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Energy, water vapor and carbon fluxes in Andean agroecosystems: conceptualization and methodological standardization

Flujos de energía, vapor de agua y carbono en agroecosistemas andinos: conceptualización y estandarización metodológica

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Abstract

This paper presents the conceptualization, methodological adjustment and experimental application of the micrometeorological technique eddy covariance - EC, to measure energy, water vapor and CO_2 fluxes in two coffee agroecosystems: the first under full sunlight, and the second under shade, both with equatorial Andean hillslope conditions. With a footprint and fetch calculation, the required distance from the edge of the field in the prevailing wind direction to the EC tower is three times higher under shade than full sun. The shaded agroecosystem reached maximum average carbon fixation rates of 21.26 ± 2.469 $\mu molCO_2.m^{-2}s^{-1}$ (α = 0.05) (61% higher than under 100% sunlight) which gives a high carbon sink capacity to the association of coffee plants with shading Pigeon peas (*Cajanus cajan* L). The average evapotranspiration rate was 2.33 ± 0.0102 $mm.d^{-1}$ (α = 0.05) and 2.08 ± 0.00732 $mm.d^{-1}$ under shade and 100% sunlight, respectively. The proportion of net radiation that reached the soil was 2% under shade and 4% under 100% sunlight. Likewise, the soil energy loss during the night was lower under shade, indicating less day-night temperature range in the latter agroecosystem. The methodological adjustment and the results of this first work using EC in Colombian coffee plantations, contribute to the development of reliable research regarding gas and energy exchanges between the atmosphere and ecosystems in conditions of the equatorial Andean hillslope.

Keywords: Agroecosystem coffee, Andean hillslope, eddy covariance, energy fluxes, gas exchange.

Resumen

Este artículo presenta la conceptualización, ajuste metodológico y aplicación experimental de la técnica micrometeorológica covarianza de remolinos – *EC* (eddy covariance, en inglés), para medir flujos de energía, vapor de agua y CO_2 en dos agroecosistemas cafeteros: a libre exposición solar y bajo sombra, en condiciones de ladera andina ecuatorial. Con el cálculo del *footprint* y el *fetch* se encontró que la distancia requerida desde el borde del lote en la dirección predominante del viento hasta la torre *EC*, es tres veces mayor bajo sombra que a libre exposición solar. El agroecosistema bajo sombra alcanzó tasas máximas promedio de fijación de carbono de 21.26 ± 2.469 $\mu molCO_2m^{-2}s^{-1}$ (α = 0.05) (61% mayores que a libre exposición) lo cual atribuye características de alta capacidad de fijación de carbono a la asociación de cafetos con sombrío de Guandul (*Cajanus cajan* L). La tasa de evapotranspiración promedio fue de 2.33 ± 0.0102 $mm.d^{-1}$ (α = 0.05) y 2.08 ± 0.00732 $mm.d^{-1}$ bajo sombra y a libre exposición, respectivamente. Se encontró que la proporción de la radiación neta que llegó al suelo fue de 2% bajo sombra y 4% a libre exposición; así mismo la pérdida de energía del suelo durante la noche fue menor bajo sombra, indicando menor amplitud térmica día-noche en este último agroecosistema. Con el ajuste metodológico y con los resultados de este primer trabajo utilizando *EC* en cafetales colombianos, se busca contribuir al desarrollo de investigaciones confiables en cuanto al intercambio gaseoso y energético entre la atmósfera y ecosistemas en condiciones de ladera andina ecuatorial.

Palabras clave: Agroecosistema cafetero, ladera andina, covarianza de remolinos, Flujos de energía, Intercambio gaseoso.

Introduction

Quantification of mass and energy fluxes in terrestrial ecosystems is essential to understanding the relationships between climate and biosphere. It enables the evaluation of ecophysiological parameters in plants, modeling and simulation of crop responses to environmental changes and assessing the effect of variations in atmospheric concentrations of gases (Zhu *et al.*, 2011).

