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# Water, energy and carbon dynamics over an intercropped sun-grown coffee and corn system

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## ABSTRACT

The energy dissipation and the evapotranspiration processes, are factors involved in the ecosystem net carbon exchange and are determinants in the ability of a self-regulating system to balance high carbon emissions. To discover these relationships, a corn production system intercropped with coffee was monitored during the first 19 months after the system establishment, to determine the flux of energy, water, gases, and carbon by implementing the eddy covariance technique. From the net carbon exchange ecosystem balance, during the first cycle of corn intercropped with coffee, 63 g C $m^{-2}$ was fixed. For the next phase of coffee culture, maintaining the corn stalks and coffee branches, 5.4 g C $m^{-2}$ was emitted. In the second cycle with intercropped corn, the fixation was 291 g of C $m^{-2}$; and in the last period of the first reproductive stage of the coffee trees, 172 g C $m^{-2}$ was fixed. Throughout the analysis period, the system behaved as a carbon sink with a potential fixation between 4.7 and 5.6 ton C $ha^{-1}$. The energy, measured as net radiation, was estimated at 274.53 ± 5.2 W $m^{-2}$ $day^{-1}$, and it was dissipated mainly as sensible heat (26.5% - 53.6%), latent heat (45.7% - 71, 9%) and soil heat (0.5% - 1.6%). The crop coefficient (Kc) in the coffee vegetative stage in the monoculture, fluctuated between 0.79 ± 0.05 and 0.99 ± 0.04. For the intercropping system with corn, the Kc was calculated at 0.84 ± 0.05, 1.05 ± 0.06, 1.60 ± 0.09, and 1.22 ± 0.05 for the vegetative, pre-flowering, maximum foliar development and harvest maturity stages of corn, respectively.

**Key words:** Eddy covariance; Net ecosystem exchange; Evapotranspiration; Water fluxes; Carbon dioxide fluxes.

## 1 INTRODUCTION

Coffee crop has been prioritized in the Colombian Strategy for Low Carbon Development. All the actions that are implemented to mitigate greenhouse gas (GHG) emissions are opportunities that will support the GHG mitigation commitments that need to be reached by 2030 and adhered to for the United Nations Framework Convention on Climate Change (Federación Nacional De Cafeteros et al., 2017). One of the strategies that the Food and Agriculture Organization (FAO) considers agroforestry like a GHG mitigation mechanism, and coffee grown under shade trees is one strategy (FAO, 2017). However, other coffee production systems that include companion crops are also an option for GHG mitigation and should be evaluated to determine their contribution as carbon sinks. One of the proposals supported by the National Federation of Coffee Growers of Colombia (FNC) occurs in the first year of the coffee crop, during the vegetative growth phase and is based on the establishment of intercropped crops or transitional shade. Among those alternatives is intercropping with corn, which has benefits such as providing shade, reducing costs for weed management, and generating additional income (Rendón, 2020). The evaluation of energy, water and carbon dynamics in a system of coffee trees in the vegetative stage, which involves transitory crops, will allow us to answer: 1. How is the system energy dissipation under climate variability conditions? 2. How is the ability of the system to use water in the different development stages? 3. Has the system the potential to serve as a carbon sink?

To answer these questions, the dynamics of carbon, water and energy fluxes were monitoring using the eddy covariance (EC) technique in a corn system intercropped with coffee stumps in the first 19 months after the system was established. The system evapotranspiration rates and crop coefficient were determined for each growth stage.

### 1.1 Eddy covariance (EC) technique

Micrometeorology is a branch of meteorology where the main object of research is the atmospheric surface layer, which varies between 0.5 and 2 km in depth. Micrometeorology focuses on the processes of energy and gas exchange between the atmosphere and the surface (water, soil, and plants) (Foken, 2017).

The atmosphere contains turbulent movements, which move air that carries trace gases such as $CO_2$ up and down. The eddy covariance technique samples these turbulent movements (instantaneous covariance) to determine the net difference in the material displaced through the canopy-atmosphere interface (Baldocchi, 2003, 2014).

The EC technique is based on the theory of turbulent transport in the outer layer of the atmosphere and is used to calculate scalar and energy fluxes from the covariance between the vertical wind speed and the gas concentration at a distance determined above the surface (Moncrieff; Jarvis; Valentini, 2000).

In comparison to traditional approaches such as lysimetry, microlysimetry, or sap flow observations, the EC technique has advantages because it is the only direct measurement method and has the highest frequency of observations (10-20 Hz). Additionally, it provides a direct measure of the density of the flow through the interface of the atmosphere - ecosystem, without disturbing vegetation and the soil (Baldocchi, 2014).

In addition, the EC technique is beneficial because it provides measurements of net ecosystem carbon exchange (NEE) to determine the capacity of different production systems to compensate for increasing $CO_2$ concentrations (Baker; Griffis, 2005).

## 1.2 Energy balances

An energy balance allows the determination of the partition of the net radiation (Rn) into sensible heat flow (H), which is the energy used to increase the air temperature; latent heat flux (LE), which is the energy necessary for evapotranspiration; and, to a lesser extent, soil heat flux (G), which is the energy stored in biomass and used in photosynthesis and other processes (Rosenberg; Blad; Verma, 1983). Modification of these components affects the surface temperature and the structure of the boundary layer of the atmosphere.

Energy balance measurement techniques allow the monitoring of how the components vary temporally and spatially in relation to the changes that occur during the phenological phases of a crop. In a study conducted by Jaramillo and Escobar (1983), in a sun-grown Caturra variety coffee crop, LE corresponded to 66.9% of the net radiation, while H and G were estimated at 29.6% and 3.5%, respectively. Gutiérrez and Meinzer (1994), in Catuai Amarillo coffee plantations, found that LE dissipated between 40 and 60% of the Rn, with an increased response to the increase in the leaf area index. Ramírez and Jaramillo (2009), in an area of sun-grown coffee trees, found that Rn fluctuated between 111.9 and 119.6 W $m^{-2}$, of which between 105.7 and 78.05 W $m^{-2}$ dissipated as LE, between 2.87 and 30.54 W $m^{-2}$ dissipated as H, and 3.36 W $m^{-2}$ dissipated as G. The highest LE and lowest H were recorded under conditions of high wind speeds (2.0 m $s^{-1}$). More recently, Castaño et al. (2022) used the EC technique in a system of corn intercropped with the coffee variety Castillo® Paraguaicito during the first year of the crop and found that LE, H dissipated between 24.0% and 51.4%, 12.2% and 41.1% of the Rn, respectively. Castaño et al. (2022) for a sun-grown coffee crop of the Castillo® Paraguaicito variety in its productive phase, up to 42 months of age, found that the Rn was dissipated mainly as LE and H with ranges between 24.8% and 47.6% and 18.9% and 33.1%, respectively.

## 1.3 Components of gas exchange

Evaporation and transpiration, integrated as evapotranspiration (ET), are two processes that occur simultaneously and vary according to the age and condition of a crop (Allen et al., 2006). Reference ET (ETo) relates the ET of a hypothetical crop, in this case, a grass, which grows actively and uniformly in a large area, with a height of 8 to 15 cm, without water stress that completely covers the soil (Allen et al., 2006; Doorenbos; Pruitt, 1977). ETo can be calculated through the Penman-Monteith method, which uses climatic parameters at a specific location and time of year and does not consider the characteristics of the crop or soil (Allen et al., 2006). The ET of a crop (ETc) refers to the ET when that crop is cultivated in an extensive field free of diseases, under optimal conditions of water supply and nutrition, and under these conditions with the appropriate management practices, the crop reaches its maximum production potential (Doorenbos; Pruitt, 1977). Allen et al. (2006) refers to this scenario as the ET of a crop under standard conditions. The differences in crop vegetation and aerodynamic resistance relative to the reference crop are considered in the Kc. The Kc corresponds to the integration index of all physical and physiological differences between crops (Allen et al., 2006) and varies according to their age.

