationship between canopy cover and the environmental characteristics (air temperature and humidity, soil temperature, and moisture) of each farm was analysed by Pearson's correlation, with 5% significance. Soil CO_2 efflux and soil physical and chemical properties were first analysed by descriptive statistics. The spatial variability of soil CO_2 efflux was characterised for each measurement by calculating the coefficient of variation (CV; i.e. the ratio between the standard deviation and the mean value), using data from all the sampling points of the two systems at the three farms. The comparison of soil CO_2 efflux normalized to 25 °C between farms was carried out by analysis of variance (ANOVA) and applied the Tukey test at 5% probability.

Multiple stepwise analyses were used to model and identify the environmental variables and physical and chemical soil characteristics that most influenced soil CO_2 efflux in the two systems at each farm. In the multivariate regression analysis, soil CO_2 efflux was the dependent variable and the soil physical, chemical, and environmental characteristics were the independent variables. The relative importance of each parameter from equations was measured and then applied diagnostics tests for heteroscedasticity, normality, and influential observations. Principal Components Analysis (PCA) was also used to reduce the complex dataset to a lower dimensionality, to reveal simplified structures that explain the complex dataset. PCA analysis was performed with all variables from the three farms combined to assess how the variables were correlated. The program R was used to perform the statistical analysis.

3. RESULTS

3.1. Chemical and physical soil characteristics

Table 2 presents the average of the physical and chemical characteristics from soils. The soils were classified as clay (RO and GI) and sand clay loam (PA), with both coffee systems presenting the same soil texture at each farm. Mean soil BD was similar in the two systems at each farm, with the highest values being obtained at PA, followed by GI and RO. Mean TP was lowest in AF_{PA} (49%) and highest in AF_{RO} (58%), while mean PMa was lowest in AF_{GI} (13%) and highest in AF_{RO} (21%). Mean PMi was lowest in FS_{PA} (33%) and highest in FS_{RO} (39%). Mean WFPS was lowest in FS_{PA} (26.3%) and highest in AF_{GI} (50%). Mean TOC was lowest in AF_{PA} (28.4 g kg^{-1}) and highest in FS_{RO} (39.7 g kg^{-1}). Mean TN was lowest in AF_{GI} (0.20 dag kg^{-1}) and highest in FS_{RO} (0.34 dag kg^{-1}). Mean LC was lowest in AF_{GI} (3.25 g kg^{-1}) and highest in FS_{RO} (5.20 g kg^{-1}).

Table 2: Average of the soil physical (n = 30 per system) and chemical (n = 10 per system) characteristics from agroforestry (AF) and full-sun (FS) coffee systems at the three farms (RO, PA, GI) at 0-10 cm soil depth in Minas Gerais, Brazil.

Systems	AF_{RO}	FS_{RO}	AF_{PA}	FS_{PA}	AF_{GI}	FS_{GI}
Soil physical characteristics						
Textural Class	Clay		Sandy Clay Loam		Clay	
Particle Density (g cm^{-3})	2.37		2.52		2.42	
Sand (%)	37.7		41.7		58.9	
Silt (%)	11.9		13.7		10.5	
Clay (%)	50.4		44.6		30.6	
BD ($g.cm^{-3}$)	0.98 (0.01)	1.06 (0.01)	1.26 (0.02)	1.21 (0.01)	1.16 (0.02)	1.1 (0.01)
TP (%)	58 (0.55)	55 (0.55)	49 (0.73)	52 (0.55)	51 (0.73)	54 (0.37)
PMa (%)	21 (0.91)	15 (0.91)	13 (0.91)	19 (0.65)	13 (0.91)	18 (0,73)
PMi (%)	37 (0.55)	39 (0.37)	36 (0.37)	33 (0.34)	38 (0.37)	35 (0.18)
WFPS (%)	46.4 (2.56)	39.6 (1.9)	45.8 (2.83)	26.2 (1.28)	50.0 (1.83)	31.8 (1.15)
Soil chemical characteristics						
TOC (g kg^{-1})	35.3 (2.09)	39.7 (1.33)	28.4 (2.37)	30.7 (1.45)	28.7 (2.5)	31.5 (1.36)
TN (dag kg^{-1})	0.27 (0.16)	0.34 (0.01)	0.22 (0.01)	0.27 (0.02)	0.2 (0.02)	0.22 (0.01)
LC (g kg^{-1})	4.36 (0.29)	5.2 (0.19)	4.17 (0.35)	4.95 (0.3)	3.25 (0.24)	3.78 (0.18)

The numbers between parentheses means (± standard error). ; BD = Soil bulk density, TP = Total Porosity, PMa = Macroporosity, PMi = Microporosity, WFPS = Water Filled Pore Space, TOC = Total Organic Carbon, TN = Total Nitrogen; LC = Labile Carbon.

3.2. Canopy cover

Canopy cover was higher in all AF systems compared to the FS systems (Figures 1 and 2). Comparing the percentage of covering, canopy cover level was, on average, 31% higher in AF_{RO} than FS_{RO}, 38% higher in AF_{PA} than FS_{PA} and 35% higher in AF_{GI} than FS_{GI}. Among the AF systems, AF_{GI} had the highest level of canopy cover, whereas AF_{RO} had the lowest (Figure 2).