Research conducted in order to understand the process of gas and energy exchange between plant ecosystems and the atmosphere addressed to different spatial and temporal scales, from hours to years and from leaves to plant arrangements. For several crops around the world, including Coffea arabica L., in the Colombian coffee zone, it is possible to estimate the net photosynthesis of a whole plant from measurements recorded on leaves using validated models (Goudriaan, 1986). However, the equipment used for these measurements can alter the natural microclimatic conditions under which gas exchanges (Pérez *et al.*, 2010).

Currently, one of the techniques used to determine the net fluxes of trace gases such as CO_2 and energy exchange between the atmosphere and different types of terrestrial ecosystems is "Eddy Covariance - EC" (Tallec *et al.*, 2013; Zhu *et al.*, 2011). This method allows direct measurement of exchanges in an entire ecosystem without disturbing natural conditions and to monitore over the maximum canopy height.

The EC method is being used in analysis of balances on global scale networks such as FLUXNET (Baldocchi *et al.*, 2001), in order to quantify and understand the spatio-temporal variations in carbon storage in plants and soil and the exchange of carbon dioxide, water vapor and energy in several types of vegetation. In Colombia, the first microclimatic tower was introduced in 2012. La Libertad, an experimental station of CORPOICA, located in Villavicencio. In addition, five EC stations were installed to assess fluxes in different agricultural systems: Cenipalma (Centro Experimental Palmar de La Vizcaína, Barrancabermeja), Cenicaña (Cenicana Experiment Station, Florida), and Cenicafé (Estación Experimental Paraguacito, Buenavista). The number of this type of station tends to increase due to its importance.

Basic concepts for understanding the EC method and the methodological standardization process used in this research and a first approach to the use of micrometeorological towers associated with this technique for determining energy, water vapor and CO_2 fluxes in coffee agroecosystems under conditions of the Andean hillslope.

Material and methods

Basic concepts

In order to understand and apply methodologies for measuring exchanges of matter and energy between the atmosphere and agroecosystems, it is required mainly to know the following key aspects:

Turbulent transport

Gases and energy exchange processes occur within the atmospheric boundary layer in the turbulent surface sublayer, which is close to 100 meters thick. Depending on the height of the canopy, a dynamic sublayer whose height varies from a few centimeters to 10 meters, this is where gas and energy exchange occurs between ecosystems and the atmosphere. This region is affected by turbulence caused by mechanical and thermal forces induced by the physical characteristics of the surface (roughness) and temperature differentials between the atmosphere and vegetation (Prueger & Kustas, 2005). There, the airflow is highly irregular and characterized by bursts of varying intensity which carry eddies with three-dimensional components, including vertical air movement.

Eddy covariance

This method is associated with measures of energy and matter exchange fluxes in the dynamic sublayer of the atmosphere (flux is defined as the amount of an entity that passes throughout an area in a unit of time) (Hatfield *et al.,* 2005). Fluxes, are calculated from direct measurements taken instantaneously, with a frequency sampling between 10 and 50 Hz.

Net difference of materials transported by the Eddy covariance throughout the interface between canopy and the atmosphere, which is determined by the covariance between the concentration of interest and the vertical wind speed. However, the mean density of turbulent flux is approximately equal to the average density of air multiplied by the average covariance between fluctuations in instantaneous vertical wind speed and the mixing ratio (Burba *et al.,* 2013), the following basic equation (Equation 1) is derived:

- Net CO_2 Flux (*FCO_2*)

$$FCO_2 = \overline{\rho_a}.\overline{w'c'}$$

Equation 1

Where:

FCO_2 = mean CO_2 flux over a period of time, $mg.m^{-2}.s^{-1}$

ρ_α = air density, $kg.m^{-3}$

w = instantaneous vertical wind speed, $m.s^{-1}$

c = CO_2 mixing ratio (c = ρc / ρa where ρc is the density of CO_2), $kg.m^{-3}$

w', c' = deviations from mean ($w - \overline{w}$) and ($c - \overline{c}$) respectively, the bar represents the integration of the data during the sampling time, which is recommended to be between 30 minutes and 1 hour to include eddies of different sizes and frequencies. A positive covariance represents net transfer of CO_2 to the atmosphere, and a negative one denotes net transfer of CO_2 from the atmosphere (Equation 2)(Baldocchi, 2003).