An important finding related to the changes in the behavior of the ETc in coffee trees of the Arabica variety is that plants younger than 20 months are associated with lower values of ETc, between 0.87 and 4.56 mm $d^{-1}$ (Antunes et al., 2000; Castaño et al., 2022; Gutiérrez; Meinzer, 1994; Oliveira; Silva; Castro, 2003). The highest ETc values correspond to the flowering stage, and the variation in the range is explained by the physiological phase. In cultures older than 20 months, ETc values are between 1.23 and 5.31 mm $d^{-1}$ (Castaño et al., 2022; Cisneros et al., 2015; Flumignan; De faria; Prete, 2011; Gutiérrez; Meinzer, 1994; Oliveira; Silva; Castro, 2003; Sato et al., 2007) with higher values in the fruit-filling stage. The works of Castaño et al. (2022) and Gutiérrez and Meinzer (1994) note in their methodologies that they used the energy balance technique to determine the ETc.

Castaño et al. (2022) obtained the ETc values in a coffee production system with intercropped corn. The ETc maintained the same dynamics of the radiation flux throughout the day. In the vegetative phase of the coffee trees, when corn had its maximum leaf area index, the ETc value was calculated to be between 4.17 and 4.71 mm $d^{-1}$.

Several researchers (Antunes et al., 2000; Castaño et al., 2022; Cisneros et al., 2015; Costa et al., 2020; Flumignan; De Faria; Prete, 2011; Gutiérrez; Meinzer, 1994; Oliveira; Silva; Castro, 2003; Sato et al., 2007) have calculated ETo, using the equation proposed by Allen et al. (2006) to derive the values of Kc in coffee trees of the Arabica variety, with fluctuations between 0.16 and 1.38 and a tendency toward lower values at ages below 20 months (0.16-0.87) and higher values at ages over 30 months of age (0.49-1.38).

## 2 MATERIAL AND METHODS

### 2.1 Site and cultivation

The location used to monitor the flows was the Paraguaicito de Cenicafé experimental station, located in the municipality of Buenavista in the department of Quindío (Colombia), located at 75°44´W and 4°24´N, at an altitude of 1200 m a.s.l. The soil at the site is classified as Typic Udivitrand of the Quindío unit, characterized by volcanic ash, with the first horizon being 88 cm in depth with loamy sandy texture and a phosphate fixation of 40%. During this study, between 06-13-2019 and 12-14-2020, the following climatic conditions were recorded: 2479 hours of cumulative solar brightness; 2931 mm of cumulative precipitation; daily average, minimum and maximum temperatures of 22.3 °C, 17.4 °C and 28.4 °C, respectively; and an average relative humidity of 78.3%.

The area occupied by the *Coffea arabica* crop of the Castillo Paraguaicito® variety was 20000 m$^2$, and the sun-grown crop was planted in June 2014 with a distance of 1.0 m between plants and 1.4 m between rows. In May 2019, the crop was stumped. To start the present investigation, the branches and leaves in the plot were stumped, and the stems were removed. On June 1, 2019, the first intercropping cycle began, and the second cycle began on March 18, 2020, both with corn hybrid SGBIOH2. The corn crop was established in the middle of the coffee rows at a distance of 50 cm between sites, and each site corresponded to two corn plants. The replanting of coffee trees at the missing sites and cultivation practices such as application of amendments, nutrition based on soil analysis, regulation of regrowth and phytosanitary management were carried out according to agronomic and productivity practices (Centro Nacional De Investigaciones De Café, 2018). The agronomic management of corn was independent of that of coffee and included a fertilization plan based on soil analysis and corresponding phytosanitary control (Jaramillo; Salazar, 2021). Figure 1 shows the phenological stages of the evaluated system.

### 2.2 Monitoring system

The fluxes of energy, gases, water, and carbon were monitored through the implementation of an EC system (Campbell Scientific, Inc., USA), with an open path gas analyzer and a sonic anemometer (Open Path - Irgason, USA). The data were taken at a frequency of 10 Hz and stored in a CR3000 datalogger (Campbell Scientific, Inc). To calculate the fluxes, the values measured for periods of 30 minutes were integrated.

The tower location criteria of the EC system, such as the predominant wind direction, location, and height of the Irgason sensor and the tracking and adjustment footprint, were set as described by Castaño et al. (2016). Based on these criteria, the azimuth point of 315° was established as the most representative of the predominant wind vector. A "fetch" of 110 m and a measurement height of 1 m above the canopy was used.

In the tower where the system was implemented, barometric pressure (Vaisala PTB110), precipitation (Texas Electronics TE525MM), temperature, relative humidity (Vaisala HMP60), and Rn (Kipp and Zonen NR-Lite) sensors were installed. Global radiation (Rg - Apogee SP110), photosynthetically active radiation (PAR - Apogee SQ110 Quantum), soil heat flux (G, HFP01SC), and soil temperature, with a measurement frequency of 30 minutes, were measured.

To measure volumetric soil moisture (VSC), Campbell Sci. Inc. CS616 sensors were installed, and soil samples were obtained at two installation depths, 15 and 30 cm, for the determination of the permanent wilting point (PWP - 15 bars), field capacity (FC - 0.3 bar), and the calibration curve of the sensors.

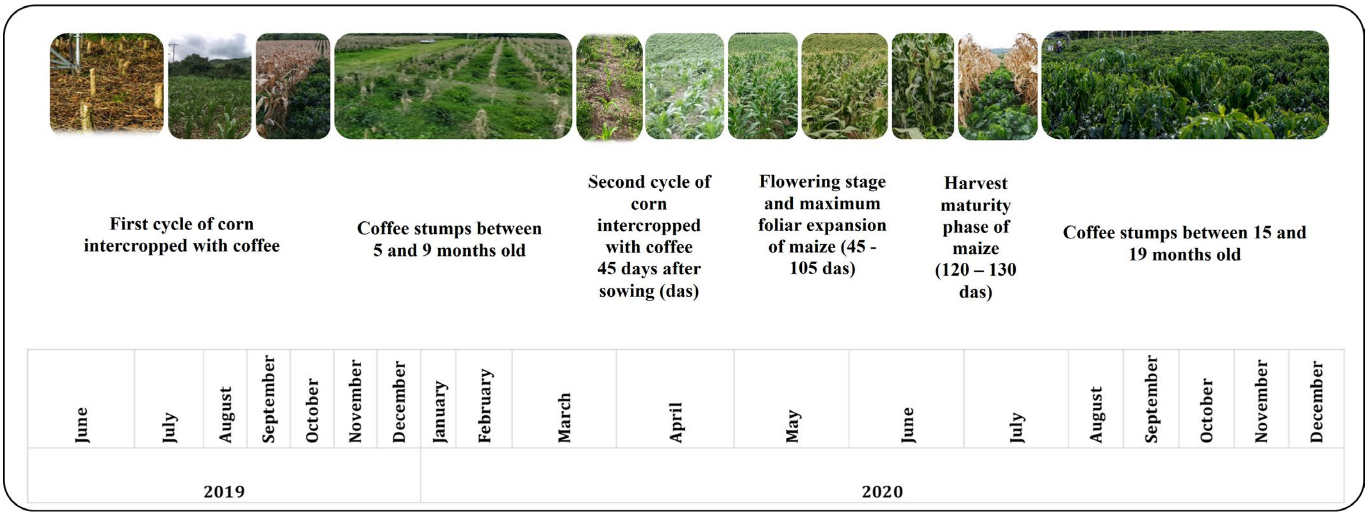


**Figure 1:** Diagram of the phenological stages of the crops.

## 2.3 Calculation of fluxes, control, filters and gap filling

The turbulent flows of $CO_2$, $H_2O$, H, and LE were calculated from the direct measurements of the eddies that originated between the canopy-atmosphere interface and the open path measured by the Irgason censored. These values were averaged by the covariance between the concentration of the analytes and the vertical wind speed. EddyPro® software version 6.2.1 was used (LI-COR BIOSCIENCES, 2017) for fluxes calculation. Techniques of filtering, removing, banding, and correcting were incorporated. These techniques correspond to double rotation of coordinates (Lee; Finnigan; Paw, 2004; Lee; Massman; Law, 2004); frequency loss (Moncrieff et al., 2004), Webb, Pearman, Leuning density (WPL) (Webb; Pearman; Leuning, 1980); and stationarity or weakly developed turbulent conditions (Foken et al., 2012; Vickers; Mahrt, 1997).