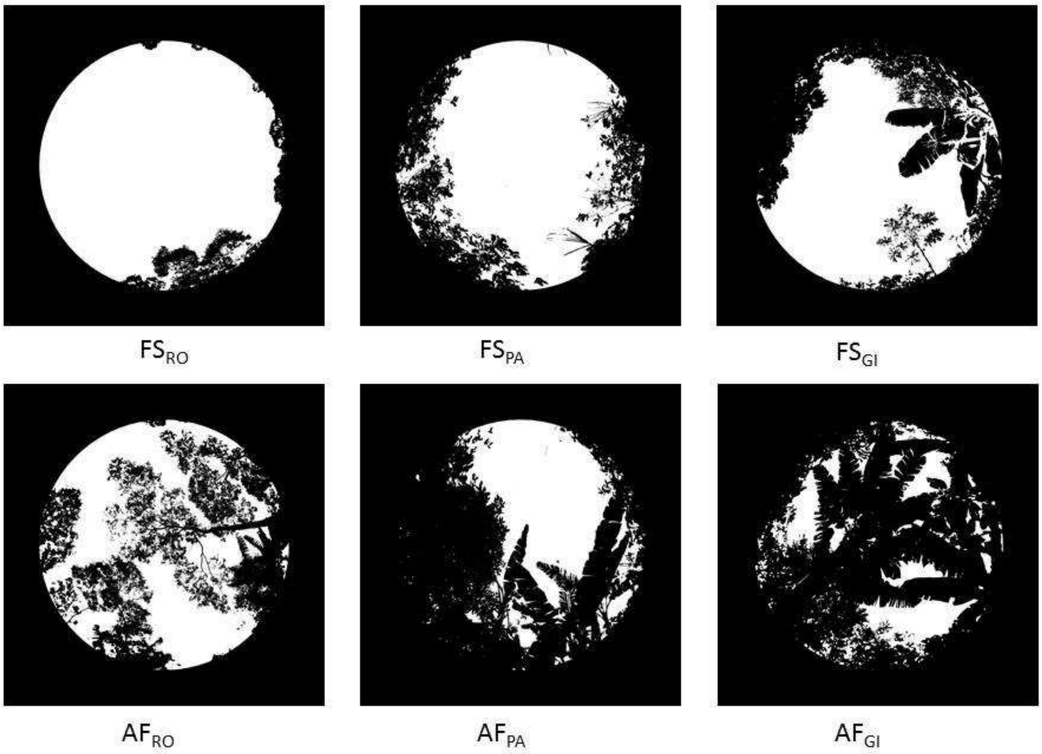

Figure 1: Representative images from Hemispherical Photographs (140º angle of view) taken at 80 cm from soil surface from agroforestry (AF) and full-sun (FS) coffee systems studied in the three farms (RO, PA, GI), Minas Gerais, Brazil.

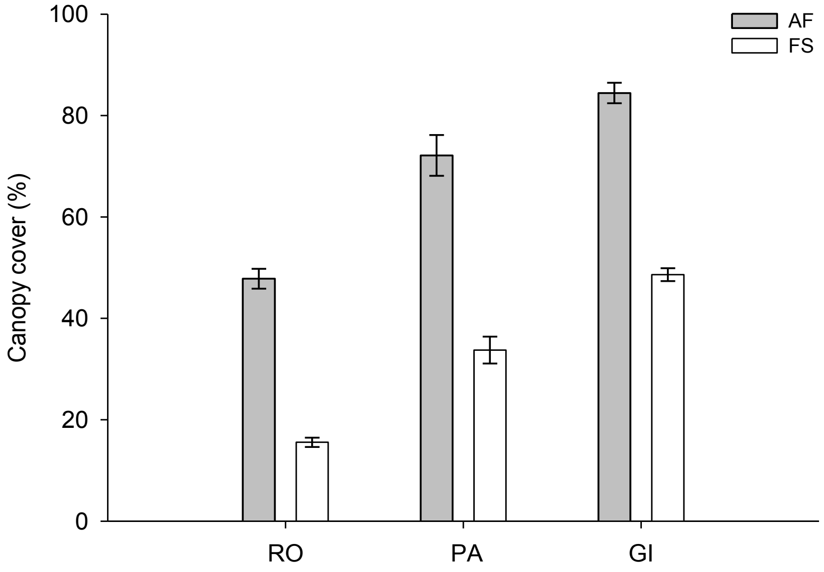

Figure 2: Mean (n = 10) canopy cover (%) in the agroforestry (AF) and full-sun (FS) coffee systems studied in the three farms (RO, PA, GI), Minas Gerais, Brazil. Bars represent mean ± standard error.

3.3. Air and soil temperature and humidity

Table 3 presents the air temperature and humidity, soil temperature at 5 and 10 cm depth and soil moisture at 0–5 cm depth. On average, air temperature was 4.1 ^{o}C less in the AF than in the FS systems; air humidity was 5.1% more in the AF than in the FS systems; soil temperature at 5 cm was 4.3 ^{o}C and at 10 cm 3.1 ^{o}C less in the AF than in the FS systems; soil moisture content was 6.4% more in the AF than in the FS systems.

Table 3: Average (n = 30) air temperature (AT) and Humidity (HU), soil temperature (ST) at 5 and 10 cm depths and soil moisture content (SM) in the agroforestry (AF) and full-sun (FS) coffee systems studied in the three farms (RO, PA, GI), Minas Gerais, Brazil.

Systems	AF_{RO}		FS_{RO}		AF_{PA}		FS_{PA}		AF_{GI}		FS_{GI}	
Period	8 h	12 h	8 h	12 h	8 h	12 h	8 h	12 h	8 h	12 h	8 h	12 h
AT (ºC)	22.8 (0.39)	26.7 (0.46)	25.2 (0.61)	27.8 (0.67)	24.6 (0.19)	32.7 (0.28)	28.0 (0.32)	39.5 (0.47)	27.9 (0.26)	35.5 (0.34)	32.6 (0.48)	41.5 (0.75)
HU (%)	68.9 (0.36)	63.4 (0.66)	66.5 (0.74)	62.2 (1.02)	60.6 (0.79)	42.9 (0.74)	56.2 (0.73)	34.6 (0.75)	58.3 (1.04)	40.1 (0.36)	49.3 (1.07)	32.3 (1.02)
ST_{5cm} (ºC)	18.7 (0.2)	20.2 (0.17)	20.4 (0.21)	22.9 (0.24)	19.6 (0.13)	23.1 (0.42)	21.1 (0.17)	30.8 (0.4)	21.9 (0.19)	27.1 (0.46)	25.3 (0.31)	35.7 (0.45)
ST_{10cm} (ºC)	18.4 (0.18)	19.5 (0.18)	19.8 (0.18)	21.7 (0.16)	19.5 (0.11)	21.6 (0.22)	20.8 (0.12)	26.5 (0.32)	21.4 (0.14)	25.0 (0.31)	23.7 (0.20)	31.3 (0.30)
SM (%)	27.5 (1.61)	27.1 (1.44)	21.5 (1.32)	19.9 (1.16)	17.4 (0.77)	17.6 (0.79)	12.3 (0.67)	10.4 (0.67)	22.6 (0.96)	21.4 (0.95)	17.5 (0.97)	13.9 (0.57)

The numbers between parentheses means (± standard error).

3.4. Soil CO_2 efflux

Average soil CO_2 efflux was lowest in the AF_{RO} (2.66 µmolm^{-2}s^{-}1) and FS_{RO} systems (2.39 µmolm^{-2}s^{-1}) and highest in the AF_{GI} (8.26µmolm^{-2}s^{-1}) and FS_{GI} systems (8.95 µmolm^{-2}s^{-1}) of the three farms (Table 4). Spatial variation in soil CO_2 efflux (expressed as coefficient of variation (CV) in Table 4) were higher in the AF (average 34.1%) than in the FS (average 24.2%) coffee systems.

