

**UNIVERSIDAD NACIONAL
SISTEMA DE ESTUDIOS DE POSGRADO
MAESTRÍA EN AGRICULTURA ECOLÓGICA**

**Efecto de la sombra sobre las propiedades ecosistémicas
del suelo de un sistema de producción de café (*Coffea
arabica*) en Poás de Alajuela**

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San José, 2025.

**Tesis sometida a consideración del Tribunal Examinador del Posgrado en Agricultura Ecológica
de la Escuela de Ciencias Agrarias, para optar por el grado de *Magister Scientiae* en
Agricultura Ecológica.**

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arabica*) en Poás de Alajuela**

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Tesis presentada para optar al grado de *Magister Scientiae* en Agricultura Ecológica. Cumple con los requisitos establecidos por el Sistema de Estudios de Posgrado de la Universidad Nacional, Heredia, Costa Rica.

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Descriptores

Agroecología, sistema agroforestal, café, dióxido de carbono, reservorio de carbono, suelo tropical, *Coffea arabica*, *Ocotea insularis*, hojarasca, ciclo de carbono.

Resumen

Comprender la dinámica de los ciclos biogeoquímicos, particularmente del carbono, es crucial para evaluar la función de los sistemas agroforestales (SAF). Si bien el almacenamiento de carbono en la biomasa aérea aumenta con el crecimiento de los árboles, la cuantificación de los reservorios de carbono en el suelo dentro de estos sistemas representa un desafío debido a la compleja dinámica del carbono y al constante aporte de hojarasca por parte de los árboles. La producción y descomposición de la hojarasca influye en la microbiología del suelo y la disponibilidad de nutrientes, desempeñando un papel clave en la dinámica del carbono en los SAF. Sin embargo, aún se comprende poco cómo factores como la composición química foliar, el manejo agronómico y las condiciones climáticas afectan el almacenamiento de carbono en el suelo dentro de estos sistemas.

Por este motivo, este estudio investigó la producción y las tasas de descomposición de hojarasca, los reservorios de carbono del suelo y la dinámica del flujo de dióxido de carbono (CO_2) del suelo en un sistema de producción de café en Poás de Alajuela, Costa Rica, comparando un sistema de monocultivo de café a pleno sol contra un SAF incipiente. Las mediciones incluyeron temperatura y humedad del suelo, flujos de CO_2 del suelo, hojarasca y sus tasas de descomposición durante tres años, capturando la variabilidad por patrones de lluvia contrastantes y las fases de la Oscilación Sur del Niño (ENOS).

Los resultados mostraron un mayor reservorio de carbono del suelo en el sistema a pleno sol ($169 \pm 4 \text{ Mg C ha}^{-1}$) en comparación con el SAF ($138 \pm 4 \text{ Mg C ha}^{-1}$). Se determinó que los patrones de lluvia estacionales impactaron la descomposición de la hojarasca, con tasas más rápidas observadas durante la estación lluviosa en comparación con la estación seca. Por otra parte las tasas promedio de flujo de CO_2 del suelo no mostraron diferencias estadísticas significativas entre sistemas de producción, con rangos entre los $2.3 \pm 0.1 \mu\text{mol CO}_2 \text{ m}_2 \text{ s}^{-1}$ y $5.2 \pm 0.1 \mu\text{mol CO}_2 \text{ m}_2 \text{ s}^{-1}$. Sin embargo los flujos si muestran un patrón estacional e incrementan con el inicio de la estación lluviosa. Estos resultados pueden estar influenciados por factores como el historial de uso del suelo, la edad del sistema, la clase de suelo, las

especies de árboles de sombra y la cantidad y calidad de la hojarasca. A pesar de que no se observaron diferencias en algunas de las propiedades evaluadas, los sistemas agroforestales son fundamentales para la mitigación del cambio climático, la conservación del suelo y los servicios ecosistémicos a largo plazo. Este estudio resalta la necesidad de investigar más a fondo la dinámica de los reservorios de carbono y el comportamiento del flujo de CO₂ en sistemas dinámicos bajo condiciones variables de clima y manejo.

Abstract

Understanding the dynamics of biogeochemical cycles, particularly carbon, is crucial for assessing the role of agroforestry systems (AFS). While carbon storage in aboveground biomass increases with tree growth, quantifying soil carbon reservoirs within these systems remains challenging due to the complex carbon dynamics and the continuous input of litter fall from trees. The production and decomposition of litter fall influence soil microbiology and nutrient availability, playing a key role in carbon dynamics in AFS. However, little is known about how factors such as foliar chemical composition, agronomic management, and climatic conditions affect soil carbon storage in these systems.

For this reason, this study investigated litter fall production and decomposition rates, soil carbon reservoirs, and soil carbon dioxide (CO₂) flux dynamics in a coffee production system in Poás de Alajuela, Costa Rica, comparing a full-sun coffee monoculture with an incipient AFS. Measurements included soil temperature and moisture, soil CO₂ fluxes, litter fall production and decomposition rates over three years, capturing variability due to contrasting rainfall patterns and phases of the El Niño-Southern Oscillation (ENSO). The results showed a higher soil carbon reservoir in the full-sun system ($169 \pm 4 \text{ Mg C ha}^{-1}$) compared to the AFS ($138 \pm 4 \text{ Mg C ha}^{-1}$). Seasonal rainfall patterns were found to impact litter decomposition, with faster rates observed during the rainy season compared to the dry season.

On the other hand, average soil CO₂ flux rates did not show statistically significant differences between production systems, ranging from $2.3 \pm 0.1 \text{ } \mu\text{mol CO}_2 \text{ m}^2 \text{ s}^{-1}$ to $5.2 \pm 0.1 \text{ } \mu\text{mol CO}_2 \text{ m}^2 \text{ s}^{-1}$. However, fluxes exhibited a seasonal pattern, increasing at the onset of the rainy season. These results may be influenced by factors such as land use history, system age, soil type, shade tree species, and the quantity and quality of litter fall. Although no significant differences were observed in some of the evaluated properties, agroforestry systems play a fundamental role in climate change mitigation, soil conservation, and long-

term ecosystem services. This study highlights the need for further research on carbon reservoir dynamics and CO₂ flux behavior in dynamic systems under variable climate and management conditions.

Agradecimiento

A mis padres Rafael y Cecilia que siempre han creído en mí y me han apoyado.

A mi esposo Jeremy por estar ahí, por su apoyo, motivación y entusiasmo.

A mi hermana Grettel, que de una u otra forma me apoyó siempre.

A la Dra. Cristina Chinchilla, por su acompañamiento, dedicación y entusiasmo, por sus consejos académicos y personales, que me han ayudado a crecer.

A la MSc. Gabriela Soto, por su aporte a este proyecto, sus consejos prácticos, y la motivación que siempre me brindó, y su amor por la agroecología.

A la Dra. Martha Orozco Aceves por su acompañamiento durante todo el proceso de investigación y sus consejos académicos.

Al Dr. Juan Chin por su motivación y apoyo en todo momento.

A la Dra. Ana María Duran y al Dr. Marco Gutiérrez por su valioso aporte en la revisión de los documentos y el desarrollo de los proyectos.

A mis compañeros y compañeras del CICA, por el apoyo y la motivación para desarrollar el proyecto.

A Cristian Porras, Eddy Valle y José Miguel Araya, de la Estación Experimental Fabio Baudrit Moreno.

A todos los asistentes que participaron en los muestreos, en especial a Yamilka Corrales.

A Finca La Hilda y el Grupo Santa Eduviges, en especial a Mariano Vargas por su colaboración durante toda la investigación.

A la Universidad de Costa Rica por el financiamiento mediante los proyectos C0454: Flujos de carbono y eficiencia en el uso del agua en agroecosistemas cafetaleros innovadores, C2059 CARBOSEC: Evaluación del efecto de tres formas de manejo contrastantes de un cultivo de café en la actividad biológica y la capacidad de secuestro de carbono del suelo y C3651 DIC2AFE: Dinámica de la captura de carbono en agroecosistemas cafetaleros innovadores, este último financiado por los fondos FEES-CONARE. Al proyecto PUBLICARE por brindarme las herramientas para la escritura de artículos científicos.

A los profesores y profesoras del Programa de la Maestría en Agricultura Ecológica de la Universidad Nacional, por la formación brindada.

A los productores de café de Costa Rica, por su ardua labor.

Y a todos los que colaboraron de una u otra forma para el desarrollo de esta investigación.

Dedicatoria

A mis padres, Rafael y Cecilia,

Gracias

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C	Carbono
CO ₂	Dióxido de carbono
SAF	Sistemas agroforestales
SPS	Sistema pleno sol
SCS	Soil carbon stock
FSS	Full-sun monoculture coffee system
AFS	Agroforestry system
ENSO	El Niño-Southern Oscillation

Capítulo I: Introducción

En las regiones tropicales, Centroamérica es considerada una zona particularmente vulnerable frente al cambio climático, debido a un mayor aumento de temperatura e impactos que se agravan por cambios en el uso de la tierra, un desarrollo socioeconómico bajo y sistemas de producción deficientes en comparación con regiones no tropicales (Birkel et al., 2021). Para Costa Rica se proyecta una tendencia al incremento de temperatura de alrededor de 2.6 °C con una variabilidad espacial de ± 0.4 °C y un aumento leve en la precipitación promedio (de 120 mm) hasta el año 2040, principalmente en el Caribe costarricense y el Pacífico Sur; estos cambios podrían resultar en alteraciones en la biodiversidad en un futuro cercano (Birkel et al., 2021). Proyecciones regionales de Alvarado-Gamboa (2021) para Costa Rica también señalan un aumento de la temperatura de 1 a 2 °C y un incremento de las lluvias en el Caribe Norte, la Zona Norte, y la península de Nicoya con una disminución de las precipitaciones en el Valle Central, partes altas del Pacífico Central y Valles del General y Coto Brus.

El sector agrícola es uno de los sectores con mayor vulnerabilidad frente a los cambios proyectados en el régimen de precipitaciones y temperatura a causa del cambio climático. Para hacer frente a estos cambios, en la actividad agrícola se promueven comúnmente los enfoques de adaptación y mitigación. La adaptación busca fortalecer capacidades para convivir con los cambios con perspectivas a largo plazo y la mitigación busca disminuir las causas del cambio climático a través del rediseño de los sistemas productivos para aumentar significativamente la captura de carbono (C) (Acevedo-Osorio et al., 2017).

Independientemente de si se sigue la vía de la adaptación o la mitigación, es urgente generar investigación y difundir prácticas que incrementen la resiliencia de los agroecosistemas ante los eventos climáticos extremos (Nicholls y Altieri, 2019). En este sentido, la Agroecología plantea una serie de prácticas para generar resiliencia de los ecosistemas, al hacerlos más biodiversos en comparación con

sistemas de manejo convencional o monocultivos. Donde, además se generan servicios ecosistémicos como la polinización y dispersión de semillas, la producción de biomasa, eficiencia y resiliencia productiva. Los sistemas agroecológicos tienen más estabilidad y sostenibilidad en términos de un mayor reciclaje de nutrientes, control del microclima local, regulación de procesos hidrológicos y regulación de plagas y enfermedades, así como la reducción del uso de compuestos químicos nocivos para el ambiente, respecto a sistemas de producción convencional (Barrera, 2017).

Con el objetivo de que el sector agropecuario pueda adaptarse y enfrentar eficientemente los efectos del cambio climático, es necesario crear políticas que vayan encaminadas a fortalecer e incrementar la resiliencia de los sistemas productivos ante los eventos climáticos adversos y fortalecer las capacidades locales para generar un desarrollo bajo en emisiones. Una de estas acciones en Costa Rica es la implementación de las Acciones de Mitigación Nacionalmente Apropriada (NAMA por sus siglas en inglés), las cuales promueven sistemas productivos más eficientes y competitivos.