Additional quality control consisted of removing the flows from wind directions between 0 and 90° because there was noise attributed to an area of bamboo located in that range, the signal intensity of $CO_2$, and $H_2O$ lower than 70% for the negative nocturnal $CO_2$ values (which indicate nonphysical $CO_2$ absorption) and those flagged as low quality.

As a result of the filtering, 53% of missing data were obtained, which were corrected using the algorithm described by Reichstein et al. (2005) based on the covariance of flows and temporal correlation of meteorological elements. Part of the consideration was that if the data of the variable of interest (for example, $CO_2$ or LE fluxes) and those of the meteorological variables (air temperature - Tair; global radiation - Rg, and vapor pressure deficit - VPD) were available in whole or in part, criteria could be established with similar meteorological conditions in the time windows that involved the same time of the missing data of the variable of interest out to 140 days. Similar meteorological conditions are present when Rg, Tair and VPD do not deviate by more than 50 W $m^{-2}$, 2.5 °C, and 5.0 hPa, respectively.

## 2.4 Partition of the net exchange of $CO_2$

The net exchange of the ecosystem was calculated in EddyPro® software from the net fluxes of $CO_2$ at half-hour intervals using Equation 1.

$$FCO_{2=\overline{\rho_a}\cdot\overline{w'c'}} \tag{1}$$

where
$FCO_2$ = average flow of $CO_2$ in a given period of time, mg $m^{-2}$ $s^{-1}$
= air density, kg $m^{-3}$
w = instantaneous vertical wind speed, m $s^{-1}$
c = proportion of $CO_2$ mixture (c = ρc/ρa, where ρc is the density of $CO_2$ (kg $m^{-3}$))

The carbon dynamics were evaluated in relation to the partition of the NEE as a function of the gross primary productivity (GPP) and respiration of the ecosystem (Reco) (Tagesson et al. 2015) (Equation 2).

$$NEE = GPP + Reco \tag{2}$$

where
NEE = Net carbon exchange
GPP = Gross primary productivity
Reco = Ecosystem respiration

The NEE was disaggregated into GPP and Reco through a nonexponential function that relates carbon assimilation with the measured PAR. Using the Mitscherlich light response function, the NEE was calculated (Goudriaan; Monteith, 1990; Tagesson et al., 2015) (Equation 3)

$$NEE = -\left(F_{csat} + R_d\right) * \left(1 - e^{\left(\frac{-\alpha * PAR}{Fcsat + Rd}\right)}\right) + R_d \tag{3}$$

where
$F_{csat}$ = Capture of $CO_2$ at light saturation (μmol $CO_2$ $m^{-2}$ $s^{-1}$)
Rd = Dark respiration (μmol $CO_2$ $m^{-2}$ $s^{-1}$)
α = Quantum efficiency (μmol $CO_2$ μmol $PAR^{-1}$)
PAR = Photosynthetically active radiation (W $m^{-2}$)

GPP was calculated based on Equation 4

$$GPP = -\left(Fcsat + Rd\right) * \left(1 - e^{\left(\frac{-\alpha * PAR}{Fcsat + Rd}\right)}\right) \tag{4}$$

The parameter $F_{csat}$ was replaced by a decreasing exponential function to consider the effect of the VPD on the GPP (Lasslop et al., 2010) in Equations 5 and 6:

$$VPD > VPD_0 \rightarrow F_{csat} = \left\{F_{csat} * e \wedge -Kf\left(VPD - VPD_0\right)\right\} \tag{5}$$

$$VPD < VPD_0 \rightarrow F_{csat} = F_{csat} \tag{6}$$

where
$VPD_0$ = 10 hPa
*Kf* = Correction parameter for the incidence of VPD in the maximum carbon assimilation.

The diurnal Reco was calculated by subtracting the GPP in the diurnal records of each half hour of NEE. The NEE, GPP and Reco data were integrated into daily intervals (gC $m^{-2}$ $d^{-1}$) and accumulated monthly (gC $m^{-2}$ $month^{-1}$).

## 2.5 Dynamics of the energy and gas balance components

The behavior of ETc was determined through measurements of the energy balance and its partition into LE and H using the EC technique.

The evaporation of the agroecosystem was calculated from the LE in EddyPro® software. According to Equation 7, to evaporate 0.035 mm of water per day, 1 W $m^{-2}$ of energy is required (Rosenberg; Blad; Verma, 1983), and ETc was calculated by Equation 8.

$$LE = \lambda \frac{\epsilon}{p} \rho a \cdot \overline{w'e'} \quad (7)$$

where
*LE* = latent heat flux; energy used in the evapotranspiration process, W m $^{-2}$
ϵ = proportion of the molecular weights of water vapor and air = (Mw/Mα)
P = atmospheric pressure, kPa
= air density, kg $m^{-3}$
e = water vapor, g $m^{-3}$
λ = latent heat of water vaporization, J $kg^{-1}$
w´e´ = deviations from the mean $(w-\overline{w})$ and $(e-\overline{e})$ in a data integration period.

$$ET_c = LE \times 0.035 \quad (8)$$

where
ET = Evapotranspiration, mm $d^{-1}$
LE = Latent heat flux, W $m^{-2}$

For the calculation of the H in Eddy Pro® software, Equation 9 was used.

$$H = \rho a \, C\rho \, \overline{w'T'} \quad (9)$$

where
*H* = Sensible heat flow; energy used for air heating, W $m^{-2}$.
ρα = Air density, kg $m^{-3}$
*Cp* = Specific heat of air at constant pressure, J $kg^{-1}$ $K^{-1}$
*w* = Instantaneous vertical wind speed, m $s^{-1}$
*T* = Air temperature, °C.
*w', T'* = Deviations from the mean $(w-\overline{w})$ and $(T-\overline{T})$ in a period of integration of data.

The principle of Bowen's ratio energy preservation was used to adjust the closure of the energy balance as implemented by Chávez et al. (2009) as in the following (Equations 10 to 16):

$$\text{Energy balance discrepancy} = D = (Rn - G) - (H + LE) \quad (10)$$

$$\text{Bowen ratio} = \beta = H / LE \quad (11)$$

$$\text{Latent heat discrepancy} = \Delta LE = D / (1 + \beta) \quad (12)$$

$$\text{Sensible heat discrepancy} = \Delta H = D - \Delta LE \quad (13)$$

$$\text{LE (adjusted)} = \text{LE (Observed)} + \Delta LE \quad (14)$$

$$\text{H (adjusted)} = \text{H (Observed)} + \Delta H \quad (15)$$

$$\text{Energy balance closure} = \text{EBC} = \\ = \text{Rn}/(\text{LE (adjusted)} + \text{H (adjusted)} + \text{G}) \quad (16)$$

where Rn, LE, H and G are expressed in W $m^{-2}$.

The ETo was determined with the Penman-Monteith equation through direct measurements of the variables that make up this equation (Equation 17).

$$ETo = \frac{0,408\,\Delta\,(Rn - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0,34\, u_2)} \quad (17)$$

where
ETo = Reference evapotranspiration (mm $day^{-1}$)
Rn = Net radiation on the crop surface (MJ $m^{-2}$ $day^{-1}$)
Ra = atmospheric radiation (mm $d^{-1}$)
G = Soil heat flux (MJ $m^{-2}$ $day^{-1}$)
T = Mean air temperature at 2 m altitude (°C)
$u_2$ = Wind speed at 2 m height (m $s^{-1}$)
$e_s$ = Saturation vapor pressure (kPa)
$e_{at}$ = Actual vapor pressure (kPa)
es - ea = Vapor pressure deficit (kPa)
Δ = Slope of the vapor pressure curve (kPa °$C^{-1}$)
ϒ = Psychrometric constant (kPa °C $^{-1}$)

The Kc was obtained through Equation 18:

$$ETc = Kc * ETo \quad (18)$$

## 3 RESULTS

### 3.1 Partition of the net $CO_2$ exchange

As a result of applying the nonlinear regression Mitscherlich's light response function (Equation 3), with time windows of 7 days, Figures 2 to 5 were obtained the behavior of the NEE relative to the PAR incident in the crop canopy is described by the Mitscherlich's function. These results provide a model that integrates each stage of the production system. In Figure 4, the vegetative stage of the coffee stumps was divided into the phenological phases of the corn crop.