Table 4: Average (n=30), standard error (s.e.) and coefficient of variation (CV) of soil CO_2 efflux (µmol m^{-2}s^{-1}) in agroforestry (AF) and full-sun (FS) coffee systems in the farms (RO, PA, and GI), Minas Gerais, Brazil.

System	AF_{RO}		FS_{RO}		AF_{PA}		FS_{PA}		AF_{GI}		FS_{GI}	
Time (hours)	8	12	8	12	8	12	8	12	8	12	8	12
CO_2 efflux	2.66	2.83	2.39	2.45	4.21	4.79	3.48	6.52	6.73	8.26	5.82	8.95
s.e.	0.15	0.20	0.15	0.13	0.24	0.29	0.14	0.18	0.47	0.47	0.21	0.40
CV (%)	31.96	39.61	35.18	29.23	30.64	33.18	21.81	15.04	38.18	31.13	19.76	24.69

s.e = standard error; CV = Coefficient of Variation (%).

3.5. Soil temperature sensitivity and R_{25}

Of all three farms, the Q_{10} was highest in both the AF (2.41) and FS (1.90) systems of RO, whereas it was lowest in the AF (1.26) system of PA. Only FS_{PA} (1.84) and FS_{GI} (1.41) had Q_{10} values with significant determination coefficients, since soil CO_2 efflux and soil temperature at 5 cm depth exhibited higher variation in FS versus AF systems during the day (Table 5). The highest soil temperature variation from morning to midday was observed in FS_{PA} (+ 9.74 °C) and FS_{GI} (+ 10.45 ºC). The highest soil CO_2 efflux variation was observed in FS_{PA} (+ 89.7%). Interestingly, both AF and FS systems exhibited similar soil CO_2 efflux variation (from 4 to 5%) in RO.

Table 5: Q_{10} values and coefficients of determination (R^2) for the mean (n = 60 evaluations of soil CO_2 efflux) and variation in soil temperature (Δ T5 cm) and soil CO_2 efflux (Δ CO_{2ef}) at each sampling point from the morning to midday periods in agroforestry (AF) and full-sun (FS) coffee systems at the farms (RO, PA and GI), Minas Gerais, Brazil.

System	AF_{RO}	FS_{RO}	AF_{PA}	FS_{PA}	AF_{GI}	FS_{GI}
Q_{10}	2.41	1.9	1.26	1.84	1.49	1.41
R^2	0.09	0.11	0.02	0.73	0.14	0.45
Δ T5 cm (°C)	+ 1.48	+ 2.45	+ 3.46	+ 9.74	+ 5.18	+ 10.45
Δ CO_{2ef} (μmolm^{2}s^{-1})	+ 0.16	+ 0.05	+ 0.58	+ 3.03	+ 1.51	+ 3.13
Δ CO_{2ef} (%)	+ 5.17	+ 4.21	+ 14.46	+ 89.73	+ 26.61	+ 53.36

When normalised to 25 °C, soil CO_2 efflux in the systems were similar ($p > 0.05$) at farms PA and GI, but not at RO. Soil CO_2 efflux increased ($p < 0.05$) when the altitude decreased. Thus, soil CO_2 efflux: RO (1000 m altitude) < PA (800 m altitude) < GI (650 m altitude; Figure 3).

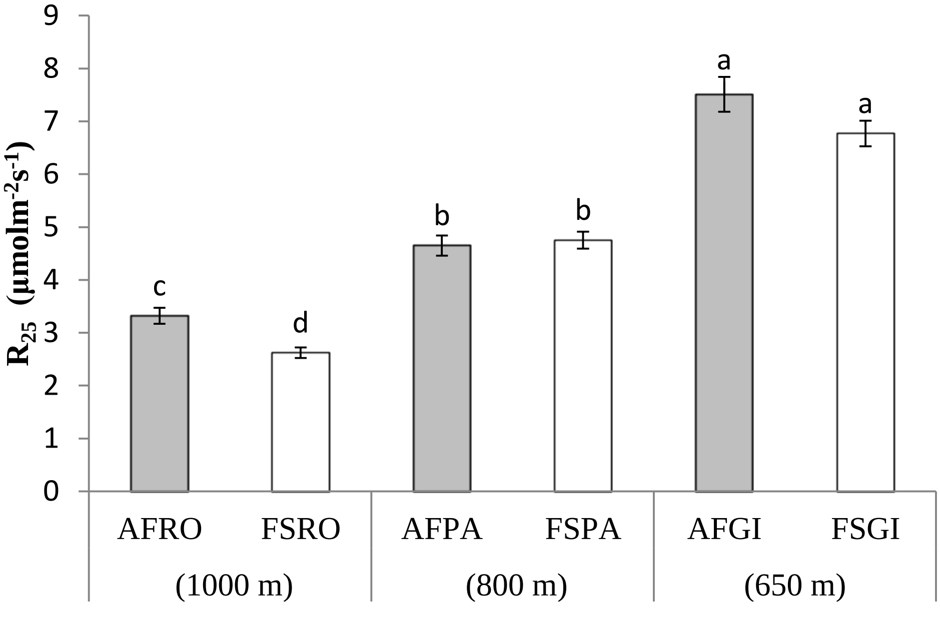

Figure 3: Mean (n = 60 evaluations of soil CO_2 in each system) soil CO_2 efflux (R_{25}) normalised at 25 °C soil temperature in the agroforestry (AF) and full-sun (FS) coffee systems at the three farms (RO, PA, and GI), Minas Gerais, Brazil, which were located at different altitudes (expressed as meters in parentheses). Bars with the same letters are not significantly different ($p < 0.05$) among all systems. Bar represent the mean ± the standard error.

3.6. Canopy cover versus climatic conditions and soil CO_2 efflux

The air temperature were negatively correlated ($p < 0.001$) and air humidity were positively correlated ($p < 0.001$) with canopy cover (%) (Figure 4) at all farms. Soil temperature (at both 5 cm and 10 cm depths) were negatively correlated ($p < 0.001$) at all farms and soil moisture content (%) was positively correlated ($p < 0.001$) with canopy cover (%) at two of the farms (PA and GI), but showed no correlation at the third farm (RO) (Figure 5).