La NAMA café por ejemplo, dentro de sus políticas promueve los sistemas agroforestales (SAF) (NAMA, 2021), los cuales son sistemas donde se combinan árboles con cultivos agrícolas en el mismo sitio, ya sea dentro del cultivo o en los alrededores. Los SAF de café son ejemplos de sistemas agrícolas con alta complejidad estructural (Gomes et al., 2020).

Los SAF son una práctica agrícola sostenible que promueven una mayor biodiversidad y resiliencia de los agroecosistemas. Al combinar especies arbóreas, cultivos y, en ocasiones, animales, los SAF ofrecen múltiples beneficios ambientales y socioeconómicos, como la mejora en la calidad del suelo, la regulación del microclima, la protección de los recursos hídricos y la prevención de la erosión (Mayer et al., 2022; Sivaranjani y Panwar, 2023). Además, estos sistemas contribuyen a reducir el uso de insumos sintéticos y restaurar el equilibrio biológico del suelo, lo que aumenta la productividad de los cultivos y, en consecuencia, genera ingresos adicionales para los agricultores (Mahmud et al., 2021; Pardo-Plaza et al., 2019; Tschora y Cherubini, 2020).

Uno de los roles más importantes atribuidos a los SAF es el secuestro de carbono, que ocurre a través de dos vías diferentes: la fijación atmosférica de dióxido de carbono (CO_2) por los árboles en la fotosíntesis (por encima del suelo), y por la deposición, descomposición de la hojarasca y la exudación de raíces (en el suelo) (Mayer et al., 2022; Sivaranjani y Panwar, 2023). La presencia de una capa de hojarasca en el suelo es una contribución importante al ciclo del C. La hojarasca puede modificar los flujos de CO_2 suelo-atmósfera de varias maneras, en primer lugar, al actuar como una barrera bidireccional para la difusión de gases desde la atmósfera al suelo y viceversa (Walkiewicz et al., 2021). En segundo lugar, la hojarasca funciona como sustrato y fuente de energía para los microorganismos del suelo, los cuales emiten CO_2 mediante la respiración, y estos flujos a su vez puede ser utilizados como indicador de la actividad biológica del suelo (Durango et al., 2015; Gomes et al., 2016).

La mayoría de las emisiones de CO_2 en la actividad agrícola se originan en el suelo, que a su vez es el mayor reservorio de C en la biosfera terrestre (Chataut et al., 2023). Aunque se estudian los reservorios de C del suelo (SCS, siglas en inglés) de los sistemas de gestión de bosques y cultivos en las regiones tropicales, persiste una alta incertidumbre sobre los factores que controlan las pérdidas de C, como flujos de CO_2 , y cómo las prácticas agrícolas podrían afectar estas emisiones. Varios factores climáticos, como la humedad del suelo, la textura, la porosidad, la agregación y la temperatura, junto con las comunidades microbianas y la cantidad y el tipo de caída de hojarasca, pueden influir en la respiración del suelo (Walkiewicz et al., 2021), así como afectar la difusión, producción y transporte de CO_2 a la superficie del suelo (Gomes et al., 2020).

En Costa Rica, los SAF han sido particularmente importantes en la producción de café, ofreciendo diversos servicios ecosistémicos, entendidos como las funciones, procesos ecológicos o características que contribuyen, de manera directa o indirectamente, el bienestar humano (Costanza, et al., 2017). Si bien los SAF tienen beneficios tanto para el cultivo como para el ambiente, existe poca investigación sobre la influencia directa de la sombra y el aporte de la hojarasca en las propiedades ecosistémicas del

suelo. Los beneficios que brinda el suelo son importantes para el desarrollo de los sistemas productivos de café y son estratégicos para la adaptación al cambio climático.

Dentro de los servicios ecosistémicos que brindan los suelos a los sistemas cafetaleros se encuentran: la disponibilidad de nutrientes, la resistencia a la erosión, la capacidad de enraizamiento, la disponibilidad de agua, la disponibilidad de actividad microbiológica, actúan como un regulador de la emisión de gases y como un sumidero de C (Bedoya-Gómez et al., 2021). Conocer cómo estos factores influyen en mayor o menor medida y las dinámicas que operan entre ellos es fundamental para proponer prácticas agroecológicas que puedan reducir y mitigar las emisiones de CO₂, así como incrementar la captura de C en el suelo.

Para obtener una perspectiva más completa de la dinámica del C en los SAF enfocados en la producción de café, en este trabajo se estudian los depósitos de C en la hojarasca y el suelo, y cómo interactúan entre sí. Esta investigación tiene como objetivo estudiar las prácticas de manejo para mejorar la captura de C del suelo y el ciclo de nutrientes, en el contexto de variabilidad climática contrastando fases del modo de Oscilación del Sur de El Niño (ENSO) de "La Niña" y "El Niño"; para lo cual se estudiaron la dinámica de la hojarasca de *Coffea arabica* y el árbol de sombra *Ocotea insularis* en un SAF incipientes durante dos años, así como los flujos de CO₂ del suelo, bajo patrones de precipitación contrastantes durante tres años, para determinar su posible impacto en la dinámica del C del suelo.

La presente investigación se justifica por la importancia nacional de la producción de café, por su contribución al desarrollo socioeconómico del país y valor histórico cultural. Por ejemplo, durante el año 2023 esta actividad aportó un 2.14% del producto interno bruto agropecuario y un 0.09 % del producto interno bruto nacional (Instituto del Café de Costa Rica [ICAPE], 2023), para el año cafetalero 2022-2023 (de octubre a setiembre), la actividad generó 350 740 944 dólares en divisas para el país, (ICAPE, 2023), y para el año 2023 la siembra cafetalera abarcó un área de 77 352.49 ha (Instituto Nacional de Estadísticas

y Censos [INEC], 2023). Además, la producción cafetalera genera empleos directos durante la etapa de cosecha, con oferta de trabajo temporal para los migrantes.

Por lo tanto, considerando la importancia económica que representa la producción de café para el país, y el impacto que genera esta producción en el medio ambiente, es necesario conocer aspectos relacionados con los servicios ecosistémicos que aportan los cafetales con enfoques de SAF y el papel de aspectos estructurales y funcionales de los mismos en condiciones del trópico. Además, es relevante conocer el rol de la sombra en la dinámica de los flujos de C, así como los factores físicos, químicos y microbiológicos que influyen en dichas emisiones.

Los resultados de la investigación se han plasmado en dos artículos científicos. En el Capítulo III “Litter dynamics and soil carbon stock in a coffee agroforestry system in Costa Rica” se exploran las tasas de producción y descomposición de dos especies de plantas coexistentes (*Coffea arabica* y *Ocotea insularis*) en un SAF incipiente comparado con un sistema de monocultivo de café a pleno sol, además, se cuantifican las reservas de C del suelo. En el Capítulo IV “Dynamics of soil CO₂ flux of coffee agroforestry and full-sun coffee tropical systems”, se estudian las dinámicas de los flujos de CO₂ del suelo durante tres años en el SAF incipiente comparado con el sistema de monocultivo de café a pleno sol bajo.

Objetivos de la investigación

Objetivo general

Determinar el efecto de la sombra sobre los servicios ecosistémicos del suelo (ciclaje de materia orgánica) en un sistema agroforestal de café en contraste con un sistema de producción de café a pleno sol, para entender la respuesta del sistema productivo ante los efectos potenciales del cambio climático.

Objetivos específicos

1. Caracterizar la dinámica de producción y descomposición del mantillo en un cafetal con sombra en comparación con uno a pleno sol.
2. Monitorear la variación estacional de indicadores de aspectos estructurales y funcionales de la comunidad microbiana del suelo de un cafetal con sombra y compararla con uno a pleno sol.
3. Determinar la emisión anual de dióxido de carbono del suelo de un cafetal con sombra y compararla con uno a pleno sol.

Capítulo II: Marco teórico

Generalidades del cultivo del café

El café es uno de los productos agrícolas más comercializados en todo el mundo, consumido por aproximadamente un tercio de la población mundial, se cultiva en aproximadamente 80 países tropicales y se estima que alrededor de 25 millones de familias en todo el mundo son productores de café, con una mayor producción en manos de pequeños agricultores y familias (DaMatta et al., 2019). En Costa Rica, el cultivo del café forma parte de la historia e identidad nacional y tiene un impacto directo sobre el desarrollo socioeconómico del país. En el año 2023 aportó un 2.14% del producto interno bruto agropecuario y un 0.09 % del producto interno bruto nacional (ICAFFE, 2023), en ese mismo año hubo un área de producción de 77 352.49 ha (INEC, 2023). El café es producido en gran parte por pequeños y medianos productores y beneficia directamente a más de 40.000 familias, además de la participación de miles de personas en procesos asociados, como cosecha, procesamiento y comercialización (Platteeuw, 2009).

La planta de café pertenece a la familia botánica Rubiaceae, al género *Coffea*, siendo *Coffea arabica* y *Coffea canephora* las dos especies con mayor importancia comercial (Farah y Ferreira dos Santos, 2015). El cafeto posee siete fases fenológicas: germinación y almácigo, crecimiento vegetativo, desarrollo y reposo de yemas florales, floración, llenado de frutos, maduración o cosecha y reposo o defoliación (Vignola et al., 2018). El cultivo del cafeto se desarrolla idealmente a una altitud entre 500 y 1700 msnm, con una precipitación entre 1000 a 3000 mm anuales, una temperatura entre los 17 a 23 °C y una humedad relativa menor al 85% (ICAFFE, 2011). En Costa Rica, las variedades más utilizadas son Caturra, Catuaí, Híbrido F1, Venecia, Catimores y Obatá. Estas variedades se cultivan principalmente por su alta productividad y calidad, y se manejan a densidades de siembra de 5000 a 4000 plantas ha⁻¹ según la variedad (Vignola et al., 2018).

Sistemas agroforestales

Los Sistemas Agroforestales (SAF) se definen como modelos de producción en los que se combinan árboles con cultivos agrícolas en un mismo espacio (Nationally Appropriate Mitigation Actions [NAMA], 2021). Estos sistemas se fundamentan en principios ecológicos como la diversificación, el reciclaje de nutrientes, los procesos biológicos y la imitación de hábitats naturales. Su implementación abarca diversas técnicas, incluyendo el uso de árboles como cortavientos, sistemas silvopastoriles, cultivos intercalados y su establecimiento en los linderos de las parcelas, entre otras variaciones (Notaro et al., 2014).

Además de su función productiva, los SAF destacan por su capacidad para actuar como reservorios de C a lo largo del tiempo. Esta acumulación de C es particularmente notable en la biomasa de árboles y arbustos, cuya capacidad de almacenamiento depende de la densidad arbórea y del tamaño de los individuos presentes en una determinada área (Espinoza-Domínguez et al., 2012). Asimismo, los SAF representan una alternativa sostenible para el uso del suelo y la conservación del medio ambiente, ya que contribuyen al incremento de la productividad agrícola (Pardo-Plaza et al., 2019) y promueven el desarrollo ambiental, social y económico. En este sentido, su implementación puede generar ingresos adicionales para los agricultores (Notaro et al., 2014).

Otro beneficio clave de los SAF es la mejora de la calidad del suelo, atribuida a la incorporación de hojarasca y materia orgánica, lo que favorece el equilibrio de las poblaciones de organismos edáficos. Entre sus múltiples ventajas, se destacan la optimización del ciclo de nutrientes, el aumento de la actividad microbiana, la reducción de la escorrentía y la erosión, la disminución de la densidad aparente del suelo y el incremento de la infiltración de agua. Además, algunos SAF incluyen especies fijadoras de nitrógeno (N), lo que mejora la fertilidad del suelo y fortalece la sostenibilidad del agroecosistema (Notaro et al., 2014; Pardo-Plaza et al., 2019).