The first two stages behaved similarly (Figures 2 and 3) and from June 15, 2019, to March 14, 2020, in the transects, the residues of twigs and leaf products of the renovation work were found in the process of decomposition. Additionally, water deficits occurred in the soil under restrictive temperature and humidity system conditions, which will be addressed in the next section focused on the dynamics of the energy balance components.

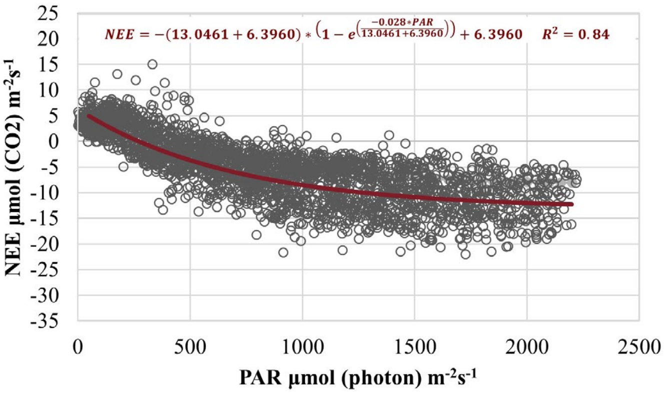


Figure 2: Changes in the behavior of the net carbon exchange of the ecosystem (NEE) of corn intercropped with coffee stumps, as a response to photosynthetically active radiation (PAR) between 15 and 130 days for both crops. The final date corresponded to the corn harvest.

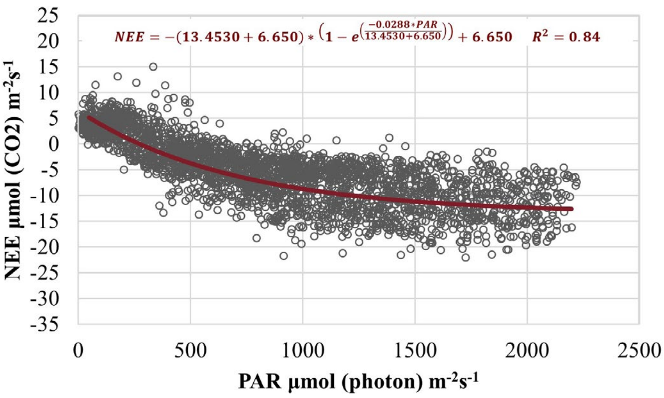


Figure 3: Changes in the behavior of the NEE in the sun-grown coffee crop that is between 5 and 9 months of age, as a response to PAR.

During the second cycle of corn, without abiotic restrictions such as periods of water deficits, with high temperatures and low relative humidity, between March 15 and July 31, 2020, the changes in the behavior of NEE in comparison to the phenological state of the corn are shown in Figure 4. During the first 25 days, in the vegetative phase (Figure 4 A), the light response decelerated, which was attributable to the growth of both crops. Subsequently, with the exponential growth of the corn crop, between 25 and 45 days after sowing (das), the NEE increased and exceeded the efficiency of the first vegetative stage (Figure 4 B). As observed in Figure 4 C, with the maximum foliar expansion of corn, the maximum response of NEE occurred and finally decreases in the last 20 days during harvest maturation (Figure 4 D).

After the corn cycle, in the coffee crop without shade and with a foliar area index below 3.0, a progressive response was presented with maximum asymptote with the PAR between 1250 and 1300 µmol (photons) $m^{-2}$ $s^{-1}$ (Figure 5).

The GPP was determined by subtracting the Reco in the second part of the Mitscherlich light response function equation, to which the VPD correction parameter was applied. In Table 1, the parameters are derived from *Equation 4*, applying the restriction according to *Equations 5* and 6 and the standard error of each parameter.

### 3.2 Monthly carbon fluxes, g C $m^{-2}$

In Figure 6, the dynamics of the monthly carbon flux in the production system of corn intercropped with coffee were observed. At 19 months, negative values corresponded to fixation or capture, and positive values corresponded to emissions.

Based on from the monitoring of the carbon fluxes assimilated by the vegetation, the GPP was calculated at -5.38 kg C $m^{-2}$, with daily values of -9.76 ± 0.15 g C $m^{-2}$, of which 90% was emitted, corresponding to Reco. The product of the NEE balance per stage, during the first cycle of corn intercropped with coffee, was fixed at 66 g C $m^{-2}$ (-0.53 ± 0.19 g C $m^{-2}$ $day^{-1}$). During the next phase of coffee grown, which maintained the stems of the corn and the branches of the coffee trees, 5.4 g C $m^{-2}$ was emitted (0.035 ± 0.16 g C $m^{-2}$ $day^{-1}$). In the second cycle with intercropped corn, fixation was quantified at 291 g C $m^{-2}$ (-2.09 ± 0.21 g C $m^{-2}$ $day^{-1}$), and in the last period, corresponding to the first reproductive stage of the coffee trees, fixation was at 172 g C $m^{-2}$ (-1.27 ± 0.17 g C $m^{-2}$ $day^{-1}$).

The months with the highest carbon fixation during the cycle of corn intercropped with coffee were May 2020 and June 2020, with 151.31 ± 10.34 kg $CO_2$ $ha^{-1}$ $day^{-1}$ and 143.53 ± 13.44 kg $CO_2$ $ha^{-1}$ $day^{-1}$, respectively, and the months with the highest emissions were October 2019 and March 2020, with 79.93 ± 5.0 kg $CO_2$ $ha^{-1}$ $day^{-1}$ and 49.92 ± 7.23 kg $CO_2$ $ha^{-1}$ $day^{-1}$, respectively.

The carbon accumulated in the biomass by the photosynthetic process, measured as NEE, was calculated from the net fluxes in half-hour intervals using the EC technique, and the result showed that the highest carbon capture occurred when the corn had the maximum leaf area index, specifically in the pre- and post-flowering stages, in August 2019 in the first corn cycle and between May and June 2020 for the second corn cycle.