- Sensible heat flux (H)

$$H = \rho_a C_p \overline{w'T'}$$

Equation 2

Where:

H = sensible heat flux; energy used for heating the air, $W.m^{-2}$.

ρ_α = air density, $kg.m^{-3}$

C_p = specific heat of air at constant pressure, $J·kg^{-1}·K^{-1}$

w = instantaneous vertical velocity of the wind, $m.s^{-1}$

T = air temperature, °C

w', T' = deviations from mean ($w - \overline{w}$) and ($T - \overline{T}$) respectively, in a data integration period (Equation 3).

- Latent heat flux (LE)

$$LE = \lambda \frac{\epsilon}{P} \rho_a \overline{w'e'}$$

Equation 3

Where:

LE = latent heat flux; energy used for evapotranspiration process, $W.m^{-2}$

ϵ = ratio of molecular weights of water vapor and air = (M_w / M_α)

P = atmospheric pressure, kPa

ρ_α = air density, $kg.m^{-3}$

e = water vapor, $g.m^{-3}$

λ = water vaporization latent heat, $J.kg^{-1}$

$w'e'$ = deviations from the mean ($w - \overline{w}$) and ($e - \overline{e}$) respectively, in a period of data integration.

Methodological standardization

In order to adjust the EC methodology to Andean hillslopes using experimental data, two coffee agroecosystems were evaluated: Castillo® cultivar 1-year old, with planting density of 10000 trees per hectare, a) under 100% sun light exposure and b) shaded with Pigeon peas.

The research was carried out at the Paraguacito experimental station (Centro Nacional de Investigaciones de Café, CENICAFE, Buena Vista - Quindío), (04°23´00´´ N, 75°44´ W, 1203 m.a.s.l.). The mean values of climate variables are performed in Table 1.

Table 1. Climatic characteristics of the experimental station Paraguaicito (Anuario meteorológico de Cenicafé, 2011)

Air Temperature (°C)			Average Relative Humidity (RH)	Accumulated Solar Brightness (SB)	Cumulative Rainfall (CR)
Maximum (T_{max})	Mean (T_m)	Minimum (T_{min})			
28.1°C	21.6 °C	16.9 °C	77.5 %	1796 h	2118 mm

Two installed systems were performed.

1. An EC system, type IRGASON® (Campbell Scientific Inc., USA) with an Open-Path gas analyzer (EC 150, USA), which measures absolute concentrations of carbon dioxide and water vapor,

2. A sonic anemometer (CSAT3-3D, USA), which measures orthogonal components of the wind and an air temperature sensor (Vaisala HMP 60, USA). These systems are integrated with the EC system.

3. A barometric pressure sensor (Apogee Bs 100, USA),

4. Sensors to measure air temperature (Ta), relative humidity (RH) (Vaisala HC2-S3, Finland), net radiation (NR) (Kip & Zonen NR-LITE, Netherlands), solar global radiation (GR) (Apogee CS300 pyranometer, USA), and photosynthetically active radiation (PAR) (Apogee SQ110 Quantum, USA).

5. Leaf wetness (devices Decagon, LWS-L, USA), soil heat flux (G) (huksflux, HFP01SC, Netherlands), soil water content between 15 and 30 cm depth (Campbell Sci. Inc., CS616, USA) and soil temperature (Ts) (Campbell Sci. Inc., TCAV, USA) sensors were added.