Servicios ecosistémicos de los SAF de café

Los SAF en café son modelos agrícolas de alta complejidad estructural que favorecen el ciclaje de nutrientes mediante la incorporación de hojarasca, incrementan la biodiversidad y contribuyen al almacenamiento de C (Gomes et al., 2020). De acuerdo con Farfán-Valencia (2020), estos sistemas se definen como un conjunto de prácticas de manejo que integran especies arbóreas con el cultivo de café, con el objetivo de conservar el suelo y el agua, incrementar y mantener la producción, así como fortalecer la sostenibilidad y el desarrollo social y económico de las familias cafetaleras.

Los SAF con alta diversidad de especies se consideran más sostenibles que los monocultivos, ya que los árboles de sombra desempeñan un papel clave en la conservación de la materia orgánica (MO) del suelo, un factor esencial para mitigar diversos problemas ambientales que afectan la productividad de los cultivos tropicales (Romero-López, 2006). Además, la sombra en los SAF ofrece importantes servicios ecosistémicos, entre ellos la regulación de plagas y enfermedades. Villarreyra et al., (2016) destaca que la mayor complejidad estructural del dosel en los cafetales agroforestales fomenta la creación de nichos ecológicos, lo que favorece la coexistencia de un mayor número de especies, incluyendo aquellas con capacidad de biocontrol sobre plagas del cafeto. Asimismo, la presencia de árboles reduce la energía cinética de las gotas de lluvia, disminuyendo la dispersión de esporas por salpique, y atenúa la velocidad del viento, lo que protege las hojas del cafeto contra daños mecánicos y limita la propagación de hongos oportunistas.

Otro beneficio de los SAF en café, es la sombra, utilizada como una estrategia para mitigar los efectos del cambio climático. Esta práctica, contribuye a la estabilidad térmica del agroecosistema, ya que modera las fluctuaciones de temperatura (Vaast et al., 2016). Adicionalmente, el sombreado mejora la eficiencia en el uso del agua al modular la conductancia estomática del cafeto y proteger el suelo de la

radiación solar directa, lo que reduce la temperatura del suelo y minimiza la evaporación del agua (Gómez et al., 2016).

No obstante, la producción de café bajo sombra ha sido objeto de debate debido a la posible restricción de la incidencia de la radiación solar, un factor determinante en la productividad del cultivo (Farfán-Valencia, 2020). En contraste con los sistemas a pleno sol, algunos estudios sugieren que la sombra puede disminuir el rendimiento del cafeto. Sin embargo, cuando se mantiene en torno al 30 %, la sombra no solo resulta beneficiosa para el cultivo, sino que también agrega valor a la producción debido a los servicios ecosistémicos asociados mencionados anteriormente (Cerdeira et al., 2017; Sarmiento-Soler et al., 2020).

El diseño adecuado del SAF es un aspecto clave para maximizar sus beneficios. El Instituto del Café de Costa Rica (ICAFE, 2011) recomienda establecer la sombra simultáneamente con la siembra del cafeto, en la misma hilera del cultivo, y utilizar barreras cortavientos de árboles durante los primeros años de crecimiento. En un estudio realizado por Roupsard et al. (2017) en un SAF de café en Turrialba, Costa Rica, se monitorearon los flujos de C, agua, nutrientes y sedimentos durante ocho años. Los resultados indicaron que: 1) los árboles de sombra reducen significativamente la escorrentía superficial y la erosión en comparación con los sistemas de café a pleno sol, y 2) en los SAF, la tasa de reciclaje de nutrientes es mayor cuando se realizan podas en los árboles de sombra. Específicamente, cinco meses después de la poda de *Erythrina sp.*, el 26 % del N originalmente presente en los materiales podados permanecía en la hojarasca, un 15 % en el suelo, y un 23 % en la planta de café y sus frutos.

En otro experimento llevado a cabo en Turrialba, en un SAF de café (*Coffea arabica* variedad Caturra) con sombra de tres especies arbóreas: *Erythrina poeppigiana* (poró), *Chloroleucon eurycyclum* (cashá) y *Terminalia amazonia* (roble coral), solas y/o combinadas, se evaluó el aporte de materia seca y el reciclaje de nutrientes (Ca, Mg, K, P y N), bajo tres niveles de manejo: alto convencional, medio

convencional y alto orgánico. Los resultados mostraron que los tratamientos bajo manejo orgánico y aquellos asociados con leguminosas podrían sostener la productividad del cultivo por períodos más prolongados en caso de reducción o cese de la fertilización. Asimismo, los valores de eficiencia en el uso de nutrientes indicaron que los tratamientos orgánicos y aquellos asociados con *Erythrina* fueron los más efectivos en el reciclaje de nutrientes, lo que sugiere una mayor disponibilidad de estos elementos para el cultivo (Romero-López, 2006).

Flujos de CO₂ de suelos como indicador de actividad biológica

Entre los indicadores biológicos más relevantes para evaluar la calidad del suelo se encuentran aquellos relacionados con la actividad biológica sobre la materia orgánica, tales como la biomasa microbiana, la respiración del suelo y las actividades enzimáticas. Estas variables están estrechamente vinculadas a los flujos de CO₂ del suelo, los cuales reflejan la intensidad de los procesos de descomposición y respiración microbiana (Coleman et al., 2004; Durango et al., 2015; Pardo-Plaza et al., 2019).

Los flujos de CO₂ del suelo están determinados por diversos factores ambientales, siendo la temperatura y la humedad dos de los más influyentes. Un aumento en la temperatura del suelo, por ejemplo, puede intensificar la respiración radicular y acelerar las tasas de descomposición de la MO, lo que conlleva un incremento en la emisión de CO₂ (Gomes et al., 2016).

La dinámica de estos flujos ha sido objeto de estudio en plantaciones de café bajo diferentes sistemas de manejo. Gomes et al. (2016) investigaron los flujos de CO₂ en SAF y en cultivos de café a pleno sol en Brasil, analizando variables como la temperatura y humedad del suelo y del aire, el porcentaje de cobertura del dosel y los flujos de CO₂. Los resultados indicaron que la temperatura y humedad del aire fueron significativamente más bajas en los SAF en comparación con los sistemas a pleno sol. En cuanto a la emisión de CO₂, los SAF presentaron una mayor estabilidad a lo largo del día.

Durante la mañana (8 a 10 a. m.), los flujos fueron relativamente constantes, mientras que en la tarde (12 a 2 p. m.), se observó un aumento del 15 % en los SAF, en contraste con el incremento del 49.1 % en los sistemas a pleno sol. Estos resultados sugieren que la regulación del flujo de CO₂ en los SAF está influenciada por la variación del C lábil y el N total, así como por la temperatura del suelo a 10 cm de profundidad.

Con base en estos hallazgos, Gomes et al. (2016) concluyeron que los SAF favorecen la estabilidad del microclima y reducen la variabilidad de los flujos de CO₂ del suelo en comparación con los sistemas de café a pleno sol, lo que podría representar una estrategia efectiva para mitigar las emisiones de C en agroecosistemas tropicales.

Capítulo III: Litter dynamics and soil carbon stock in a coffee agroforestry system in Costa Rica

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Abstract

Understanding litterfall dynamics and nutrient fluxes, particularly carbon, is crucial for evaluating ecosystem function in agroforestry systems. While aboveground biomass carbon storage increases with tree growth, quantifying litterfall's contribution to soil carbon stocks is challenging due to complex carbon partitioning across various biological compartments. Litter production and decomposition can influence crop performance by affecting soil microbiology and nutrient availability. However, the dynamics of standing litter stocks in agroforestry systems and how factors like leaf chemistry, management, and climatic conditions influence carbon storage remain poorly understood. This study investigated litter production and decomposition rates of two co-occurring plant species (*Coffea arabica* and *Ocotea insularis*) in a Costa Rican coffee production system. We compared a full-sun coffee monoculture system (FSS) and an incipient agroforestry system (AFS), quantifying soil carbon stocks. Results showed greater soil carbon stocks in the FSS compared with the AFS. This result is shaped by factors such as land-use history, system age, soil type, shade tree species, and organic matter/litter input quantity and quality. Additionally, seasonal rainfall patterns impacted organic matter decomposition, with faster rates observed during the rainy season as compared with the dry season. Our results showed the impact of rainfall on the characteristics and behavior of soil carbon at the sub seasonal to interannual scales, this underscores the need to advance the analysis of carbon stocks in dynamic systems with varying rainfall.

Purpose: To obtain a more comprehensive perspective of C dynamics in AFS for coffee production, we studied C pools in litter and soil, as well as their interactions with contrasting management for two years, under variable annual precipitation budgets, to determine their potential impact on the soil C dynamics.

Methods: We examined litter production and decomposition rates in two co-occurring plant species, *Coffea arabica* and *Ocotea insularis*, within a Costa Rican coffee production system. Comparisons were made between a full-sun monoculture coffee system (FSS) and an incipient agroforestry system (AFS) for two years with contrasting climate variability phases of El Niño-Southern Oscillation (ENSO) mode. Soil carbon stocks were quantified in both systems. **Results:** Results showed greater soil carbon stocks in the FSS compared with the AFS. This result is shaped by factors such as land-use history, system age, soil type, shade tree species, and organic matter/litter input quantity and quality. Additionally, seasonal rainfall patterns impacted organic matter decomposition, with faster rates observed during the rainy season as compared with the dry season. **Conclusions:** Our results showed the impact of rainfall on the characteristics and behavior of soil carbon at the sub seasonal to interannual scales, this underscores the need to advance the analysis of carbon stocks in dynamic systems with varying rainfall.

Keywords: agroecology, litterfall, ecosystem services, CO₂ fluxes.

Introduction

Agroforestry systems (AFS) are widespread in tropical countries such as Costa Rica, where they are associated to multiple crops (coffee, cocoa) and cropping strategies. These agroecosystems integrate trees into the agricultural landscape and provide ecosystem services, such as soil fertility improvement, erosion control, protection of water resources, development of favorable microclimates, pest outbreak prevention, and habitat for biodiversity, among others (Mayer et al., 2022; Sivaranjani and Panwar, 2023). AFS contribute to reduce the use of synthetic inputs and restore soil biological balance, thus

increasing crop productivity and in consequence generating additional incomes to farmers (Mahmud et al., 2021; Pardo-Plaza et al., 2019; Tschora and Cherubini, 2020). The canopy composition and management of AFS differ among regions and farms, as well as the use and type of inputs (synthetic, organic), presence and types of woody perennials, and environmental and ecological conditions of the system (Mahmud et al., 2021). In tropical regions, crops such as coffee, cocoa, and tea are traditionally produced as AFS (Mahmud et al., 2021; Sauvadet et al., 2019), which are envisioned as a key component of climate change adaptation strategies (Cardinael et al., 2021).

One of the most important roles attributed to AFS is carbon (C) sequestration, as to climate change adaptation and mitigation strategies (George et al., 2024). That C sequestration occurs through fixation of atmospheric CO₂ by photosynthesis, and it is introduced into soil by litter deposition and decomposition and by root exudation (Mayer et al., 2022; Sivaranjani and Panwar, 2023). Leaf litter generated by trees contributes to maintain the soil reservoir of organic (e.g., sugars, phenolics, hydrocarbons, and glycerides) and inorganic materials (e.g., nitrogen, phosphorus and calcium) (Lorenz and Lal, 2014), that can be decomposed and used by soil organisms and by plants for their metabolic processes (Lal, 2018; Walkiewicz et al., 2021). The rates of decomposition, recycling and movement of nutrients from the litter to soil depend on the litter decomposability associated with different tree species, planting density, microclimate, management practices, soil type, sunlight, and decomposers density, among others (Nayak et al., 2022; Pieristè et al., 2020).