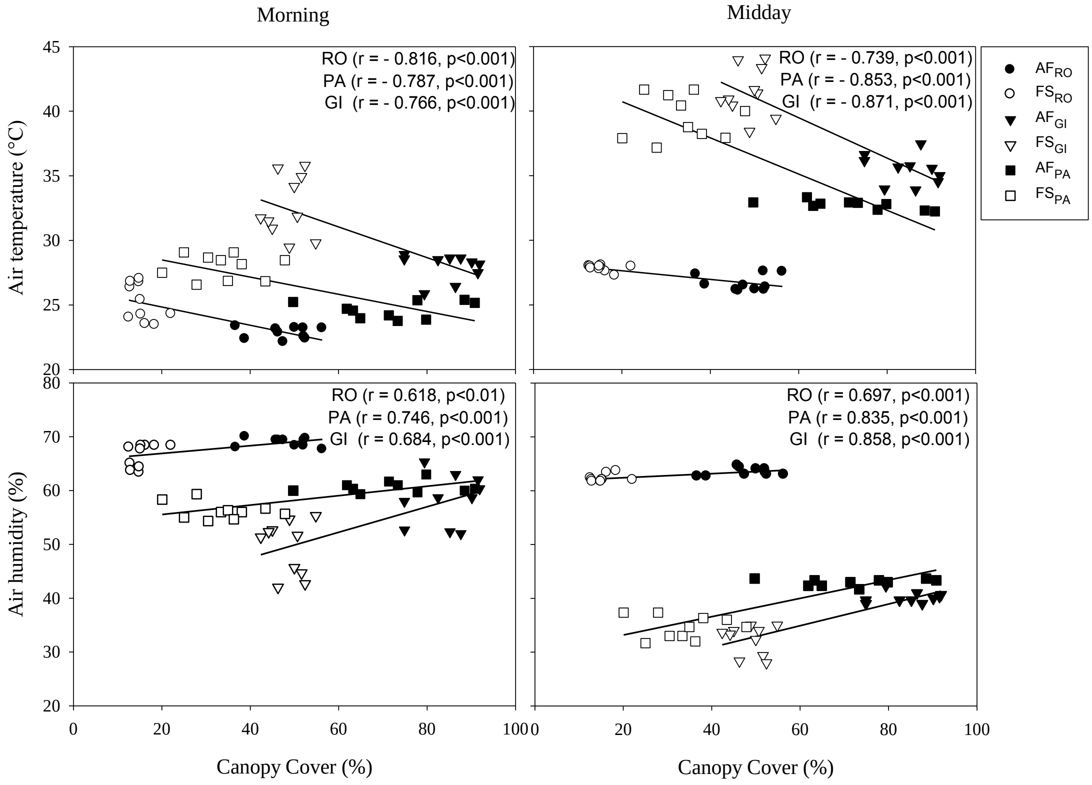

Figure 4: Person's correlations between canopy cover (%) and air temperature and humidity in the morning (08:00–10:00 h) and midday (12:00–14:00 h) in the agroforestry (AF) and full-sun (FS) coffee systems at three farms (RO, PA, and GI), Minas Gerais, Brazil.

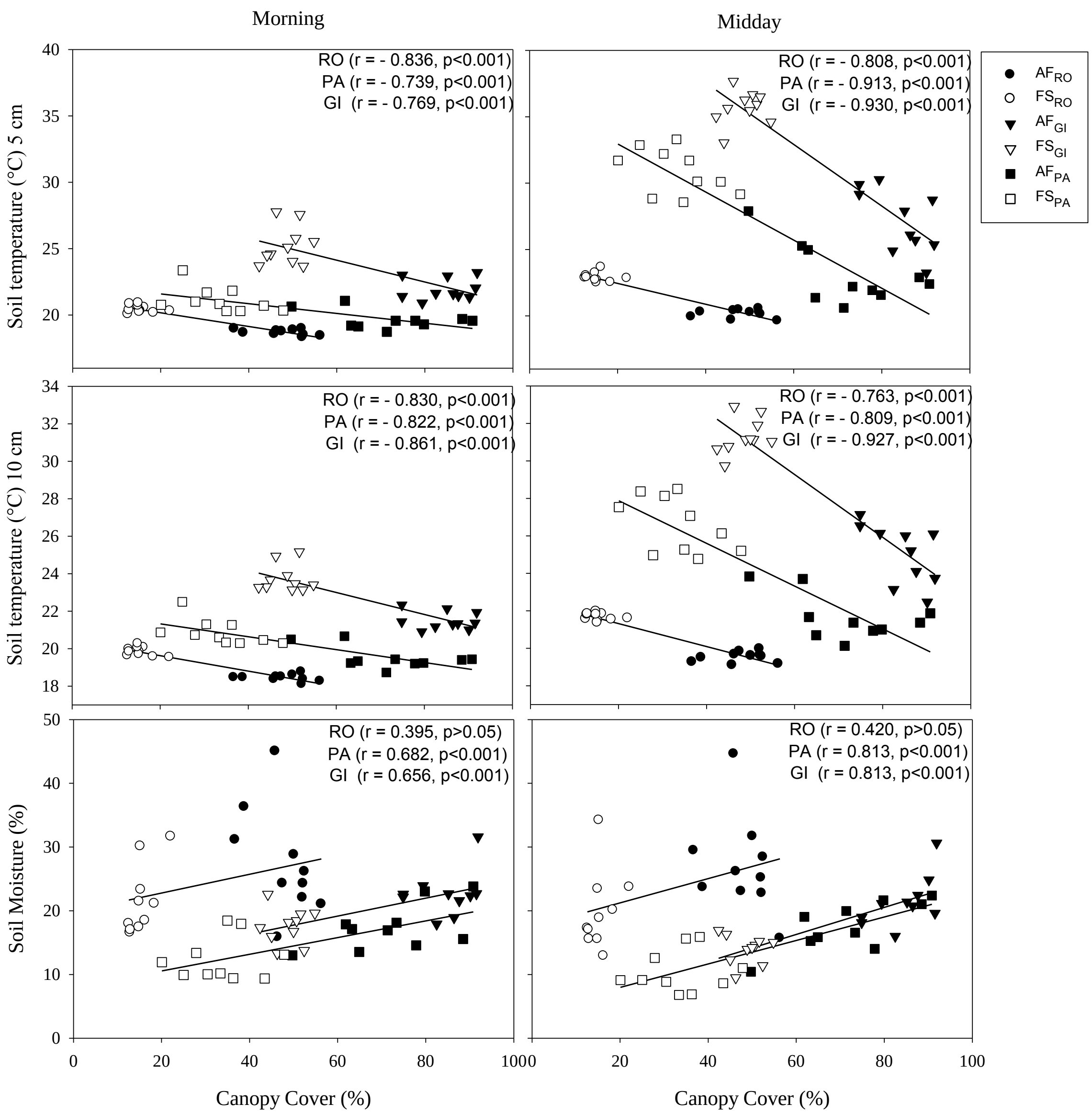

Figure 5: Person's correlations between canopy cover (%) and soil temperature at 5 and 10 cm depth and soil moisture in the morning (08:00–10:00 h) and midday (12:00–14:00 h) in the agroforestry (AF) and full-sun (FS) coffee systems at three farms (RO, PA, and GI), Minas Gerais, Brazil.