Sensors for *Ta*, *RH* and *PAR* installed within the canopy in the shaded system in order to record the radiation actually reaching the coffee trees after it is intercepted by the set of leaves of shade trees. The first IRGASON® installed 4 m above the canopy in a metal structure 6 meters height, 2 m wide and 2 m long into shaded coffee agroecosystem, whose canopy height was 2 m (Figure 1a). The second one was installed 1m above the canopy on a 2 m height tripod into the full sun coffee agroecosystem, whose canopy was 1 m height (Figure 1b).

Figure 1. Micrometeorological Eddy Covariance towers: a. Shaded coffee agroecosystem b. 100% sun light coffee agroecosystems.

Data were collected at a sampling frequency of 10 Hz and were stored in a CR3000 datalogger (*Campbell Scientific Inc., USA*). They were integrated for periods of 30 minutes in order to calculate fluxes. A 12V, 48A battery (*Genesis, USA*), charged with a solar panel 60W (*SP60-PW, Campbell Scientific Inc., USA*) was used. The information was transmitted real time via modem Raven XTG (*Sierra Wireless, Canada*) through a GPRS network to the Cenicafé central station.

EC system Criteria for adjusting the installation conditions

For optimum installation of the EC system so that the measured fluxes correspond to the agroecosystem of interest, some considerations were taken into account:

- Prevailing wind direction

Two wind roses, the first one from 07:00 to 17:30 and the second one from 18:00 to 06:30, were determined prior to the installation of the measuring unit, using WRPLOT View ™ (Wind rose plots for meteorological data, Canada). The diurnal predominant wind direction was from NorthWest, and during the night from SouthEast. The wind roses allow placement of the tower and IRGASON® at the point that represents the best condition to measure fluxes on the dynamic sublayer and to ensure the parallelism of the sensor with the prevailing wind direction vector. Therefore, the IRGASON® was installed to the NW (azimuth angle 315°).

- IRGASON® Height and location

The manufacturer and literature recommend IRGASON® to be installed over the top of the canopy at least twice its height and 100 times less than the distance from the tower to the edge of the field in the dominant direction from the wind (this distance is named "fetch") (Burba & Anderson, 2007). Thus, for a fetch of 100 meters, the measurement height should be 1 meter above the canopy.

In addition, the following criteria must be considered: 1. The land must be predominantly flat. 2. The area to assess the agroecosystem must be representative and be influenced by the prevailing wind direction so that the contribution of the latter is at least 80% to determine the fluxes between the agroeosystems and the atmosphere (Baldocchi, 2003).

- Footprint

The footprint allows for the tracking of the contribution of fluxes measured in a given space (Soegaard et al., 2003). This is the area covered by the IRGASON® from the tower, and determines the location of the instrument height and fetch, so that most of the data for flux calculations come from the area to be measured (Burba *et al.*, 2013).

The model described by Schuepp *et al.*, (1990), was performed, to determine the fetch from the footprint (Equation 4).

$$CNF\ (X_L) = -\int_0^{X_L} \frac{U(z-d)}{u^* k x^2} e^{-\frac{U(z-d)}{u^* k x}}\, dx = e^{-\frac{U(z-d)}{u^* k x_L}}$$

Equation 4

Where:

CNF = cumulative normalized contribution to flux measurements, %

X_L= upwind distance from the tower, m (*fetch*)

U= mean integrated wind speed, ms^{-1}

z = IRGASON® height, m

u^* = friction velocity, ms^{-1}

d = zero plane displacement (m), found by Log10d = 0.979log10h - 0.154, where h is the canopy height.

K = 0.4, Von Karman constant

The cumulative normalized flux contribution (*CNF*) above 80% and fetch were determined for both agroecosystems. Given that u* can be related to the effectiveness of the turbulent exchange on the surface, Equation 4 shows that as the friction velocity is reduced, the fetch necessary to ensure that 80% of the measured fluxes come from the area of interest increases.