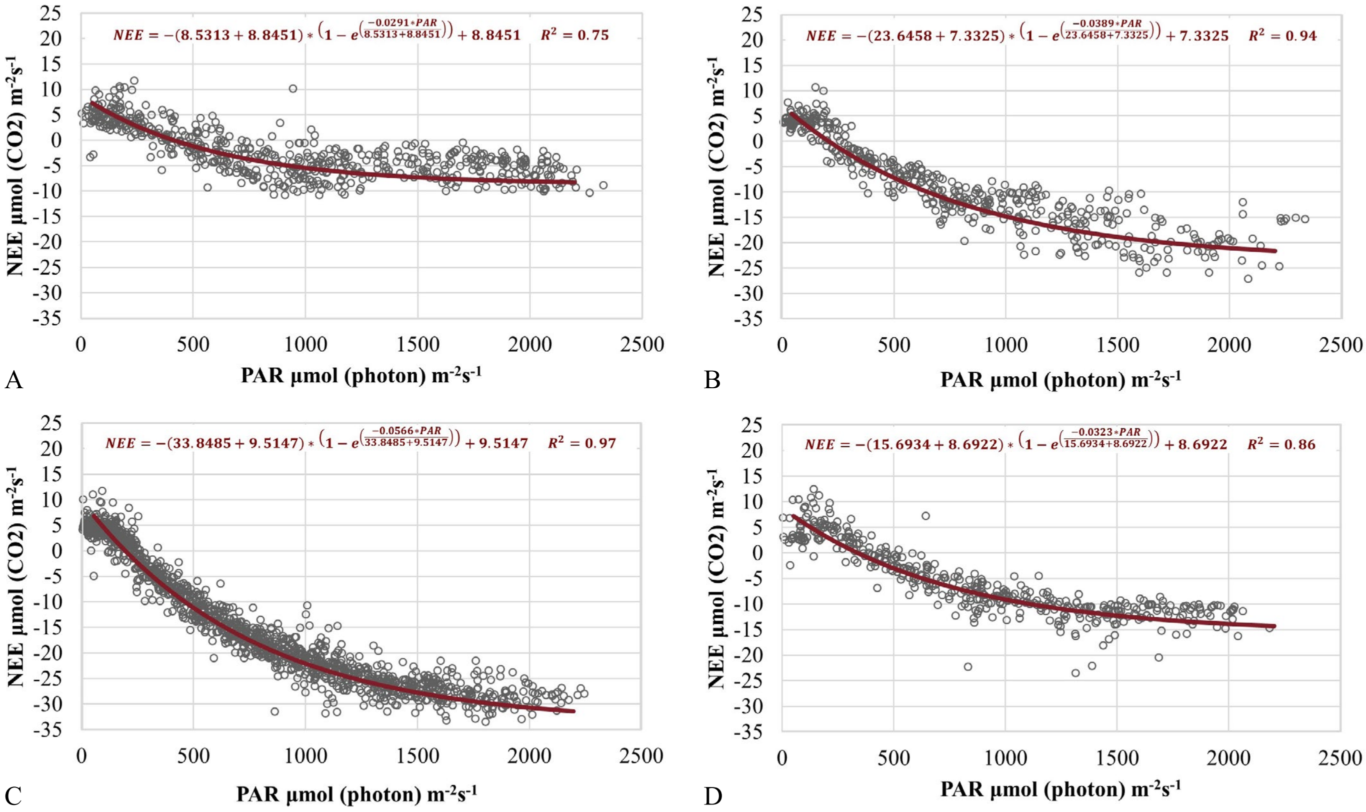


**Figure 4:** Changes in the behavior of the NEE of corn intercropped with coffee stumps, as a response to PAR. 4A. Vegetative phase of corn (up to 25 days after sowing - das) and coffee trees aged 10 months; 4B. vegetative phase of corn (26-45 das) and coffee trees aged 11 months; 4C. flowering phase and maximum foliar development of corn (between 45 and 105 das), and coffee trees aged between 12 and 13 months; 4D. harvest maturity phase of corn, between 120 and 139 das, and coffee trees aged 14 months.

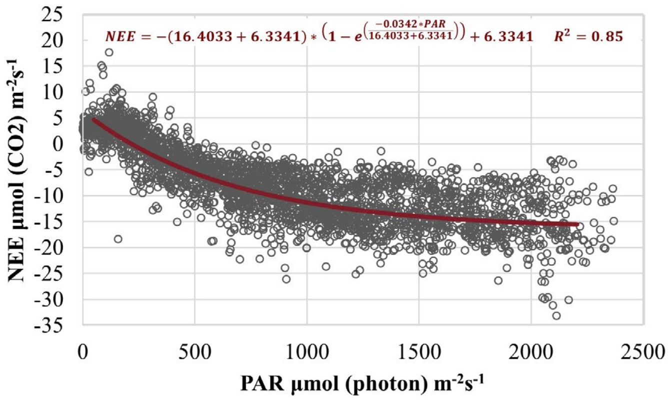


**Figure 5:** Changes in the behavior of the NEE of the coffee stumps that were between 15 and 19 months old, as a response to PAR.

## 3.3 Energy balance

The analysis of the energy flows derived from the EC technique, with closure and without adjustment of the LE and H values, showed percentages of dissipation of the Rn between 68% and 83%, for which the adjustment was made according to the proposed methodology by Chávez et al. (2009). After adjusting the energy balance closure, it was found that the Rn, estimated at 274.53 ± 5.2 W $m^{-2}$ per day, was dissipated mainly in the form of H (26.5% - 53.6%), LE (45.7% - 71.9%) and G (0.5% - 1.6%) (Table 2).

In the first stage, between June and September 2019, there were humidity restrictions due to the events related to El Niño 2019 and its lag effect on the conditions at the site. In particular, in September 2019, H dissipated a greater amount of energy in the system, attributable to autotrophic respiration processes. An analysis of the Bowen ratio (β), which corresponds to the ratio between H and LE, showed that between June and August 2019, β fluctuated between 0.74 and 1.0. Under the outlined conditions, the system allocates less energy to the water vapor exchange processes and invests energy in air heating. However, the quality of the system and intercropping with corn allowed the coffee trees aged between 1 and 4 months old after stumping to not experience negative effects from abiotic stress at the expense of the deterioration observed in the corn.

## 3.4 Soil moisture

In Figure 7, the curves of the evolution of soil moisture are presented by decay periods. No major differences were observed between the volumetric content at 15 and 30 cm depths. Between July and September 2019, a water deficit occurred when the water content in the soil (WCS) decreased below 75% of the usable water surface, indicated as maximum depletion. For the period in which the water stress conditions occurred, the coffee crop, between 2 and 4 months old, had corn intercropped, and no wilting conditions or other symptoms that would indicate negative effects to the coffee trees were evident, but these conditions were observed in the corn cultivation.

The identified water stress conditions were accompanied by other types of abiotic stresses related to temperature and humidity. As shown in Table 3, on a high percentage of the days in the months of August and September 2019, during several hours of the day (between 3.9 and 4.5 hours), the VPD remained at levels higher than 20 hPa, and these levels were closely related to the occurrence of temperatures above 28 °C and a relative humidity lower than 55% between 11:00 AM and 5:00 PM.

### 3.5 Components of gas exchange

Table 4 shows the evolution of the gas exchange components and their relationship with the variation in the production system over time. In the first five months, between June and October 2019, the soil was covered by the residues of the branches and leaves resulting from the stumping of the coffee trees. As mentioned in the analysis of the $CO_2$ fluxes, the results implied that both crops invested more energy in respiration processes, and in the case of corn, between August and September 2019 as the dominant crop, it reduced its ET potential. In the case of the first corn cycle, the abiotic stress conditions did not allow us to establish with good criteria the performance of the Kc. For the second stage of the production system, in the vegetative phase of coffee, in which the dried corn stalks were left in the streets, there were restrictive environmental conditions related to DPV> 20 hPa between January and March 2020 (Table 3), although the soil moisture condition was not limiting. For the indicated stage, the Kc fluctuated between 0.79 ± 0.05 and 0.99 ± 0.04. In the period of the second corn cycle, there were no cultivation restrictions (water or thermal). As shown in Table 4, in the first two months of cultivation, the Kc was between 0.84 ± 0.05 and 1.06 ± 0.06. The maximum Kc value occurred between the third and fourth months, with maximum foliar development and Kc values greater than 1.5; finally, at the time of physiological maturity and harvest, the coefficient decreased to 1.22. In the last stage of the cycle analyzed, with the coffee trees in the reproductive stage, the Kc remained between values of 0.9 and 1.0.