Figure 6 shows that decreasing soil CO_2 efflux variation from morning to midday is related to increasing canopy cover. Daytime soil CO_2 efflux variation (%) was negatively correlated with canopy cover (%) in PA (r = -0.787, $p < 0.0001$) and GI (r = -0.710, $p < 0.001$). Soil CO_2 efflux variation (%) was not correlated with canopy cover in RO.

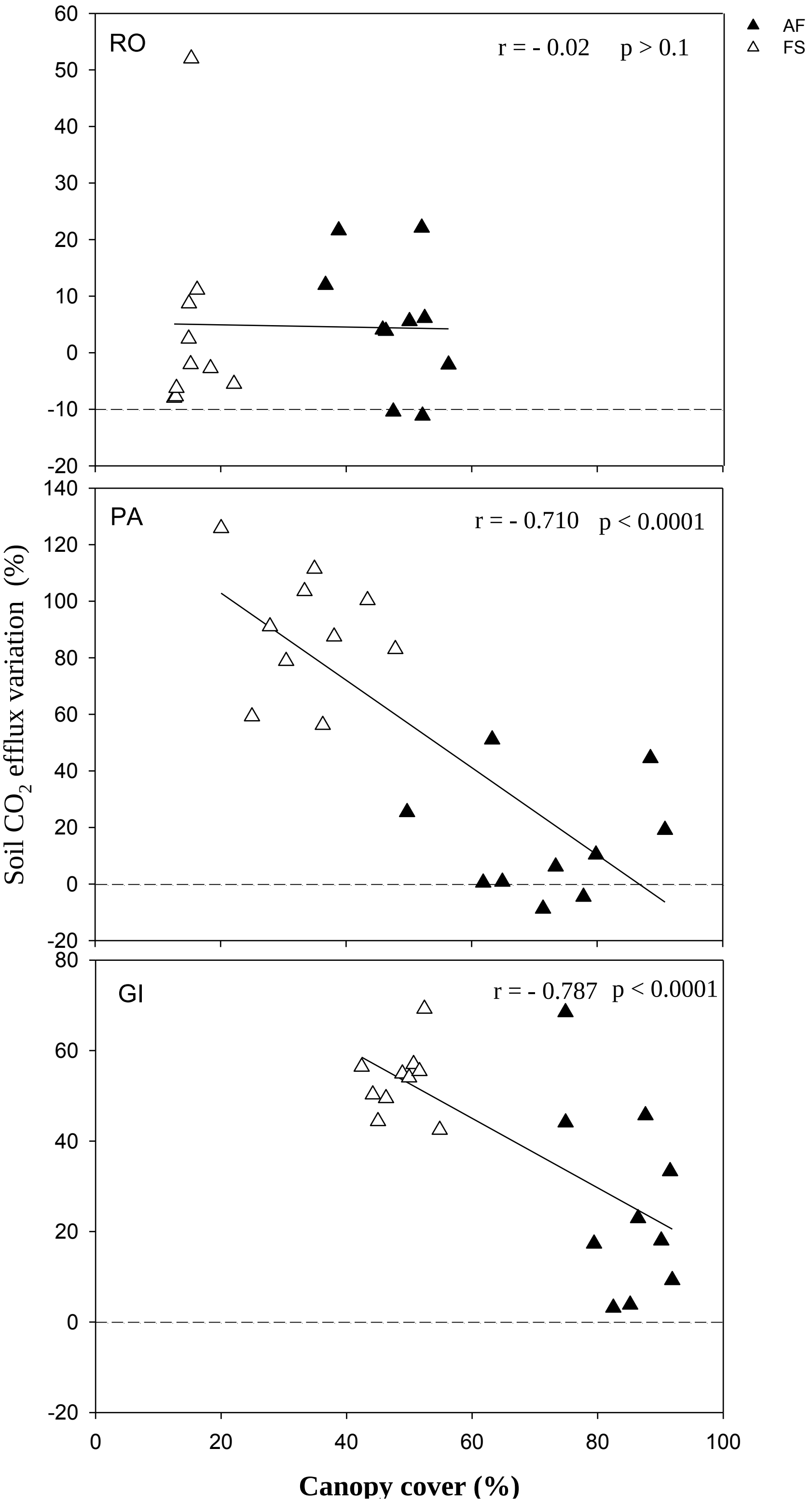

Figure 6: Pearson's correlations between canopy cover (%) and soil CO_2 efflux variation (%) from the morning (08:00–10:00) to midday (12:00–14:00) at each sampling point in the agroforestry (AF) and full- sun (FS) coffee systems at three farms (RO, PA, and GI), Minas Gerais, Brazil.

3.7. Multivariate analysis of soil CO_2 efflux

The multivariate equations (Table 6) showed that different factors control soil CO_2 efflux in the AF and FS coffee systems. Soil CO_2 efflux was more correlated with variation in LC and TN in the AF systems, whereas it was primarily correlated with soil temperature (especially at 10 cm depth) in the FS systems. Soil CO_2 efflux variation was primarily explained by TN (47%) and LC (24 %) in AF_{RO}, whereas it was explained by TN (30%), LC (60%), and soil temperature at 10 cm depth (9%) in FS_{RO}. Soil CO_2 efflux variation was primarily explained by soil BD (36%), LC (21%), and TN (18%) in AF_{PA}, whereas it was explained by soil temperature at 10 cm depth (97%) in FS_{PA}. Soil CO_2 efflux variation was primarily explained by soil temperature at 10 cm depth (28%), TN (27%), and total soil moisture (23%) in AF_{GI}, whereas it was explained by soil temperature at 10 cm depth (55%), TN (23%), and total soil moisture (22%) in FS_{GI}.