Frequency analysis with all *CNF* values obtained during the period from August to December 2013, was performed for each of the agroecosystems evaluated in order to find the ideal fetch. Data were divided into daytime (07:00 to 17:30), in which photosynthetic activity was evident in agroecosystems and nightime (18:00 to 06:30).

Net Ecosystem Exchange (NEE)

Net fluxes at half-hour intervals, were calculated using Equation 1 and daily by integrating the latter during 24 hours. This represents the net ecosystem exchange, NEE (Grace, 2004) or net exchange of CO_2, which incorporates the dynamics of biomass carbon accumulated by the photosynthesis process: dark respiration of species in coverage and soil, and microflora and microfauna respiration in the process of mineralization of organic matter. Thus, it is established whether the agroecosystem acts as carbon source or sink for a given period, integration over longest time scales (months, years) can also be performed.

Agroecosystem evapotranspiration (*ET*)

From the latent heat flux (*LE*) using Equation 3. It is commonly known that 1Wm^{-2} is required to evaporate 0.035 millimeters of water per day. Therefore, the ET, is given by Equation 5.

$$ET = LE \; x \; 0.035$$

Equation 5

Where:

ET = Evapotranspiration, mm.d^{-1}

LE = Latent heat flux, W.m^{-2}

Latent heat fluxes were corrected by air density and temperature (Lee & Massman, 2010)

Soil heat flux (G)

The proportion of net radiation used in the form of soil heat flux (G) was determined. Dynamics of *G* throughout the day and its relation to soil and air temperature were estimated.

Results and discussion

Footprint

Frequency analysis indicated that a fetch of 109 meters ensures that 85% of the data will contain at least 80% of the measured fluxes coming from the area of interest, in daytime conditions over the 100% sun light agroecosystem. For nightime conditions, the same system ensures that 83% of the data contain 80% of fluxes from the area of interest with a fetch of 112 meters (Figure 2).

For the shaded coffee agroecosystem, the fetch values were 254 m in daytime and 344 m nigh-time, both with 84% of the data coming from the area of interest (Figure 2).

These data in conjunction with the calculation of prevailing wind direction, allows the optimum location of the EC system. In the case of the shaded coffee agroecosystem, it must be placed drawing a diagonal from the NorthWestern extreme (prevailing wind direction on the day) of the plot to the SouthEastern extreme (predominate wind direction at night) and a point that belongs to this diagonal and whose distance to the northwest corner is greatest or equal to 254 meters and its distance to the southeast corner is greatest than or equal to 344 meters.

Net Ecosystem Exchange (NEE)

Figure 3, shows the NEE in both of the agroecosystems throughout the day, for a month of evaluation. Carbon fixation (negative values) was higher in the shaded coffee agroecosystem, the same as respiration or carbon emission into the atmosphere (positive values); this dynamic was maintained throughout the evaluation lapse. Daytime carbon fixation is associated with *PAR* offer, from 07:00 until 17:30, showing the maximum activity between 10:00 and 14:00. The greater day and night values of CO_2 exchange in the shaded coffee agroecosystem are associated with increased photosynthetically active leaf area and biomass.

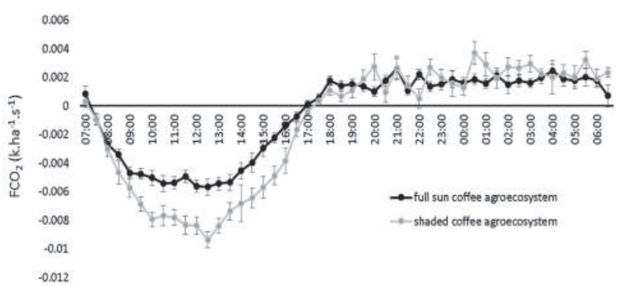

Figure 3. Mean net ecosystem exchage throughout the day in two coffee agroecosystems in October.