In Costa Rica, AFS have been particularly important in coffee production; these agricultural systems are structurally complex, in which litter deposition is a driving force that changes nutrient cycling processes, biodiversity, and C storage (Gomes et al., 2016). Common trees associated with coffee plants in AFS are *Erythrina* sp., *Inga* sp. and *Ocotea insularis* (Meisn. Mez, 1889, Laureaceae). The first two species form symbiotic associations to fix atmospheric N, therefore, these species are expected to

influence soil populations of decomposers (i.e. bacteria and fungi) due to local changes in C to N ratios (Chatterjee et al., 2020; Sauvadet et al., 2019). *Ocotea insularis* provide important ecosystem services, for example, food supply for mammals and birds, because its fruits are rich in oils and fats. This species is a wood source and contributes to the stock of organic matter of soil through defoliation (Navarrete and Rigoberto, 2021; Palacios, 2017).

To obtain a more comprehensive perspective of C dynamics in AFS for coffee production, we studied C pools in litter and soil, as well as their interactions. Specifically, we studied litter dynamics of *Coffea arabica* and the shade tree *Ocotea insularis* in two AFS with contrasting management for two years, under variable annual precipitation budgets, to determine their potential impact on the soil C dynamics. The information collected during this investigation aims to elucidate management practices that could enhance soil capture of C and nutrient cycling, within the context of the contrasting climate variability phases of El Niño-Southern Oscillation (ENSO) mode, specifically “La Niña” and “El Niño” which were active during the analysis period.

Materials and Methods

Study site

The research was conducted at La Hilda Farm, in San Pedro de Poás, Alajuela, Costa Rica (10.0893° N 84.235088° W) at 1210 m from January 2022 to December 2023. The site is in the western part of the Central Valley, under a strong influence of the Intertropical Convergence Zone (ITCZ), with a well-defined dry season (December to April) and a bimodal rainy season (May to November), interrupted in July by a short period of precipitation reduction (locally referred as *Canícula* or *Veranillo*). Total average annual rainfall is 2380 mm, the driest month is January (<15 mm), and the wettest month is October (> 500 mm). The average temperature is 20.4 °C with little annual variation (Chinchilla-Soto et

al., 2021). The study was established in two nearby coffee fields (plots) (23 m apart from each other) (Fig. 1). One plot was a full sun system (FSS), and the other plot was an incipient agroforestry system (AFS). The AFS had 16 species of trees with a predominance of *Ocotea insularis* (SI Table 1).

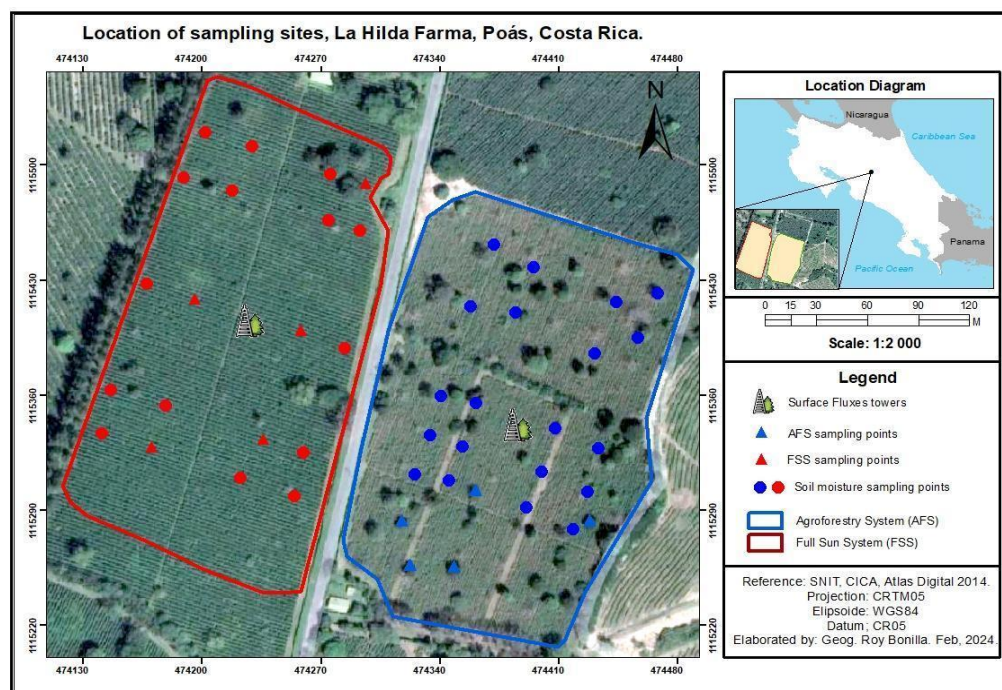


Figure 1. Distribution of sampling points in the full sun system (FSS) (left) and agroforestry coffee system (AFS) (right) at La Hilda Farm, San Pedro de Poás, Alajuela, Costa Rica.

The soil in the area was classified as Andisol, *Dystric Haplustands* (classified by Monge and Alpizar, in 2022). Both plots exhibited similar chemical and physical properties. The bulk density was similar in the first 15 cm of depth (0.6 g cm^{-3}), the porosity was approximately 70 %, the water-filled pore space was around 60 %, and the texture was sandy loam in both plots (SI Table 2). The soil did not show compaction problems or acidity, the fertility was appropriate to sustain coffee plant development (SI Table 3).

Background and plot management

The former land use of both fields was sugarcane cultivation. Coffee has been grown in the AFS since 1970 and in FSS since 1982. However, FSS was replanted with coffee plants cv. Sarchimor T-5296 variety in 2016 (4 830 plants ha⁻¹), while AFS has the Catuaí variety since 1991 (6 172 plants ha⁻¹). The average yield of the last three annual harvests (2020-2021, 2021-2022 and 2022-2023) was 63.68 qq ha⁻¹ in FSS and 26.56 qq ha⁻¹ in AFS.

Both plots have been managed similarly in terms of pesticide application (triazoles and strobilurins for coffee leaf rust control), chemical and mechanical weed control, and liming. Soil fertilization was applied according to the yield and variety, FSS received 294 kg N, 19 kg P and 171 kg of K per ha⁻¹ year⁻¹, and AFS 212 kg N, 14 kg P and 123 kg of K per ha⁻¹ year⁻¹.

Environmental conditions

Reference long-term meteorological conditions for the study were provided by a Davis Vantage automatic weather station (AWS) that operated at La Hilda during 2009-2021. During the study period, meteorological variables and surface fluxes were monitored by two surface fluxes towers instrumented with a complete Li-7200RS open path analyzer and Biomet system (LI-COR Environmental, Lincoln, NE, USA), one located in each plot. Data used in this study corresponds to precipitation, temperature, wind speed and soil water content. Soil volumetric water content (SVWC) was determined at two depths: 20 and 40 cm using a HandiTrase TDR soil moisture meter (model 6085K3, USA). A set of stainless-steel rods of 20 and 40 cm lengths were inserted into the ground at 20 points in each plot. SVWC was measured every 15 days.

Soil carbon stock and physical-chemical properties

To determine soil C stock (SCS), five sampling sites were randomly selected within each plot and, soil was collected at 5, 10, and 30 cm in depth, just one time at the beginning of the study to detect

changes in C and N concentrations due to recent land management changes (FAO, 2022). Total C and N content (%) were determined by dry combustion (Dumas method) using a Vario Macro cube CN analyzer (Elementar Analysensysteme GmbH, Germany) (Horneck and Miller, 1998). Both analyses were conducted at the Center for Agricultural Research (CIA) of the University of Costa Rica (UCR). Microbial biomass C was quantified on the soil upper layer (0–5 cm) at five sampling points, in July and November 2022. Microbial biomass C (mg C kg soil^{-1}) was determined by the fumigation-extraction method (Vance Brookes and Jenkinson, 1987) described by Durango et al. (2015).

Litter production, characterization and decomposition

To estimate litter production, the fallen material from *O. insularis* and *C. arabica* was collected using the harvest method litter traps (Harrison, 2013). Ten $1 \times 1 \times 0.30$ m litter traps (five per plot) were built with a PVC frame and polyethylene shade cloth. In the AFS, litter traps were placed halfway between a coffee plant and an *O. insularis* tree. In FSS, the traps were placed halfway between two coffee plants. Litter accumulated in the traps was collected every month for two years, separated into species and oven-dried at 60°C for 72 hours.

The litter decomposition rate was evaluated over a two-year period (2022-2023) using the methodology by Castellanos and Peláez (2011). Nylon mesh bags (12 x 12 cm with 1 mm pores) were filled with 10 g of leaves collected directly from coffee plants and Ocotea trees (named litter here onwards) to ensure a homogeneous state of decomposition (Farfán and Urrego, 2007). Three composite samples of each material were dried at 60°C in an oven for 72 hours to determine the initial dry matter. To assess the effect of seasonality, two sets of bags were installed: 120 during the dry season (from January to May) and 255 during the rainy season (from May to December) each year.

Decomposition bags were placed at five sites (Fig. 1) on the soil surface (not buried) in each plot. In FSS, bags containing exclusively coffee litter were used. In the AFS, two sets of bags were placed: the

first one containing coffee litter and the second tree litter. The bags were collected weekly during the first month, then biweekly for two months, and then monthly. During each sampling date, one bag per point was removed (a total of five bags in the FFS and 10 bags in the AFS). The bags were transported to the laboratory and the litter was placed in an oven at 60 °C for 72 hours to determine the dry weight. Litter decomposition rate was calculated from the weight loss over time, expressed as a percentage of the remaining mass (weight) after drying, according to Farfan and Urrego (2007). A simple exponential decrease model was employed to estimate decomposition rates (k) (Olson, 1963).

To determine the initial dry matter content of C, N and lignin, a composite sample of fresh material was analyzed using AOAC Official Method 949.04 at the Forage and Animal Nutrition Laboratory of the National Agricultural Technology Institute. C and N were analyzed by the dry combustion method at the Agronomy Research Center of the University of Costa Rica.

To estimate the nutrient potential return to soil by leaf litter, leaf litter production (kg ha^{-1}) was multiplied by the initial nutrient concentration (%) in the leaves of each species (Castellanos et al., 2018).

Statistical analysis

The study sites differed in several key factors related to species composition, canopy structure, agronomic management, and previous land use history, conditions that make a classical statistical analysis to compare or find significant differences among sites unfeasible. For this reason, analyses by individual plots were performed for litter decomposition and SCS, specifically analysis of variance (ANOVA) and a t-test ($p < 0.05$). All statistical analyses were performed with InfoStat software version 2020.

Results

Environmental conditions during the study period

The meteorological conditions during the study period enabled us to contrast the effects of two years with different phases of El Niño-Southern Oscillation (ENSO). It is known that ENSO events have a significant influence on precipitation distribution and amount, often leading to drier than normal years, which can be prone to severe drought conditions in the Pacific coast of Central America (Pascale et al., 2021) and its corresponding influence region which includes the location of the study site. La Niña instead is known for increased precipitation in the region (Quesada-Román et al., 2020; Huguenin et al., 2023). The 2020-2023 was characterized an unusual triple dip La Niña event and the following development of an El Niño event with record-breaking high temperatures across the globe (Jiang et al., 2024). The wetter-drier contrast in the study site is shown by the total rainfall for 2022 (3610 mm), with 108 days recording more than 10 mm of rain, compared with 1932 mm (with 57 days exceeding 10 mm of rain) for 2023 (Fig 2a). The average temperature in 2022 was 23 °C (with a maximum of 25 °C and a minimum of 20 °C), while in 2023, it was 24 °C (with a maximum of 31 °C and a minimum of 17 °C) (Fig. 2b), showing the consistent temperature increase that characterized the latest El Niño event. Average relative humidity values of 66 % and 56 %, respectively in 2022 and 2023, it was noticeable a 10 % increase in humidity in 2023 (Fig. 2c), with consistent drier conditions under influence of El Niño.