Table 6: Regression equations of soil CO_2 efflux in relation to soil microclimatic, chemical and physical characteristics from the agroforestry (AF) and full-sun (FS) coffee systems at the three farms (RO, PA and GI), Minas Gerais, Brazil.

System	Parameters	Regression Equation	FD	F	R^2	p
AF_{RO}	TN (47%), LC (29%), PMi (24%)	Y = -3,49 + 2.25TN** -0,96LC* +11,35PMi	16	5.75	0.52	0.007
FS_{RO}	TN (30%), LC (60%), ST_{10cm} (9%), SM (1%)	Y= -1,41 + 0.018 ST_{10cm} + 0.85LC** -0.02SM -0.20TN	15	13.1	0.77	< 0.0001
AF_{PA}	TN (18%), LC (21%), ST_{10cm} (7%),SM (9%), BD(36%), PMi (9%)	Y= 2.57 + 0.20 ST_{10cm} + 2.50TN - 1.15LC - 9.32BD + 20.83PMi + 0.09SM	13	0.95	0.30	0.495
FS_{PA}	ST_{10cm} (97%), LC (1%) TOC (1%), BD (1%)	Y = - 9.78 + 0.51 ST_{10cm} ***+ 0.22TOC + 0.28BD + 0.36LC	15	17.2	0.82	< 0.0001
AF_{GI}	TN (27%),ST_{10cm} (28%),SM(23%),BD (10%), PMi (12%)	Y = 35.1 + 0.689 ST_{10cm}** -5,58 TN** -6,01 BD - 92.50PMi* + 0.38 SM*	14	5.42	0.66	0,005
FS_{GI}	ST_{10cm} (55%), TN (23%), SM (22%)	Y = 11.17 + 0.36 ST_{10cm}** + 4.31TN* - 0.06SM	16	11.4	0.68	< 0.0001

FD = Freedom degrees; TN = Nitrogen Total; LC = Labile Carbon; PMi = Microporosity; ST10cm = soil temperature at 10 cm depth; BD = soil Bulk Density; TOC = Total Organic Carbon and SM = Soil Moisture. The percentage between parentheses shows the relative importance of each parameter for the soil CO2 efflux.
(**) $p < 0.001$ and (*) $p < 0.05$.

The PCA analysis indicated which variables were responsible for total data variation in the systems and how the variables were correlated with soil CO_2 efflux (Figure 7). Overall, soil CO_2 efflux was positively correlated with soil temperature at 5 and 10 cm depths and negatively correlated with soil moisture, WFPS, and PMi.

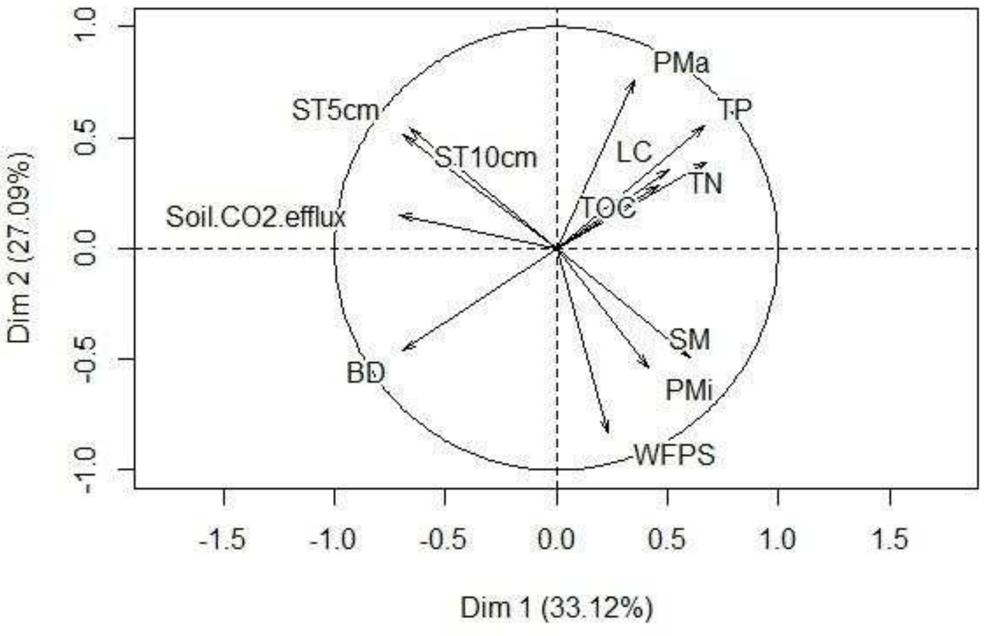

Figure 7: Principal Component Analysis of data from the agroforestry and full-sun coffee systems at the three farms (RO, PA, GI), Minas Gerais, Brazil. The plot shows the soil characteristics and environmental factors that tend to influence soil CO_2 efflux. ST5cm = soil temperature at 5 cm depth; ST10cm = soil temperature at 10 cm depth; PMa = Macroporosity; LC = Labile Carbon; TP = Total Porosity; TOC = Total Organic Carbon; TN = Total Nitrogen; SM = soil moisture; PMi = Microporosity; WFPS = Water Filled Pore Space; BD = Soil Bulk Density.

4. DISCUSSION

4.1. Influence of *canopy's* trees on soil and air variables

The agroecological management of the two systems in the three farms improved the soil quality, indicated specially by the TOC (average of 32.38 g kg^{-1} at 0-10 cm soil depth, Table 2), whereas, in the same region, TOC (n = 41) in coffee fields was 21.7 g kg^{-1} at 0-20 cm (Martinez et al., 2000) and in native forests (n=3) was 61.0 g kg^{-1} at 0-10 cm (Souza et al., 2012). Plants that grow spontaneously between coffee plant rows in AF and FS coffee systems are controlled with agroecological practices and not completely removed. In addition, the straw from corn was left on the soil after harvesting, which increases the carbon input also in FS systems. Therefore, this may explain similar amount of total organic carbon found in the two systems investigated in the current study (Table 2).

In the studied AF, the coffee was intercropped with a diversity of different tree species (Souza et al., 2010), resulting in different canopy dimensions, tree phenology and leaf density. These differences led to different percentages of soil surface cover by the canopy (Figure 1 and 2), affecting the amount of solar radiation that reached the soil (Breman and Kessler, 1995). The main tree species in AF_{RO} (Inga subnuda) were pruned during the summer of 2012 (i.e. the year before the study was conducted), which may explain why this location had lower canopy cover of the AF than FS systems.