The shaded coffee agroecosystem reached the highest rates of mean carbon fixing in October, with 0.009359 ± 0.001087 kgCO_2ha^{-1}s^{-1} (= 0.05), equivalent to 21.26 ± 2.469 µmolCO_2.m^{-2}.s^{-1}, while the highest emission rate was recorded in

November with 0.003769 ± 0.002530 $kgCO_2ha^{-1}s^{-1}$ equivalent to 8.56 ± 5.75 µmol $CO_2.m^{-2}.s^{-1}$. Nearby values were found in crops such as sugar cane (28.23 µmol$CO_2.m^{-2}.s^{-1}$ fixing, and 6.39 µmol $CO2.m^{-2}.s^{-1}$ emission) and grass (18 µmol$CO_2.m^{-2}.s^{-1}$, fixation), known for their great potential as carbon sinks (Zermeño G. et al., 2011; Zermeño G. et al., 2012). The maximum carbon capture rate for full sun agroecosystem was 12.99 ± 2.457 µmol$CO_2.m^{-2}.s^{-1}$ (α = 0.05) in October, 39% below the maximum rate of the shaded coffee agroecosystem, while the maximum emission was 6.332 ±1.266 µmol$CO_2.m^{-2}.s^{-1}$ in December.

Figure 4, shows the shaded coffee agroecosystem behaving as a carbon sink, even to double the amount of carbon fixed by the full sun agroecosystem in October and November. The full sun agroecosystem featured positive carbon balance (emissions into the atmosphere) only in September, with values around 25 $kgCO_2ha^{-1}d^{-1}$. This can be explained due to the initial measurements, the plot had soil biomass, resulting from the elimination of Pigeon peas, which had served as interim shade.

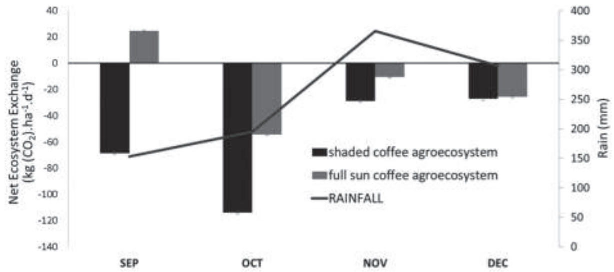

Figure 4. Mean monthly Net Ecosystem Exchange in two coffee agroecosystems, from September to December.

Shade decreased by 50% between November and December, reducing the difference between NEE values for both of the agroecosystems. The values of carbon fixation were similar in De-