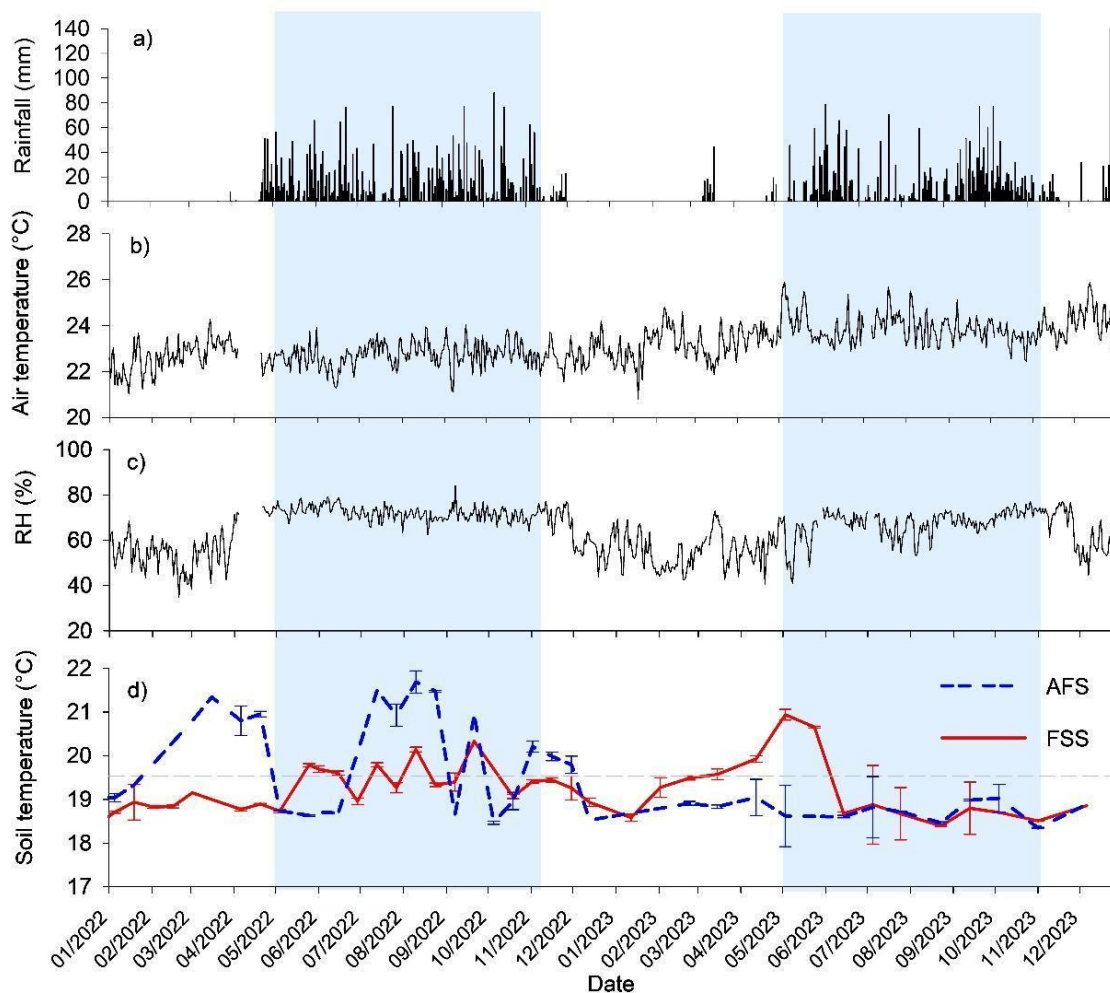


Figure 2. Daily a) rainfall (mm), b) air temperature ($^{\circ}\text{C}$) and c) relative humidity (%) in both plots, d) soil temperature ($^{\circ}\text{C}$) for full sun system (FSS) and agroforestry system (AFS) at La Hilda Farm, Alajuela. Data from January 2022 to December 2023. Shaded areas represent the rainy season, white areas represent the dry season. Vertical lines indicate standard error bars ($n=60$).

Soil properties

Soil temperature fluctuated between 18 and 22 $^{\circ}\text{C}$ over the study period, averaging 19.5 $^{\circ}\text{C}$. The AFS exhibited greater variation in 2022, with average temperatures ranging from 19.5 to 22 $^{\circ}\text{C}$. In contrast, soil temperatures were more stable in the AFS in 2023, averaging 19 $^{\circ}\text{C}$. The FSS displayed less

variation as compared with the AFS. It reached a maximum temperature of 21 °C in May 2023. Both systems exhibited similar soil temperature patterns in rainy season, from June to December 2023 (Figure 2d).

The analysis of soil moisture profiles showed the onset of the rainy season driving the increase in moisture content. SWC upper layers (0-20 cm), increased from 22 to 26 % and increased with depth from 25 to 32 % at 40 cm (Fig. 3).

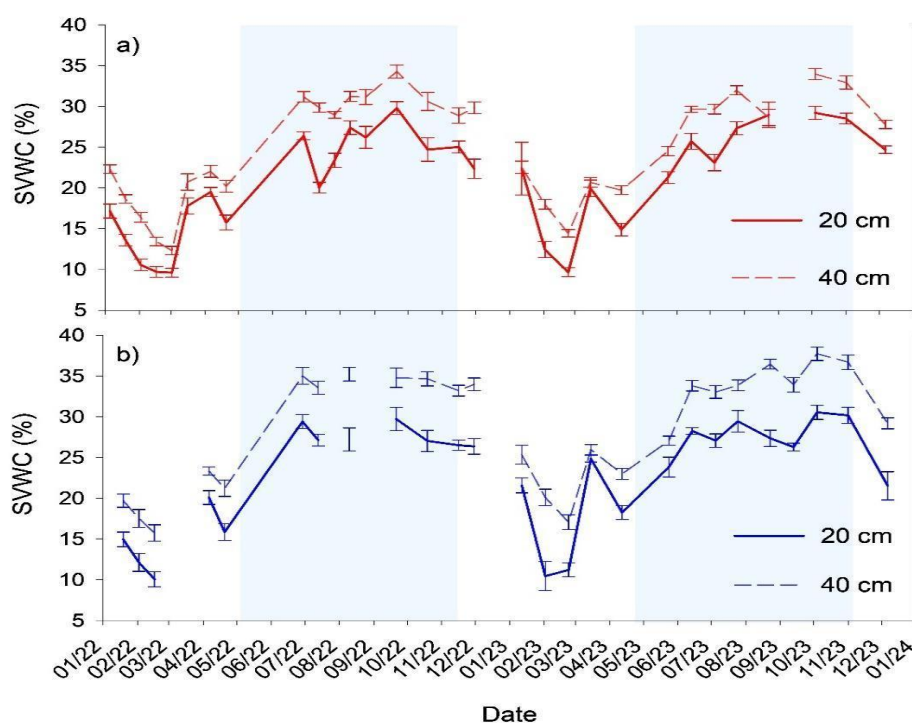


Figure 3. Vertical distribution of soil volumetric water content (SVWC) (%) from 2022 to 2023, at 20 cm and 40 cm soil depth; at La Hilda Farm a) in full sun system (FSS) and b) agroforestry system (AFS). Shaded areas represent the rainy season, white areas represent the dry season.

Soil carbon stock

In both plots, AFS and FSS, C content was higher (10.2 % and 11.2 % respectively) in the upper layer (0-5 cm) and decreased by approximately 40 % with depth (15-30 cm) (6.8 % and 7.8 % respectively) (Fig 4a). Total SCS at 0-30 cm in AFS was lower ($138 \pm 4 \text{ Mg C ha}^{-1}$) than in FSS ($169 \pm 4 \text{ Mg C ha}^{-1}$) (Fig 4b). Both variables, C content and soil carbon stock (SCS) showed statistical differences (T-test, $p < 0.05$) according to depth in the same system. Since the calculation of SCS is based on the thickness of the soil layer, it is expected a higher SCS as sampling depth increases.

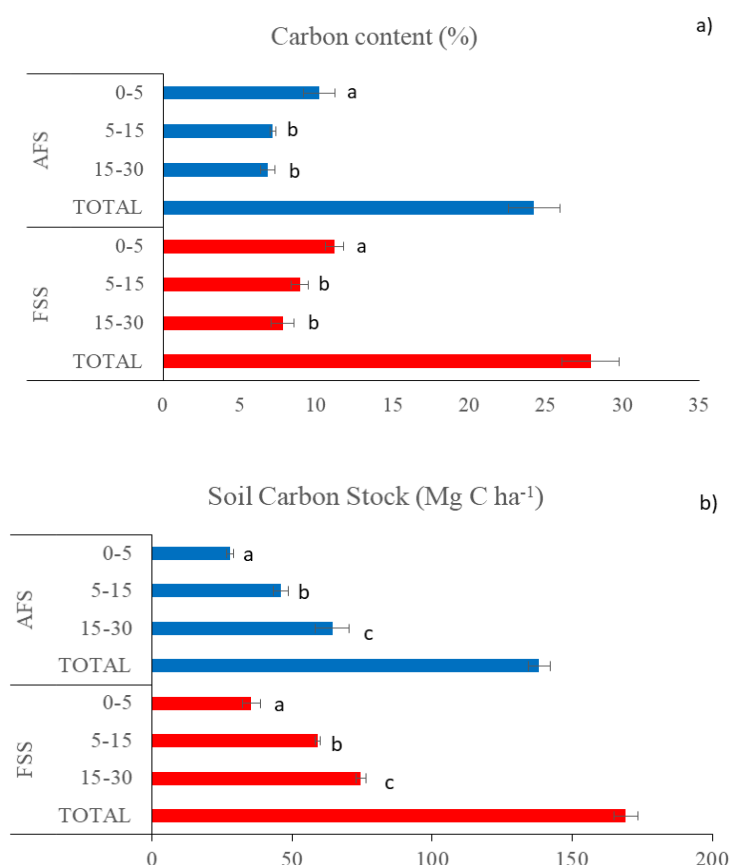


Figure 4. a) Carbon content (%) and b) soil carbon stock (Mg C ha^{-1}) at three depths: 0-5 cm, 5-15 cm, and 15-30 cm, at La Hilda Farm in a full sun system (FSS) and agroforestry system (AFS). Bars represent mean values ($n = 5$), and error bars represent the confidence interval. Different letters at the end of bars indicate significant differences ($p < 0.05$) within depths of the same agroecosystem type.

Litter production, characterization and decomposition

Leaf litter deposition was collected in litter traps during 336 days in 2022 and 286 days in 2023. In both sites, total leaf litter input was lower in 2022 “Niña year” than in 2023 “Niño year”. Total litter input to the system over the 2-year period was 27 % higher in AFS (1264 g m⁻², average 2.0 g m⁻² day⁻¹) as compared with FSS (922 g m⁻², average 1.5 g m⁻² day⁻¹).

Litter deposition was variable throughout the year (Fig 5). In 2022, *O. insularis* showed a significant increase in litterfall deposition from 40 g m⁻² in August to 140 g m⁻² in September, contrary to 2023, since this behavior was not observed, when the maximum deposition occurred in May. *C. arabica* deposition did not show a clear pattern during the evaluation period (Fig 5). Regarding the wind, there is also no clear pattern between wind and leaf litter falling (Fig. 5).