The trees in the agroforestry systems provide stability to microclimate under the canopy (Beer et al., 1997; Kiepe and Rao, 1994; Lin, 2007a; Nair, 1997), reducing, for instance, air temperature (Akpo et al., 2005; Lin et al., 2008; Souza et al., 2012), as shown in our study (Figure 4). The air temperature, despite different altitudes, different vegetation species and ages of implementation of the studied systems (Table 1) correlated with canopy cover (Figure 4).

The microclimate provided by tree canopy is important for C. arabica cultivation, which requires temperature of 18–21 ºC for optimal growth (Alegre, 1959). It has been predicted that a 2 °C increase in the average global temperature will occur by 2100 (Stocker et al., 2013). If this temperature rise occurs, many places such as the Zona da Mata of Minas Gerais (Brazil) will no longer be suitable for growing C. arabica (Assad et al., 2004). However, the ecophysiological limitations of coffee may be overcome if the plants are shaded, as in AF systems (DaMatta, 2004). Therefore, in a scenery of climate change (Stocker et al., 2013), AF systems may become crucial for continued coffee production in areas such as the Zona da Mata of Minas Gerais. In this region, AF systems are already used, but remain small-scale at present (Edenhofer et al., 2014).

Moreover, the humidity in the agroecosystem is also important topic due to predicted global climatic change. Increased canopy cover level increases soil moisture (Lin et al., 2006; Liu et al., 2013), as observed in our study (Figure 5), due to a decrease in soil evaporation (Lin, 2010). Coffee production is extremely vulnerable to water availability, which is necessary for the development of coffee beans and consequently determines the fruit size (Cannell, 1983). In the region, this is also important in January and February (rainy season), when a short dry period can occur leading to bad formation of the coffee beans. Thus, agroforestry coffee systems can provide better conditions to maintain the water in the system (Liu et al., 2013) and enhances coffee beans sizes (Vaast et al., 2006), therefore, decreasing the risk of coffee production losses.

4.2. Soil CO_2 efflux

Existing publications state that soil CO_2 efflux is one of the largest uncertainties when analysing the global carbon cycle, because it involves several processes, including different sources and multiple and varied controllers (Moyes et al., 2010). Our findings contributes towards improving our understanding about the dynamic of soil CO_2 efflux. In our study, we found that the daily mean soil CO_2 efflux was similar in both AF and FS coffee systems at all three farms (Table 4). However, the results indicated that the daily dynamics in soil CO_2 efflux differed between the two systems. We found that the soil CO_2 efflux variation during the day decreases with increases in canopy cover levels (Figure 6) and that the efflux was more stable in AF systems, presenting less temporal variation from morning to midday than in FS systems (Table 5), except in in RO farm. In RO, during the three days of the soil CO_2 efflux evaluation, the air humidity was very high and the air temperature were low and did not change much from the morning to midday period (Table 3). Therefore, the effect of canopy cover of trees on the microclimate in this farm was not pronounced (Figure 4 and 5).

The difference in the variation from morning to midday among AF and FS coffee systems can be an indication of different sources of soil CO_2. The low variation in soil CO_2 efflux between the morning and midday combined with higher spatial variation indicates that soil CO_2 efflux is due to heterotrophic soil respiration (i.e. of soil biota) rather than autotrophic respiration (i.e. of roots). Thus, AFs mimicked natural forests, with trees creating a soil microclimate that was suitable for the growth of soil microorganisms (Bach et al., 2010), which, in turn, allowed them to decompose soil organic matter and release nutrients for plant growth. In this case, CO_2 efflux is advantageous because plants obtain better conditions for growth and, hence, are able to fix more carbon through photosynthesis.

Higher variation in soil CO_2 efflux between morning and midday in the FS systems indicates that soil CO_2 efflux is primarily the result of autotrophic respiration. FS systems are subject to more stress on autotrophic and heterotrophic soil respiration because of the higher soil temperature at midday. Root respiration is driven by recent photosynthesis (Hogberg et al., 2008) and increases with air temperature (Atkin et al., 2000; Burton et al., 2002). Therefore, an increase in air and soil temperature due to lower canopy cover (Figure 4 and 5) is probably responsible for the increase in soil CO_2 efflux (Table 5). Therefore, CO_2 in FS systems, at mid-day, was returning faster than in AF to the atmosphere, probably, from root respiration. Root respiration can releases from 8 to 52% of the total CO_2 fixed by photosynthesis per day (Lambers et al., 1996).

Soil CO_2 efflux is characterised by high spatial and temporal variability (Hanson et al., 1993; Xu and Qi, 2001a). Tedeschi et al. (2006) reported the spatial variation of 31 to 45% soil CO_2 efflux in Mediterranean forests. In contrast, the spatial variation in soil CO_2 efflux was 30 to 65% in Norwegian pine forests. A study of Asian tropical forests identified spatial variation of 26 to 62% soil CO_2 efflux, with variation increasing with increasing grid (distance between sampling points) evaluation (Kosugi et al., 2007). To the knowledge of the authors, there is no such study for agroforestry systems. In our study, the highest spatial variation of CO_2 efflux (31.4%) was obtained in AFs (Table 4), which may be explained by the presence of different tree species that promote different environments conditions owing to their specific biological characteristics. Tree characteristics such as root biomass, distances between trees, and organic matter contribution influence the pattern of spatial variability in soil respiration (Katayama et al., 2009; Søe and Buchmann, 2005), therefore the CO_2 efflux. In contrast, FS systems had the lowest spatial variation in soil CO_2 efflux, which may be explained by the environmental homogeneity of soils in the monoculture plantations.

4.3. Soil temperature sensitivity and R_{25}

Because Q_{10} is sensitive to ecosystem and climatic variation (Raich and Schlesinger, 1992), several studies have used it to analyse soil CO_2 efflux and determine soil temperature sensitivity (Acosta et al., 2013; Davidson and Janssens, 2006; Kirschbaum, 2006; Reichstein et al., 2003). However, in our study, Q_{10} only showed significant coefficients of determination in FS_{PA} and FS_{GI}, due to low average variation in soil temperature and soil CO_2 efflux in the others systems during the study period (Table 5). In our study, lower Q_{10} values were found in locations that had higher soil temperature (Table 3 and 5). Over a 1-year period, Xu and Qi (2001a) identified maximum and minimum Q_{10} values during winter and summer (when temperatures were higher), respectively, supporting the results of our study despite being conducted under different climatic conditions.