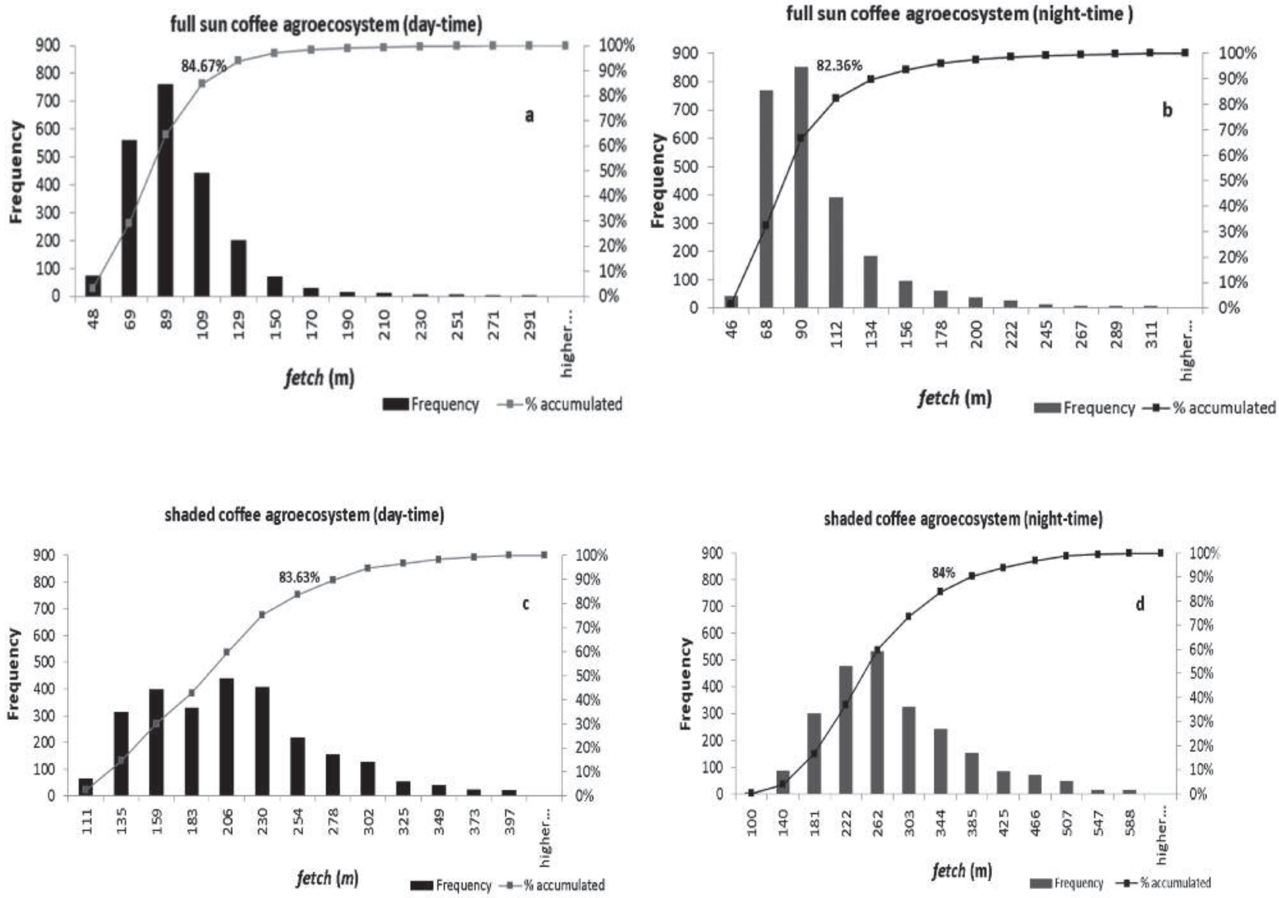

Figure 2. Frequency distribution analysis of Fetch (meters) at day and night in two coffee agroecosystems.

cember (NEE = 27.27 ± 2.241 y 25.77 ± 1.352 $kgCO_2ha^{-1}d^{-1}$ for shaded and full sun system, respectively). It is evident that the NEE must be explained not only in terms of the ecophysiological processes of each ecosystem, but also for the agronomic management carried out, and that may have an effect on the fixings rates, respiratory activity and decomposition and mineralization of organic matter.

Agroecosytem evapotranspiration (*ET*)

Figure 5 shows the average LE in October, which was similar for all months of evaluation. Daytime LE values were positive (between 7:00 and 17:30) while nightime LE values were near zero. This is because during the day the agroecosystem absorbs energy from the incident radiation.

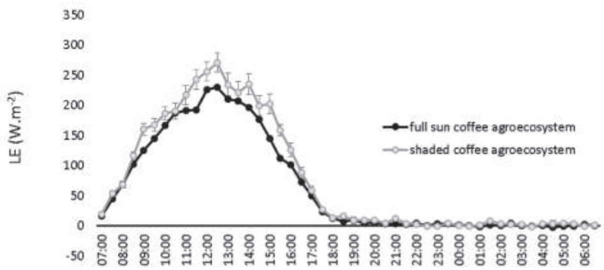

Figure 5. Mean Latent Heat Flux (LE) throughout the day in two coffee agroecosystems, in October.

The Latent Heat in the shaded coffee agroecosystem, showed higher values due to its greater amount of biomass; therefore, a greater proportion of the available energy was used in evapotranspiration.