**Table 1:** Parameters of the relationship between gross primary productivity (GPP) and carbon assimilated by photosynthesis as a function of vapor pressure deficit and photosynthetically active radiation ± standard error, where $F_{csat}$ = capture of $CO_2$ at light saturation (μmol $CO_2$ $m^{-2}$ $s^{-1}$), Rd = dark respiration (μmol $CO_2$ $m^{-2}$ $s^{-1}$), α = quantum efficiency (μmol $CO_2$ μmol $PAR^{-1}$), and *Kf* = correction parameter due to the incidence of VPD in the maximum carbon assimilation.

| Month-year | Corn stage | ***Fcsat*** | **Rd** | **α** | ***kf*** | **$R^2$ (%)** |
|---|---|---|---|---|---|---|
| | | Coffee Vegetative Stage | | | | |
| **Jun-19** | Vegetative | 11.38 ± 1.1 | 7.66 ± 0.3 | 0.026 ± 0.0018 | 0.385 ± 0.061 | 85 |
| **Jul-19** | Vegetative -pre-flowering | 16.29 ± 0.3 | 6.99 ± 0.1 | 0.033 ± 0.0015 | 0.272 ± 0.019 | 89 |
| **Aug-19** | Flowering | 14.67 ± 0.8 | 5.41 ± 0.3 | 0.037 ± 0.0018 | 0.182 ± 0.007 | 80 |
| **Sep-19** | Filling - physiological maturity | 10.54 ± 0.5 | 5.84 ± 0.3 | 0.018 ± 0.0006 | 0.396 ± 0.03 | 82 |
| **Oct-19** | Harvest maturity | 8.47 ± 0.4 | 6.42 ± 0.1 | 0.02 ± 0.001 | 0.302 ± 0.033 | 82 |
| Nov-19 | | 20.08 ± 0.9 | 6.27 ± 0.1 | 0.038 ± 0.0006 | 0.176 ± 0.013 | 91 |
| Dec-19 | | 10.44 ± 0.9 | 6.30 ± 0.3 | 0.022 ± 0.0016 | 0.357 ± 0.03 | 76 |
| Jan-20 | | 17.18 ± 0.4 | 6.22 ± 0.4 | 0.038 ± 0.002 | 0.172 ± 0.016 | 88 |
| Feb-20 | | 11.69 ± 0.7 | 6.59 ± 0.2 | 0.020 ± 0.0012 | 0.505 ± 0.058 | 84 |
| **Mar-20** | Vegetative | 7.96 ± 0.4 | 9.72 ± 0.2 | 0.029 ± 0.0016 | 0.223 ± 0.014 | 76 |
| **Apr-20** | Vegetative | 20.73 ± 1.6 | 7.46 ± 0.2 | 0.039 ± 0.0016 | 0.172 ± 0.013 | 92 |
| **May-20** | Pre-flowering - flowering | 33.38 ± 0.4 | 9.97 ± 0.1 | 0.059 ± 0.0007 | 0.158 ± 0.015 | 97 |
| | | **Coffee Reproductive Stage** | | | | |
| **Jun-20** | Filling | 34.23 ± 0.5 | 9.29 ± 0.2 | 0.055 ± 0.0012 | 0.127 ± 0.012 | 97 |
| **Jul-20** | Physiological maturity - harvest | 17.80 ± 1 | 9.37 ± 0.3 | 0.041 ± 0.003 | 0.276 ± 0.042 | 86 |
| Aug-20 | | 17.45 ± 0.8 | 7.56 ± 0.2 | 0.033 ± 0.0016 | 0.279 ± 0.031 | 88 |
| Sep-20 | | 15.92 ± 0.9 | 6.28 ± 0.3 | 0.032 ± 0.0009 | 0.209 ± 0.008 | 87 |
| Oct-20 | | 16.03 ± 1.5 | 5.96 ± 0.2 | 0.032 ± 0.0012 | 0.172 ± 0.011 | 83 |
| Nov-20 | | 19.01 ± 1 | 6.00 ± 0.1 | 0.038 ± 0.0011 | 0.12 ± 0.011 | 87 |
| Dec-20 | | 10.36 ± 0.2 | 5.28 ± 0.2 | 0.035 ± 0.0022 | 0.178 ± 0.01 | 76 |

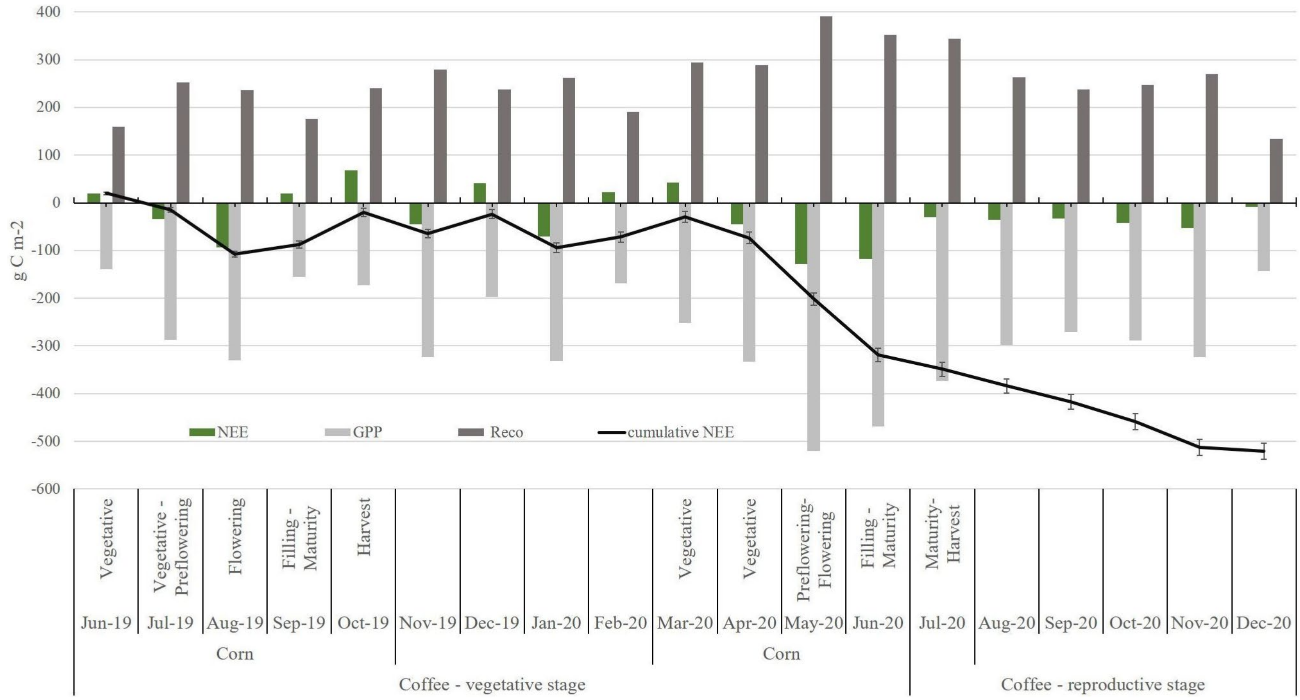


**Figure 6:** Monthly carbon fluxes, g C m-2, in a sun-grown coffee production system with coffee stumps (negative values correspond to fixation and positive values to emissions), net carbon exchange of the ecosystem (NEE), gross primary production (GPP), and ecosystem respiration (Reco). The bars in the cumulative NEE correspond to the standard error interval.

**Table 2:** Energy balance in the 19 months after establishment of a corn crop system intercropped with coffee under sun-grown conditions.

| Month -year | Corn stage | H (Sensitive heat) % | LE (Latent heat) % | G (Soil heat) % |
|---|---|---|---|---|
| | | **Coffee Vegetative Stage** | | |
| Jun-19 | Vegetative | 49.1 | 50.3 | 0.6 |
| Jul-19 | Vegetative-pre-flowering | 45.8 | 53.3 | 0.9 |
| Aug-19 | Flowering | 46.7 | 52.2 | 1.1 |
| Sep-19 | Filling - physiological maturity | 53.6 | 45.7 | 0.7 |
| Oct-19 | Harvest maturity | 47.7 | 51.7 | 0.5 |
| Nov-19 | | 31.6 | 67.4 | 1 |
| Dec-19 | | 39 | 60.5 | 0.5 |
| Jan-20 | | 32.2 | 66.9 | 0.9 |
| Feb-20 | | 41 | 58.4 | 0.6 |
| Mar-20 | Vegetative | 42 | 57.4 | 0.5 |
| Apr-20 | Vegetative | 33 | 66 | 1 |
| May-20 | pre-flowering - flowering | 28.3 | 70.1 | 1.6 |
| | | **Coffee Reproductive Stage** | | |
| Jun-20 | Filling | 26.5 | 71.9 | 1.6 |
| Jul-20 | Physiological maturity - harvest | 37.6 | 61.4 | 1 |
| Aug-20 | | 43.4 | 55.6 | 1 |
| Sep-20 | | 41.5 | 57.7 | 0.8 |
| Oct-20 | | 39.8 | 59.2 | 0.9 |
| Nov-20 | | 35.7 | 63.3 | 1 |
| Dec-20 | | 40.5 | 58.6 | 0.8 |