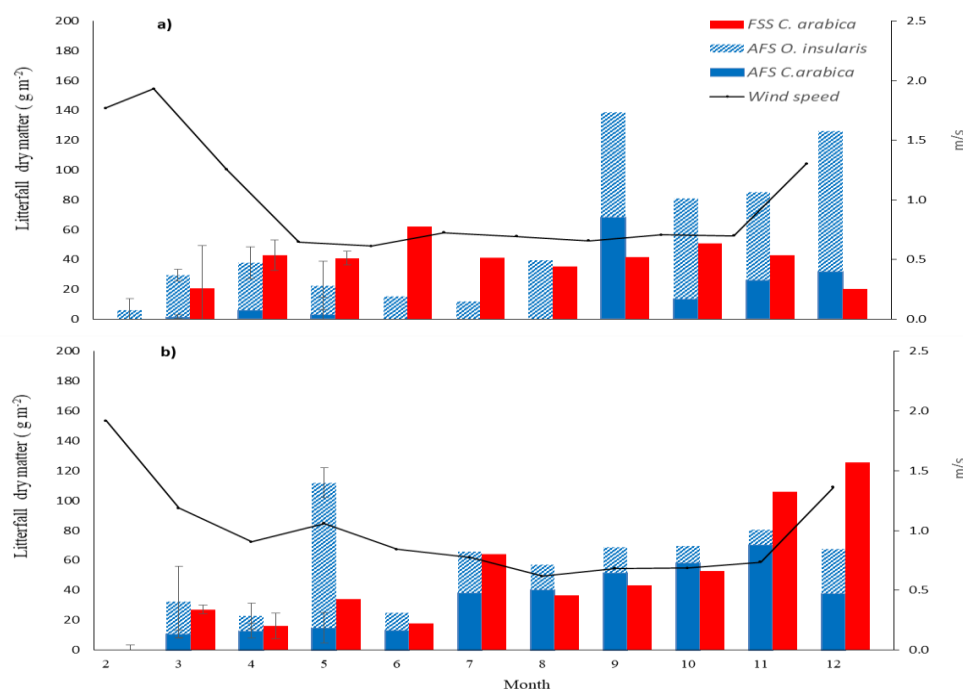


Figure 5. Mean dry weight ($\pm$ SE) of monthly leaf litter input deposition (g m⁻²) a) during 2022 and b) during 2023 at La Hilda Farm in full sun coffee system (FSS) (*C. arabica*) and agroforestry coffee system (AFS) (*C. arabica* and *O. insularis* leaves) (n = 5), and wind speed (m/s). No samples were collected in January and February because the traps were damaged during the coffee harvest season.

The decomposition pattern of coffee and tree leaves in the dry season was similar in both systems, with values of remaining mass between 69 % and 75 % in 2022 (Fig. 6a) and 63% to 78 % in 2023 (Fig. 6b); with differences between *C. arabica* in different systems, but no between *C. arabica* and *O. insularis* in AFS (SI Table 4). In the rainy season, the values of remaining mass were between 21 % and 54% in 2022 and 30 to 48% in 2023. The *C. arabica* litterbags showed less remaining mass in 2022 compared with 2023. In addition, during the rainy season, *C. arabica* decomposition rate tended to double compared with the dry season. In 2022, *O. insularis* (decomposition 55 % of remained mass) showed significant differences in the rainy season as compared with *C. arabica* (AFS: 27 %, FSS: 22 % of remained mass).

During the rainy season in 2022, the decomposition rate of *O. insularis* was significantly lower (0.003 g d^{-1}) than *C. arabica* (0.006 to 0.007 g d^{-1}) in both systems; in 2023 *C. arabica*- AFS showed differences with *C. arabica*-FSS and *O. insularis*-AFS (SI Table 4). Despite the differences observed in cumulative precipitation in the study period (Fig 2a), seasonality had little or no influence on the decomposition of *O. insularis*, as supported by the consistent k value in 2022 (0.003 g d^{-1}) and 2023 (0.004 g d^{-1}) regardless of the season (SI Table 4).

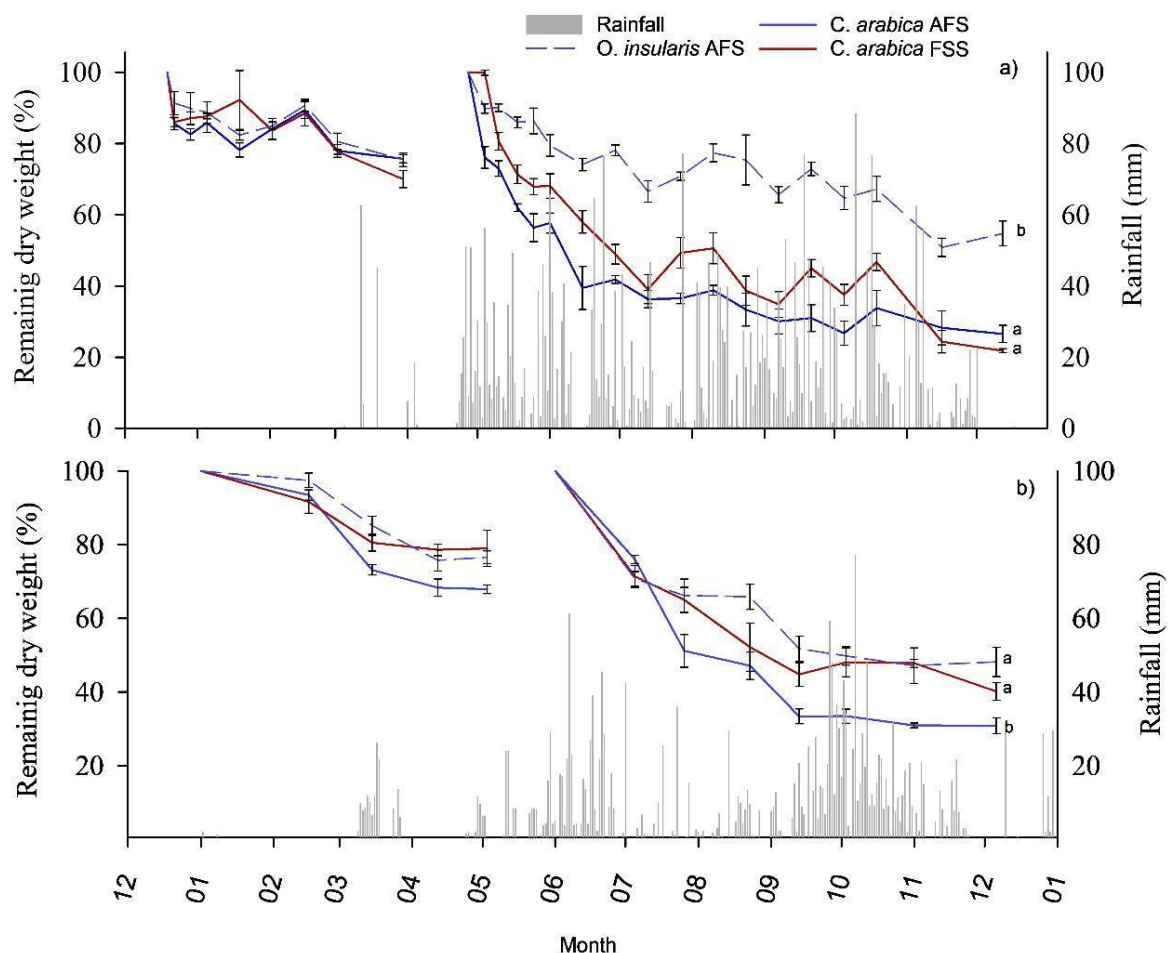


Figure 6. Change in dry weight (%) in decomposition bags of *C. arabica* and *O. insularis* in dry and rainy season in a) 2022 and b) 2023, and rainfall (mm) at La Hilda Farm in full sun system (FSS) and agroforestry system (AFS). Vertical lines represent standard error bars.

In general, leaves of *O. insularis* and *C. arabica* presented similar C, N and lignin content values despite or management. *O. insularis* presented a higher C/N ratio that was consistent over time, despite small changes in N concentrations (SI Table 5). Estimated inputs of C and N into the system (Table 1) suggest that C returns would be approximately 183 g higher in AFS compared with FSS in two years. However, the N contribution was similar with only 4 g more of N in the AFS.

Table 1. Average potential input of C and N (g m^{-2}) by litter fall in full sun system (FSS) and agroforestry system (AFS), at La Hilda Farm during 2022 and 2023.

Year	Nutrient	FSS	AFS.	AFS	Total
		<i>C. arabica</i>	<i>C.arabica</i> g	<i>O. insularis</i>	AFS
		g m^{-2}	m^{-2}	g m^{-2}	g m^{-2}
2022	Carbon	190	73	254	328
	Nitrogen	11	4	12	16
2023	Carbon	249	169	125	295
	Nitrogen	15	9	6	15

Discussion

Soil properties and carbon stock

Although AFS systems are expected to have higher soil carbon stock (SCS) than FSS, due to increased litterfall associated with tree species (Albrecht and Kandji, 2003), our data did not support this hypothesis. Instead AFS showed lower SCS (138 Mg C ha^{-1}) than FSS (169 Mg C ha^{-1}) (Figure 4b), despite both systems being established on the same soil type (SI, Table 2 and Table 3). There are several reasons that could explain this discrepancy. First, the influence of previous land use, as observed elsewhere (Chatterjee et al., 2020). Both sites were previously cultivated with sugar cane, but the AFS plot has been under coffee cultivation for 54 years, while the FSS area has been under coffee cultivation for 42 years.

Legacy effects of C deposition associated with sugar cane may persist, influencing present SCS (Carvalho et al., 2017).

For example, similar to our findings, other studies have reported no significant differences in SCS between coffee production systems (Chatterjee et al., 2020; Hergoualc'H et al., 2008; Noponen et al., 2013; Sauvadet et al., 2019). In our study, SCS in AFS was 18.34% lower than in FSS, despite both systems being established on the same soil type. Chatterjee et al. (2020) reported a 16 % increase in SCS 17 years after coffee was established as an AFS, where soil disturbance occurred during the transition from sugar cane to coffee. They attributed these results to the strong influence of the sites' prior land-use history.

Second, changes in SCS do not occur in the short term despite changes in management practices and land use (Zhuang et al., 2023). Our data (Fig. 5) suggest that even though the AFS had more litter fall entries, it cannot be assumed that tree-based agricultural systems necessarily lead to increases in SCS at least in the short and medium term (Noponen et al., 2013). An important aspect to consider when comparing SCS between systems with different management is the initial set of conditions. It is desirable for the agroecosystems to have the same starting point for research purposes; however, this is rarely the case in natural systems or long-term perennial crops (as coffee plantations) (FAO, 2019). Third, changes in SCS depend on the balance between carbon inputs, plant litter quality and root exudates, and carbon losses through microbial respiration. Frequent additions of organic matter, like litterfall in AFS, creates a microbiome that encourages beneficial microbes to thrive and multiply, and this in turn triggers a priming effect. This effect involves a shift in the composition and activity of the soil microbial community, where the microbes become more efficient at breaking down the organic matter. This results in potentially greater carbon losses (Ma et al., 2020; Zhou et al., 2021). Fourth, another important factor affecting C stock could be the different N inputs on each site, due to crop management. Evidence suggests that N management practices may influence SCS; the addition of N can potentially decrease soil

C losses as CO₂ by altering microbial demand for nutrients and retarding C mineralization; long-term N addition leads to greater soil organic C stabilization (Lu et al., 2021). In this study, the historical N application by synthetic fertilization was on average 28 % higher in FSS in comparison with AFS; this difference in N inputs could be a limiting factor for soil C retention in AFS.

Finally, several intrinsic soil properties can also influence SCS, including soil type, mineralogy, and particularly clay content (Georgiou et al., 2022). Since C storage is primarily associated with clay and silt particles, our sandy loam textured soils with a high sand content (57-82 %) and low clay content (7-2 %) might have a limited capacity for C capture. This limitation could potentially lead to a state of soil C saturation, where the soil has reached its maximum storage capacity for C and can no longer absorb significant additional amounts (Zhuang et al., 2023). Consequently, further C inputs from sources like litter may not translate into a substantial increase in overall C accumulation.

Litter production, characterization and decomposition

Our study highlights the effect of the rainfall distribution seasonality on litterfall decomposition. In the dry season, decomposition was slower regardless of leaf type and production system; only 30 % of plant material was decomposed. On the contrary, at the end of the rainy season, leaf decomposition was about 80 % for coffee leaves and 40 - 50 % for tree leaves, with a higher rate of decomposition during the first 60 days (Fig. 6). The difference in litterfall decomposition rate can be noted when comparing two seasons and two years with contrasting rain distribution and drought intensity. This indicates that the influence of rainfall distribution and amount become important factors for the analysis of decomposition rates, in the longer term.