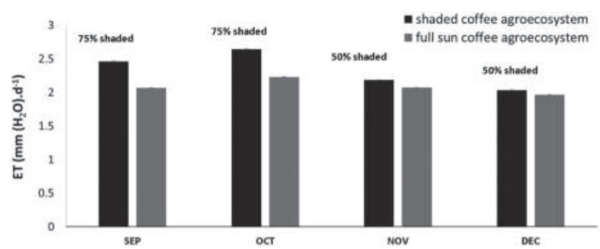

Figure 6. Mean Evapotranspiration throughout the day in two coffee agroecosystems from September to December.

Soil heat flux (G)

For every 100 units of energy available out of net radiation, 2 of them are used in heating the soil in the shaded coffee agroecosystem and 4 in the 100% sun light agroecosystem. Jaramillo (1985), found similar values for coffee plantations exposed to 100% sun light (about 3%). The mean G, showed energy gain on the soil, from 10:30 to 19:00 and from 11:00 to 21:00 in 100% sun light exposure and shaded agroecosystems, respectively (Figure 7). The rest of the time, negative values were observed, indicating radiative emission from the soil into the atmosphere.

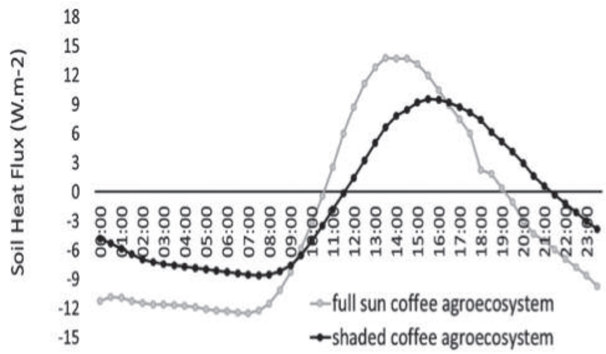

Figure 7. Mean Soil Heat Flux throughout the day in two coffee agroecosystems in October.

Figure 8, shows hourly means observed for a one month evaluation. Soil temperature increased more rapidly in the day in the full sun agroecosystem than in the shaded agroecosystem (0.46°C h^{-1} and 0.27°C h^{-1} for full sun and shaded agroecosystems, respectively). At night soil temperature loss is faster in full sun agroecosystem (0.21°C h^{-1}) compared to the shaded agroecosystem (0.12 ° C h^{-1}). As a result, the thermal amplitude in the full sun system is greater than in the shaded system.

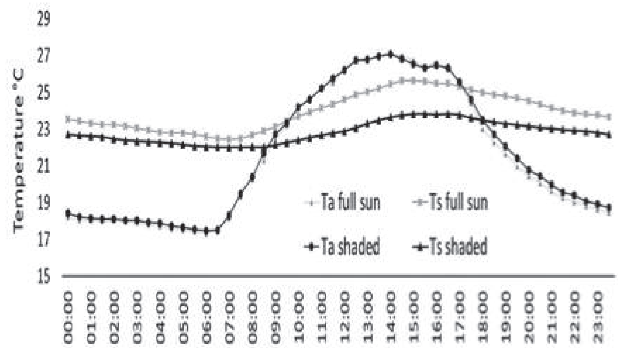

Figure 8. Mean Ambient Temperature (Ta) and Soil Temperature (Ts) throughout the day in two coffee agroecosystems in October.

Conclusions

Regarding the first approaches to fluxes dynamics in coffee agroecosystems, the shaded agroecosystem reached maximum carbon capture rates 61% highest than the 100 % sun light agroecosystem.

The percentage of energy from solar radiation that reached the soil, was lowest in the shaded system (2%) compared to the 100% sun light agroecosystem (4%). In addition, the rate of energy loss in soil during nighttime was lowest under shade, indicating less day-night thermal amplitude with respect to the 100% sun light agroecosystem. The application of the EC technique can generate knowledge about the energy and gas dynamics between the atmosphere and different agroecosystems, contributing to their ecophysiological study.

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