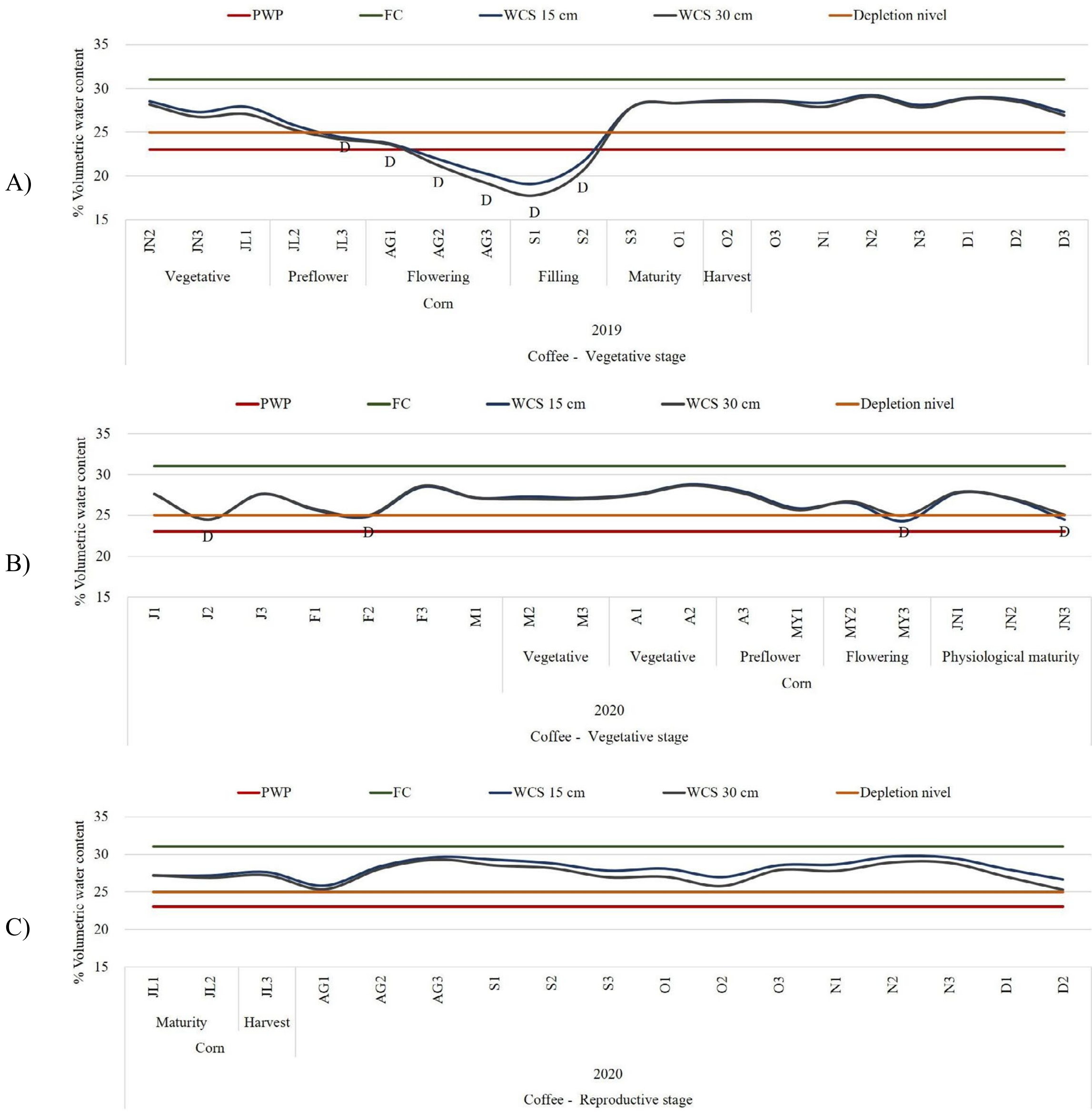


**Figure 7:** Monitoring the volumetric water content in the soil (WCS) at two depths, 15 and 30 cm, with reference to the parameters of permanent wilting point (PWP) and field capacity (FC); the letter D indicates the decades with water deficit, below the level of depletion. A) Vegetative Stage: From the second decade of June 2019 to the third decade of December 2019. B) Vegetative Stage: From the first decade of January 2020 to the third decade of June 2020. C) Reproductive Stage: From the first decade of July 2020 to the second decade of December 2020.

## 4 DISCUSSION

The behavior described herein for NEE, GPP y Reco, is in line with that described for other crops such as grasslands and high-production cropland (Gilmanov et al., 2010), thistle (Rana et al., 2016), and semiarid savannas with grazing (Tagesson et al., 2015), and this behavior is also generally consistent with the basic principles of Goudriaan and Monteith (1990).

The values recorded here for NEE were higher than those obtained by Castaño et al. (2016). In a sun-grown coffee production system, they reported maximum values for fixation and emissions of 12.99 ± 2.46 µmol $CO_2$ $m^{-2}$ $s^{-1}$ (0.281 g C $m^{-2}$) and 6.33 ± 1.27 µmol $CO_2$ $m^{-2}$ $s^{-1}$ (0.137 g C $m^{-2}$), respectively. During the research period, at the end of each corn cycle and the end of the analyzed period, fresh samples were obtained from the different organs of the crops for analysis of dry mass (Perez et al., 2013) and the content of organic carbon using the method of loss on ignition (Dabadie et al., 2018). During the first 19 months of the coffee stump cycle, the organic carbon in corn in the first and second cycles intercropped with coffee trees was 1.96 ton C $ha^{-1}$ and 2.72 ton C $ha^{-1}$, respectively, and during coffee grown was 7.04 ± 1.03 ton C $ha^{-1}$. Both indirect and direct measurements corresponded and indicated the potential for the evaluated stage to serve as a carbon sink.

**Table 3:** Analysis of the situations when vapor pressure deficit (VPD) was higher than 20 hPa and the temperature and relative humidity under this condition, in a corn crop system intercropped with coffee.

| Month Year | Corn stage | Days with VPD> 20 hPa | No. of hours per day with VPD> 20 hPa | Temperature °C | Relative humidity % |
|---|---|---|---|---|---|
| | | **Coffee Vegetative Stage** | | | |
| Jun-19 | Vegetative | 5 | 2.0 | 30.0 | 54 |
| Jul-19 | Vegetative-Preflower | 13 | 3.2 | 29.8 | 50 |
| Aug-19 | Flowering | 26 | 5.2 | 30.1 | 45 |
| Sep-19 | Filling - physiological maturity | 18 | 4.2 | 30.0 | 49 |
| Oct-19 | Harvest maturity | 3 | 1.7 | 28.7 | 53 |
| Nov-19 | | 5 | 1.4 | 28.6 | 53 |
| Dec-19 | | 4 | 1.5 | 29.1 | 55 |
| Jan-20 | | 18 | 3.4 | 29.3 | 51 |
| Feb-20 | | 20 | 4.4 | 29.8 | 50 |
| Mar-20 | Vegetative | 18 | 3.4 | 29.7 | 46 |
| Apr-20 | Vegetative | 11 | 1.8 | 29.5 | 51 |
| May-20 | Pre-flowering - flowering | 7 | 2.4 | 30.4 | 51 |
| | | Coffee Reproductive Stage | | | |
| Jun-20 | Filling | 1 | 1.0 | 28.8 | 49 |
| Jul-20 | Physiological maturity - harvest | 5 | 2.4 | 29.4 | 50 |
| Aug-20 | | 11 | 3.4 | 29.5 | 48 |
| Sep-20 | | 14 | 1.9 | 28.9 | 47 |
| Oct-20 | | 11 | 2.5 | 28.9 | 46 |
| Nov-20 | | 7 | 1.4 | 29.0 | 44 |
| Dec-20 | | 3 | 1.3 | 28.9 | 46 |

Concerning other studies on coffee where the concept of energy balance was applied have reported dissipation values of H at 29.6% and LE at 66.9% (Jaramillo; Escobar, 1983), at LE 40-60% (Gutiérrez; Meinzer, 1994), and H at 12-41% and LE at 24-51% (Castaño et al., 2022), and these values in the present study fluctuate around these documented values. The dynamics of the balance over time and changes in the production system are highlighted.