Relatively low values of C/N ratio are also related to slow decomposition rates (Martius et al., 2004; Schmitt and Perfecto, 2021). In our study, the quality of the litter, given by the initial content of

lignin, C, and N was similar in *C. arabica* and *O. insularis* (Supplementary material Table 5). However, the initial C/N ratio of *O. insularis* was higher (C/N = 21) than that of *C. arabica* (FSS:16 and AFS:18), indicating a slower decomposition process for *O. insularis* as compared with *C. arabica*, as the optimum C/N range of organic residues is between 25 and 30 (Petit-Aldana et al., 2019). In addition, a high lignin content can also slow down the degradation rate, leading to the immobilization of nutrients, particularly N (Talbot and Treseder, 2012; Petit-Aldana et al., 2019; Sari et al., 2022). A low litterfall decomposition rate caused the accumulation of an important layer of mulch at the study sites; this could translate into an accumulation of nutrients that are slowly released and are not lost due to leaching or volatilization (Petit-Aldana et al., 2019).

A factor to consider in decomposition rate, in addition to quality, is the quantity of leaf litter input. The contribution of coffee litterfall is determined by their density, development, canopy arrangement and age. Overall, coffee plants under FSS produced more litterfall than coffee in AFS, despite a lower coffee density in FSS (4 830 plants ha⁻¹) compared with AFS (6 172 plants ha⁻¹). Leaf Area Index tended to be higher in FSS (from 4 to 6) compared with AFS (0.8 to 5) (Montero, 2022). This could be related to leaf life span, as coffee leaves under full sun exposure exhibit a higher rate of leaf abscission compared with shaded conditions, potentially due to drier conditions and photodamage (DaMatta et al., 2019). Additionally, the low tree density in the incipient AFS (approximately 30 trees ha⁻¹) resulted in a low contribution of leaf litter from trees. In addition to management and climate, coffee leaf life span can be influenced by factors such as variety, plant nutritional status, and the presence and severity of diseases and pests, which were not evaluated in this study.

The rate of litter decomposition largely depends also on soil fauna and microbial communities (Glassman et al., 2018; Schmitt and Perfecto, 2021). We did not examine the soil fauna and microbial communities in detail. However, the microbial biomass analysis carried out in July and November 2022,

showed that it was higher in FSS (as compared with AFS) in November (SI Table 6), at the end of the rainy season. In 2023, it was noticeable that the reduction of the decomposition rate after September. We hypothesized that decomposer communities could be affected by pesticide application to soil for the control of nematodes in September 2023 (Fig. 6) but cannot rule out the joint influence of drier conditions as El Niño phase started during the second semester of 2023.

Conclusions

Shade tree diversification in agroforestry systems (AFS) provides multiple environmental services, but tree selection should also consider their decomposition properties, as this study reveals that C/N ratios and litterfall input rates impact the feedback mechanisms that influence soil carbon accumulation, with a pronounced seasonal variation.

The analysis period enabled us to study contrasting ENSO phases within both AFS and FSS systems. This setup allowed us to compare their responses under the influence of the same large-scale climatic conditions while also accounting for the varying microclimate effects created by different plant and shade tree densities and their impact on carbon dynamics within the systems. The findings reported here thus confirm that a better understanding of the impact of precipitation and temperature variations at local scales is required to advance current knowledge of nutrients dynamics, and to address the potential impact of global warming on nutrient cycling, especially if AFS are considered as a mitigation/adaptation strategy.

Overall, this study strengthens the idea that soil carbon accumulation is a complex mechanism that involves several factors such as the crop arrangement and age, the quantity and quality of litter input, soil legacies, the environmental conditions, as well as the interplay between all these factors. Although the major constraint of this study is the contrasting management history of AFS and FSS, the

lack of differences in SCS among systems suggests that multiple decades may be necessary to observe actual changes in SCS, highlighting the need for a long-term quantification of SCS in both systems.

Recommendations

To ensure a robust comparison, management systems should ideally initiate under similar conditions. Employing stable isotope techniques, such as using ^{13}C , can provide valuable insights into the long-term effects of different management practices on SCS. This approach can help elucidate the cumulative impacts of these practices over time, for example to track the sources of carbon, the movement and storage of carbon in the soil.

To gain a more comprehensive understanding of litter decomposition processes, future studies should investigate the functional diversity and abundance of decomposing organisms, including both microbial and faunal components. Examining the specific functional groups involved can provide valuable insights into their roles in litter decomposition and their potential impacts on soil carbon dynamics.

Acknowledgments

We thank José Miguel Araya, Cristian Porras, Eddy Valle, Federico Montero, Raquel Ramírez and other staff at the Fabio Baudrit Experiment Station; and Giovanni Mora, Yamilka Corrales, Roy Bonilla, Jorge Mora, Grattia Corrales, for the support in the measurements, and Melvin Alpízar for describing the soil profile. Special thanks to Mariano Vargas and Grupo Santa Eduvigis for their field support. The authors acknowledge the support of the UCR special grant for research groups under project C0454, C2059, C3651 and the Vice Chancellor Office of Research and of Administration for additional support for equipment installation in the field. Thanks to PUBLICARE, Program of Universidad de Costa Rica.

Statements and Declarations

Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be constructed as a potential conflict of interest.

Data Availability Statement

The datasets generated throughout this study are available from the corresponding author by request.

Funding

Universidad de Costa Rica, Vicerrectoría de Investigación. Project C0454: Flujos de carbono y eficiencia en el uso del agua en agroecosistemas cafetaleros innovadores. Project C2059 CARBOSEC: Evaluación del efecto de tres formas de manejo contrastantes de un cultivo de café en la actividad biológica y la capacidad de secuestro de carbono del suelo. Project C3-651 DIC2AFE: Dinámica de la captura de carbono en agroecosistemas cafetaleros innovadores.

Author contributions

C.C.S, M.G.S, A.D.Q, G.S.M, designed the study. Fieldwork was conducted by M.M.M and C.C.S. Data analysis, statistical analysis and data visualization were carried out by M.M.M. and C.C.S. The manuscript was written by M.M.M, C.C.S and G.S.M with all co-authors contributing to the final version. M.G.S and J.C.P secured financial support for the project leading to this publication. M.M.M and C.C.S coordinated the planning and execution of research activities.

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Capítulo IV: Dynamics of soil CO₂ flux of coffee agroforestry and full-sun coffee tropical systems

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Keywords: CO₂ fluxes, coffee, agroforestry system, tropical soils, soil carbon stocks

Abstract

This study aimed to characterize the soil CO₂ efflux dynamics of coffee plants cultivated under agroforestry (AFS) and full-sun systems (FSS), in La Hilda Farm, Alajuela, Costa Rica, for three years. CO₂ fluxes from the soil are commonly used as an indicator of soil activity, resulting from organism respiration. The soil CO₂ fluxes are affected by environmental factors and by farming management. Soil temperature, moisture and soil CO₂ fluxes were measured in 20 sampling spots in each production system. In general, the CO₂ fluxes follow the behavior of the rainfall, despite the soil average CO₂ fluxes rates do not show statistical differences between the systems productions, the agroecological approach to agroforestry systems highlights the importance of sustainable practices for climate change mitigation, soil conservation and the promotion of long-term ecosystem services.

Introduction

The majority of carbon dioxide (CO₂) emissions resulting from agricultural activities come from the soil, which also serves as the largest carbon (C) reservoir in the terrestrial biosphere (Chataut et al., 2023). While soil carbon stocks (SCS) in forests and agricultural systems within tropical regions have been partially studied, significant uncertainty persists regarding the factors influencing CO₂ fluxes, their magnitude, and the extent to which agricultural practices affect these emissions.

It is known that C enters the soil via photosynthesis and returns to the atmosphere via soil respiration (CO₂ emission). In soil, CO₂ fluxes result from two key processes: generation and transport. CO₂ generation in soil occurs primarily through microbial respiration, the decomposition of organic matter, and root respiration. CO₂ transport through the soil profile is facilitated by diffusion and mass flow.

The primary sources of CO₂ in the soil are autotrophic respiration, originating from plant roots and associated rhizospheric microorganism, and heterotrophic respiration which occurs from non-rhizospheric microorganisms, bacteria, and fungi, including the litter layer (Walkiewicz et al., 2021).

Soil management practices in agriculture can influence CO₂ fluxes. For instance, agroforestry systems play an important role in maintaining biodiversity and increasing organic matter in the soil. This is primarily due to the continuous input of leaf litter from the trees, which decomposes and enriches the soil with organic carbon contrary to conventional production systems (Gomes et al., 2020). Litter deposition plays a crucial role in C cycling by significantly influencing soil-atmosphere CO₂ fluxes in several ways. Firstly, litter acts as a physical barrier, impeding the free diffusion of CO₂ between the atmosphere and the soil. This effect can work in both directions, limiting both the release of soil-respired CO₂ into the atmosphere and the entry of atmospheric CO₂ into the soil (Walkiewicz et al., 2021). Secondly, litter serves as the primary source of C and energy for soil microorganisms. These

microorganisms utilize litter as a substrate for their metabolic activities, primarily through oxidation processes. As a byproduct of their respiration, microorganisms release CO₂, making CO₂ flux a reliable indicator of overall soil microbial activity (Durango et al., 2015; Gomes et al., 2016).

In addition to microbial processes, several climatic factors, including soil moisture, texture, porosity, aggregation, and temperature, and amount and type of litterfall (Walkiewicz et al., 2021), can influence soil respiration. Consequently, these factors can also impact CO₂ diffusion, production, and transport to the soil surface (Gomes et al., 2020).

Considering the complexity of factors influencing CO₂ fluxes in ecosystems, their characterization is an informative variable to understand soil CO₂ dynamics of soil under different management systems. This is especially important for coffee production in Costa Rica, given its contribution to the economy and society. Coffee represents more than 20% of the country's agricultural land (93 774 ha) (ICAFE, 2023) with an important production on AFS, additionally the sector is focused on strategies that contribute to soil recarbonization and environmental sustainability as the National mitigation Appropriated Actions (NAMA) program and RECSOL protocol.

Knowledge about soil CO₂ emissions in the different coffee production systems is fundamental since changes in soil can alter the respiration rates as well as soil C sequestration rates. Therefore, this study determines the dynamics of soil CO₂ fluxes from a coffee in agroforestry system (AFS) in contrast to a coffee production in a full sun system (FSS) during three annual cycles, using the chamber methods directly from the soil.

Methodology

Study site

The research was conducted at La Hilda Farm, in Poás, Alajuela, Costa Rica (10.0893° N 84.235088° W) at 1210 m.a.s.l from January 2021 to December 2023. The site is in the west area of the Central Valley, which is under a strong influence of the Intertropical Convergence Zone (Chinchilla-Soto et al., 2021). The study was conducted in two nearby plots (Figure 1), previously described by Monge-Muñoz et al., (2025). Both plots are on Andisol, Dystric Haplustands soil and were previously used for sugarcane cultivation. In 1970, coffee was introduced to the incipient agroforestry system (AFS), while the full sun system (FSS) was established in 1982. However, FSS underwent a replanting effort in 2016, replacing its existing coffee plants with the Sarchimor T-5296 variety, while AFS has maintained the Catuaí variety since 1991. Over the past three harvest cycles (2020-2021, 2021-2022, and 2022-2023), FSS exhibited a higher average yield of 63.68 quintals ha⁻¹ compared with AFS with 26.56 quintals ha⁻¹. Both plots have adhered to consistent management practices, including pesticide application, weed control, and liming.