Increasing altitude is correlated with a decrease in soil CO_2 efflux (Wang et al., 2011), with this trend being observed in the current study, with RO, located at 1000 m altitude, having the lowest values of R_{25} (soil CO_2 efflux normalized to a temperature of 25 °C) (Figure 3).The air and soil temperature, important factors that regulate soil CO_2 efflux, decrease with increase in altitude, what explain our lowest values of soil CO_2 efflux at high altitude. The lower soil CO_2 efflux at higher altitudes may be one of the explanation for higher organic carbon content in the soil at higher altitude locations (Manojlovic et al., 2011).

4.4. Multivariate analysis of Soil CO_2 efflux

Soil CO_2 efflux is complex because it is the result of the combination respiration by plant roots and microorganisms (Kuzyakov, 2002), which are influenced by soil biotic and abiotic factors (Buchmann, 2000). Certain soil physical attributes (such as soil density and porosity) are important in soil CO_2 efflux because they interfere in gas diffusion processes (Blagodatsky and Smith, 2012). However, soil physical attributes were similar in the current study (Table 2); thus, the effects of these attributes on soil CO_2 efflux variation were not visible.

In the current study, variation in CO_2 efflux was mainly explained by TN and LC, in the AF systems (Table 6), probably due to the favourable soil microclimate for high microbial activity under the tree canopy. Soil temperature at 10 cm depth primarily explained variation in CO_2 efflux in the FS systems (Table 6), probably the absence of the tree canopy, present in the agroforestry systems, led to higher soil temperature and lower soil moisture (Figure 5). The optimal depth temperature measurement that better explain the relationship between soil CO_2 efflux and soil temperature is still uncertain, but it is know that Q_{10} increases with the depth of soil temperature measurements (Pavelka et al., 2007; Peng et al., 2009). Xu and Qi (2001b) calculate the Q_{10} using soil temperature at 5, 10 and 20 cm depth and found the highest correlation at 10 cm depth. Tang et al. (2003) correlated the soil CO_2 efflux to soil temperature at 2, 8 and 16 cm depth and found the highest correlation with soil temperature at 8 cm depth, which may be the depth where most CO_2 was produced. In our case the soil temperature at 10 cm depth explain better the variation in soil CO_2 efflux (Table 6), probably due more microbial and roots activities at 10 cm than 5 cm soil depth. Closer to the surface, the soil is more subject to variation due to environmental conditions, which can interfere in the organism activity (Cardoso et al., 2003).

Soil temperature affects microbiota activity and the root respiration (Atkin et al., 2000; Schindlbacher et al., 2011). Long-term studies (1 year or more) have reported higher soil CO_2 efflux in summer, when temperatures are higher (Bilgili et al., 2013; Liu et al., 2011; Olajuyigbe et al., 2012). This phenomenon was supported by the findings of our study (Figure 7), in which soil CO_2 efflux was positively correlated with soil temperature and negatively correlated with soil moisture, as also found by other authors (Davidson et al., 1998; Kosugi et al., 2007; Liu et al., 2013).

Soil moisture together with soil temperature have the greatest influence on soil CO_2 efflux (Fang and Moncrieff, 2001; Fenn et al., 2010). Soil moisture affects gas exchange in soil because it fills the soil pore space, which lowers the amount of oxygen available for aerobic microorganisms (Melling et al., 2013) and prevents CO_2 diffusion to the soil surface (Melling et al., 2005).

4.5. Trees and the carbon cycle

Trees use photosynthesis to fix CO_2 from the atmosphere, of which some amount is deposited in the soil. Carbon deposited in the soil may enter stable fractions of soil organic matter or be released back to atmosphere as CO_2. Almost 10% of the atmosphere's CO_2 passes through the soil each year; thus, the effects of trees on aboveground and belowground biological and physical properties are important for the carbon cycle (Raich and Potter, 1995).

The carbon balance in soil is the result of carbon input through photosynthesis and carbon loss, mainly in the form of CO_2. When considering CO_2 efflux, the carbon cycle of the AF coffee systems is more closed than that of FS coffee systems. Even if we consider that the amount of carbon lost to the atmosphere was the same in both systems, part of the soil CO_2 efflux in AFs was neutralised by photosynthesis carried out by trees (other than coffee trees). Trees in the AF system add more carbon than in the FS system stored in the plant biomass (Duarte, 2007; Hergoualc'h et al., 2012).

5. CONCLUSIONS

AF increased soil moisture and decreased air and soil temperatures, due to an increase in canopy cover from trees intercropped with coffee plants.

Trees in AF did not affect the daily soil CO_2 efflux when compared to FS coffee systems, but imposes different daily emission dynamics. Daytime soil CO_2 efflux was more stable in the AF system compared to the FS system. Specifically, the AF system presented less variation from morning to midday and higher spatial variation than in the FS system. In the AF system, variation in CO_2 efflux was mainly explained by TN and LC, whereas in the FS system, it was mainly explained by soil temperature at 10 cm depth. Although similar the daily CO_2 efflux was similar in both systems, AF store more carbon in the biomass, thus, AF coffee systems were more beneficial to the carbon cycle than FS coffee systems.

Future studies are needed to identify the source of CO_2 efflux (i.e. autotrophic versus heterotrophic respiration) and to evaluate CO_2 efflux throughout the day year-round to improve our understanding about seasonal variations in soil CO_2 efflux under AF and FS coffee systems. This study shows the importance of evaluation of the soil CO_2

efflux at different periods of day in agroecosystems, avoiding overestimate or subestimate the total values of soil respiration. Our study also shows that combining measurements of soil CO_2 efflux, soil temperature and moisture conditions, soil characteristics and vegetation cover is promising and will help us to understand mechanisms underlying soil CO_2 efflux and improve the agricultural practices to capture and maintain more carbon in the soil.

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GENERAL CONCLUSIONS

Soil CO_2 efflux is a complex process that depends on the soil biological, chemical and physical characteristics and especially on the soil temperature and moisture conditions. However, the land use and vegetation type may be the main components to control the soil CO_2 efflux in agroecosystems, since they influence the soil biological and physical characteristics and control the soil temperature and moisture.

We showed that soil CO_2 efflux correlated positively with soil temperature and negatively with soil moisture and that, contrary of full-sun, in agroforestry coffee systems the soil and air temperature decreased and that soil moisture increased. Therefore, the trees in that agroforestry coffee system were considered to be the main components that control the soil CO_2 efflux.