The period in which more energy was allocated to the ET process was between May and June 2020, which coincided with the second cycle of corn in the pre-flowering and post-flowering stages, with LE values being greater than or equal to 70% of the Rn and the Bowen's ratio below 0.37. This last value corresponded to that reported by Ramírez and Jaramillo (2009) for sun-grown coffee, with average wind conditions lower than 2.0 m $s^{-1}$ and dissipation values of LE higher than 65%. In this case, the lower values of β were related to greater assimilation of $CO_2$, which was also related to an increase in the rate of ET.

The identified water stress conditions resulted in a reaction in the plant related to stomatal regulation to avoid dehydration and can cause a reduction in the photosynthetic rate (Almeida et al., 2020). Thus, the corn crop acted as a regulator of both temperature and water stress in the soil at the expense of a higher energy cost in September 2019, where H was higher than LE (Tables 2 and 3). For the first corn cycle, the damage was determined based on the obtained harvest, estimated in dry mass, which was 65% lower than the value obtained for the second cycle. When there are humidity restrictions such as events related to El Niño 2019 in this case, it is confirmed the recommendation of establishing temporary shading during the vegetative growth phase of coffee trees and the benefits of planting food economy crops, such as corn, which will have the dual functionality of providing shade and additional resources (Rendón, 2020).

Information on the Kc dynamics of the coffee stumps is innovative and is considered very useful for determining the water needs of the crop. The dynamics of this index under the conditions in this study highlight the efficiency that can be achieved with an intercropping strategy. When reviewing the values of Kc for the corn system, in the second cycle, the Kcmean in the stage of maximum foliar expansion fluctuated between 1.5 ± 0.06 and 1.6 ± 0.09, values much higher than those reported in a monoculture by Facchi et al. (2013) (Kcmean 0.96-1.02) and Allen et al. (2006) (Kcmean 1.2) and those obtained by Castaño et al. (2022) in a similar system (Kcmed 0.8 ± 0.03). The Kc levels recorded in this study were related in part to the high temperatures recorded in May 2020, which for the research site presented anomalies of +1.1 °C in the mean temperature, without moisture restrictions in the soil.

Table 4: Dynamics of crop evapotranspiration (ETc) in mm day$^{-1}$, reference evapotranspiration (ETo) in mm day$^{-1}$, and the crop coefficient (Kc) ± standard error, in a system of corn intercropped with coffee stumps.

| Month-year | Corn stage | ETc - mm | ETo - mm | Kc |
|---|---|---|---|---|
| | | **Coffee vegetative stage** | | |
| Jun-19 | Vegetative | 2.4 ± 0.15 | 3.6 ± 0.21 | 0.69 ± 0.04 |
| Jul-19 | Vegetative-preflower | *2.6 ± 0.10 | 3.4 ± 0.19 | * 0.80 ± 0.04 |
| Aug-19 | Flowering | *1.7 ± 0.14 | 2.5 ± 0.18 | *0.71 ± 0.05 |
| Sep-19 | Filling - physiological maturity | *1.6 ± 0.16 | 2.9 ± 0.19 | *0.56 ± 0.05 |
| Oct-19 | Harvest maturity | 2.6 ± 0.10 | 3.7 ± 0.24 | 0.72 ± 0.03 |
| Nov-19 | | 3.4 ± 0.18 | 3.7 ± 0.20 | 0.94 ± 0.03 |
| Dec-19 | | 2.9 ± 0.17 | 3.6 ± 0.21 | 0.84 ± 0.05 |
| Jan-20 | | 3.4 ± 0.21 | 3.4 ± 0.23 | 0.99 ± 0.04 |
| Feb-20 | | 2.1 ± 0.16 | 2.8 ± 0.19 | 0.74 ± 0.05 |
| Mar-20 | Vegetative | 2.5 ± 0.15 | 3.1 ± 0.19 | 0.84 ± 0.05 |
| Apr-20 | Vegetative | 3.3 ± 0.20 | 3.1 ± 0.17 | 1.05 ± 0.06 |
| May-20 | Preflowering - Flowering | 3.6 ± 0.21 | 2.3 ± 0.14 | 1.60 ± 0.09 |
| | | **Coffee reproductive stage** | | |
| Jun-20 | Filling | 3.7 ± 0.25 | 2.6 ± 0.19 | 1.51 ± 0.06 |
| Jul-20 | Physiological maturity - Harvest | 3.2 ± 0.17 | 2.8 ± 0.17 | 1.22 ± 0.05 |
| Aug-20 | | 2.9 ± 0.16 | 3.1 ± 0.17 | 0.94 ± 0.04 |
| Sep-20 | | 3.3 ± 0.15 | 3.7 ± 0.19 | 0.90 ± 0.03 |
| Oct-20 | | 3.2± 0.15 | 3.5± 0.16 | 0.94± 0.04 |
| Nov-20 | | 3.3± 0.18 | 3.2± 0.19 | 1.08± 0.05 |
| Dec-20 | | 3.1 ± 0.14 | 3.5 ± 0.24 | 0.92 ± 0.04 |

* Values of evapotranspiration and crop coefficient adjusted for water stress (Allen et al., 2006)

For the coffee trees in the monoculture, the Kc obtained was on average 0.88 ± 0.023 for the vegetative stage (Kcini) and 0.96 ± 0.018 at the beginning of the reproductive stage (Kcmean) as reported in different studies (Antunes et al., 2000; Castaño et al., 2022; Cisneros et al., 2015; Flumignan; De Faria; Prete, 2011; Gutiérrez; Meinzer, 1994; Oliveira; Silva; Castro, 2003; Sato et al., 2007). However, only in Castaño et al. (2022) was the dynamic nature of the intercropping condition evaluated, this study established Kc values for the vegetative and reproductive stages in the planting cycle, obtaining values of Kcini 0.78 ± 0.05 and Kcmean 0.96 ± 0.02, respectively, corresponding to those obtained in this study.

## 5 CONCLUSIONS

If we validate the system with respect to the carbon, gas and energy balances, the following benefits can be considered:

1. In the process of renewing coffee trees by the process of removing old parts of the trunk, residues would likely have a $CO_2$ emitting effect, so intercropping with other crops will have an additional function of neutralizing or counteracting these emissions.
2. Under restrictive environmental conditions, such as those reported in this study in relation to the water deficit in the soil, a system of intercropping corn with coffee can provide a buffer effect since the high evaporative rate is reduced, the temperature is regulated, and less energy is dissipated.
3. In terms of $CO_2$ dynamics, the first phase evaluated indicated that the corn system intercropped with coffee served as a carbon sink, with a fixation potential between 4.9 and 6.6 ton C ha$^{-1}$.
4. The dynamics observed in the gas exchange values, attributable to the changes in the production system, would suggest an adjustment in parameters such as ETo and Kc in the water balance model of coffee crop.

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## 7 AUTHORS' CONTRIBUTIONS

JCGL wrote the manuscript, supervised the experiment, conducted statistical analyses, review and approved the final version of the work, NGSH co-worked the manuscript, contributed statistical analyses and review and approved the final version of the work, CRC co-worked the manuscript and review and approved the final version of the work, JPCB contributed statistical analyses and review and approved the final version of the work, NCFB review and approved of the final version of the work, DAFC supervised the experiment and review and approved of the final version of the work.

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