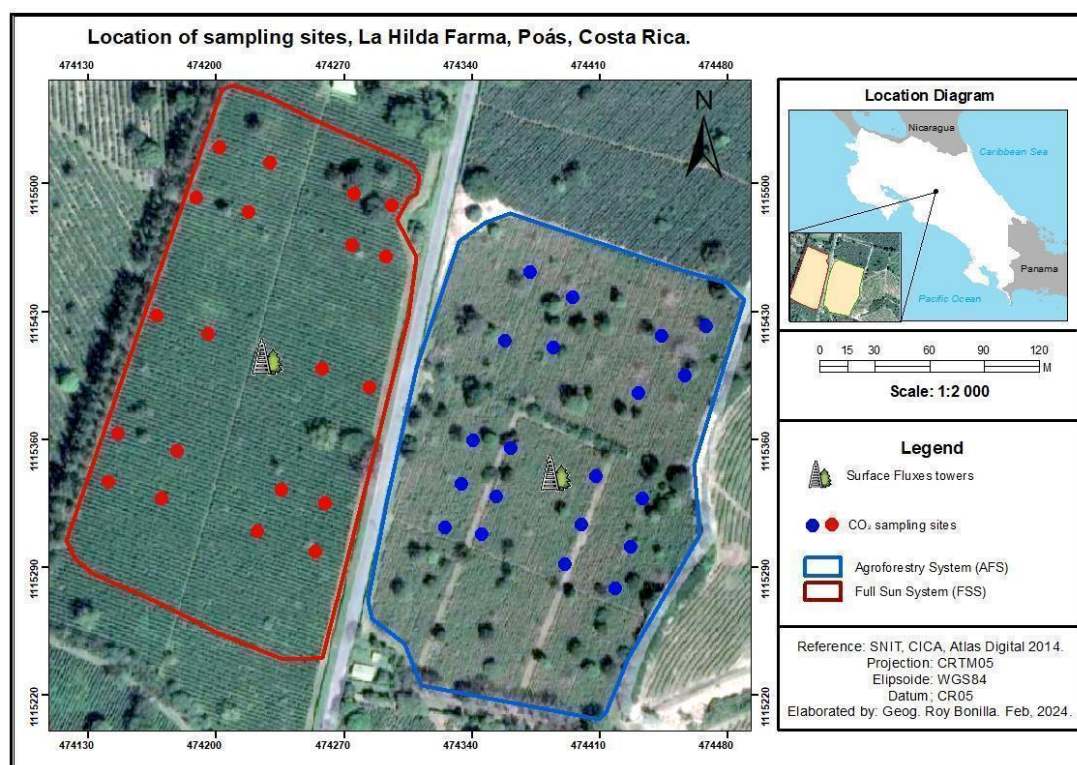


Figure 1. Distribution of sampling points in the full sun system (FSS) (left) and agroforestry system (AFS) (right) at La Hilda Farm, San Pedro de Poás, Alajuela, Costa Rica (Monge-Muñoz et al., 2025).

Environmental conditions

Reference long-term meteorological conditions for the study were provided by a Davis Vantage automatic weather station (AWS) that operated at La Hilda during the 2009-2021 period. During the study period, meteorological variables and surface fluxes were monitored by two surface fluxes towers instrumented with a complete Li-7200RS open path analyzer and Biomet system (LI-COR Environmental, Lincoln, NE, USA), one located in each plot. Data used in this study corresponds to precipitation, temperature, wind speed and soil water content. Soil volumetric water content (SVWC) was determined at two depths: 20 and 40 cm using a HandiTrase TDR soil moisture meter (model 6085K3, USA). A set of stainless-steel rods of 20 and 40 cm lengths were inserted into the ground at 20 points in each plot.

SVWC was measured every 15 days, with the flux measurements. SWVC was used to determine the water filled pore space (WFPS) (Equation 1). The WFPS allows us to evaluate the relationship between water and air in the soil, a crucial factor for root respiration and microbial activity.

$$WFPS (\%) = \frac{SWVC}{1 - \frac{\rho_b}{\rho_s}} \times 100 \quad \text{Equation 1}$$

Where, $SWVC$ (m^3/m^3), ρ_b = bulk density (g/cm^3), ρ_s = particle density (g/cm^3)

Soil CO₂ fluxes

For soil flux measurements, CO₂ fluxes were measured using a closed chamber system with a Li-Cor 8100 (Li-Cor Inc., Lincoln, NE, USA). 20 PVC anchors were installed in the soil at depth of 12 cm, in each plot. Fluxes were measured at least once a month from January 2021 to January 2024. CO₂ measurements were carried out with a chamber deployment of one minute and three repetitions per anchor, and fluxes were calculated with the standard flux equation using SoilFluxPro™. Simultaneously, soil temperature and moisture were measured with the integrated sensor of Li-Cor 8100. The data was collected in the morning (8:00 am to 12:00 pm). In total, we carried out 56 measurements of soil CO₂ flux at the two plots (in 2021: 16, in 2022: 25 and in 2023: 15).

Data processing

CO₂ data

The processing of CO₂ flux data was carried using the SoilFluxPro™ program. For the data analysis, the criteria to accept the data as valid were only positive values, R^2 greater than 0.99, a measurement time of one minute and three consecutive repetitions of the same point in an approximate range of five minutes and a coefficient variation of 2 % (according to LICOR, 2019). Subsequently, an average was obtained for each measurement point, and finally a general average per sampling campaign

for each plot. The CO₂ flux, F_c , ($\mu\text{mol m}^{-2} \text{s}^{-1}$) was calculated using the following equation (LI-COR Biosciences, 2015):

$$F_c = \frac{10VP_0\left(1 - \frac{W_0}{1000}\right)}{RS(T_0 + 273.15)} \frac{\partial C'}{\partial t}$$

Equation 2

Where, F_c is the CO₂ flow rate ($\mu\text{mol m}^{-2} \text{s}^{-1}$), V is the volume (cm^3), P_0 is the initial pressure (kPa), W_0 is the initial water vapor mole fraction (mmol mol^{-1}), S is the ground surface area (cm^2), T_0 is the initial air temperature ($^{\circ}\text{C}$), $\frac{\partial C'}{\partial t}$ is the initial rate of change in the mole fraction of CO₂ corrected with water ($\mu\text{mol mol}^{-1}$).

Data analysis

The study sites differed in several key factors related to species composition, canopy structure, agronomic management, and previous land use history, conditions that make a classical statistical analysis to compare or find significant differences among sites, unfeasible. For this reason, analyses by individual plots were performed. Soil CO₂ fluxes were analyzed by descriptive statistics. Also, Shapiro-Wilk tests were made to determine the normally distributed data. The comparison of soil CO₂ fluxes between years and plots was carried out by analysis of variance (ANOVA). The Tukey pairwise comparison between observations was used to evaluate the significance of differences in CO₂ values. A p -value ($p < 0.05$) was considered statistically significant. Scatterplots with Pearson correlation matrix were applied to estimate the relationships between CO₂ fluxes and environmental variables. To separate the effect of the seasonality, the data were classified in three seasons: dry season from December to March, first and second legs of the rainy season, from April to July, and August to November, respectively. Principal component analysis (PCA) was conducted using the data of environmental variables to determine the principal components associated with soil CO₂ fluxes and management. All the analyses were performed using Infostat version 2020 and Sigmaplot version 14.5.

The spatial variability of soil CO₂ efflux was characterized for each measurement by calculating the coefficient of variation and interpolation maps were elaborated with ArcGIS version 10.8.1, using the interpolation method of Inverse Distance Weighted (IDW).

Results

Environmental conditions

The study period provided an opportunity to contrast the effects of divergent El Niño-Southern Oscillation (ENSO) phases on Central America. Remarkably, the 2020-2023 period featured an exceptional sequence of three consecutive La Niña events followed by a record-breaking El Niño, accompanied by unprecedented global temperatures (Jiang et al., 2024). The wetter-drier contrast in the study site is shown by the total rainfall of 3610 mm in 2022 (with 108 days recording more than 10 mm of rain), compared with 2021 and 2023, which saw 2700 and 1932 mm of cumulative rainfall respectively (with 81 and 57 days exceeding 10 mm of rain, respectively).

The average air temperature in 2021 was 22 °C (min. 19 to max. 25 °C), in 2022 it was 23 °C (min. 20 °C to max 25 °C), while in 2023, it was 24 °C (with min of 17 to max. 31 °C), showing the consistent temperature increase that characterized the latest El Niño event. Average relative humidity values of 67 %, 66 % and 56 %, respectively in 2021, 2022 and 2023, were consistent with drier conditions under influence of El Niño (Supplementary Material, Figure 1).

CO₂ flux, temperature, and soil moisture dynamics

No significant differences in soil temperature were observed between the production systems. Over the three-year study period, the average soil temperature in FSS was 19.5 °C, while in AFS it was 19.3 °C. The highest soil temperatures were recorded in 2021, and the lowest in 2023, with a difference of only 0.6 °C between the average temperatures. Although the maximum recorded temperature was

similar for both systems (22 °C), the minimum temperature was lower in AFS (16.7 °C) compared with FFS (18.4 °C) (Figure 2a).

Water filled pore space values at 5 cm of depth were consistently higher in AFS compared with FFS. On average, FFS exhibited a WFPS of 20.9 % (range: 4-35 %), while AFS had a mean of 21.8 % (range: 7-33 %). The higher WFPS values in both systems were observed in 2023, with 23 %, compared with 2022 (21 % FFS and 22 % AFS) and 2021 (19 % FFS and 21 % AFS). Is notable the average difference in systems according to season, with WFPS of 15 % during dry season in FFS, whereas in AFS was 19 % (Figure 2c).

Water content decreased with depth, as evidenced by lower WFPS values at 20 cm compared with 5 cm. However, the trend of higher WFPS in AFS persisted at both depths. Average WFPS at 20 cm was 18 % (range: 5-25 %) in FFS and 20 % (range: 8-25 %) in AFS. According to the season, WFPS was 2 % higher in AFS than FFS (Figure 2b).

Although the design does not allow for statistical comparison, (hypothetically, this comparison is made) the average CO₂ fluxes rates did not show statistical differences between systems, but differences were evident within the same system over years. In general, higher CO₂ fluxes were observed in 2023 compared with 2022 and 2021. In AFS, the year 2022 ($3.09 \pm 0.12 \mu\text{mol CO}_2 \text{ m}_2 \text{ s}^{-1}$) had the lowest value and showed statistical differences ($p > 0.05$) with respect to 2021 ($3.69 \pm 0.15 \mu\text{mol CO}_2 \text{ m}_2 \text{ s}^{-1}$) and 2023 ($3.87 \pm 0.16 \mu\text{mol CO}_2 \text{ m}_2 \text{ s}^{-1}$). In FFS, the year 2023 ($3.87 \pm 0.12 \mu\text{mol CO}_2 \text{ m}_2 \text{ s}^{-1}$) exhibit the highest values and showed significant differences when compared with 2021 ($3.35 \pm 0.12 \mu\text{mol CO}_2 \text{ m}_2 \text{ s}^{-1}$) and 2022 ($3.01 \pm 0.10 \mu\text{mol CO}_2 \text{ m}_2 \text{ s}^{-1}$) (Figure 2d).

In general, the fluxes followed the behavior of the rainfall and temperature. In all the years, the first peak of emissions occurred between April and May, corresponding to the water content increment at the beginning of the rainy season (Figure 2d). The maximum CO₂ values were registered in 2023, in

AFS in March ($5.2 \pm 0.2 \mu\text{mol CO}_2 \text{ m}_2 \text{ s}^{-1}$) and in FSS in May ($5.2 \pm 0.1 \mu\text{mol CO}_2 \text{ m}_2 \text{ s}^{-1}$) and the lowest values were registered in January 2022 (AFS, $2.3 \pm 0.1 \mu\text{mol CO}_2 \text{ m}_2 \text{ s}^{-1}$) (Figure 2d).

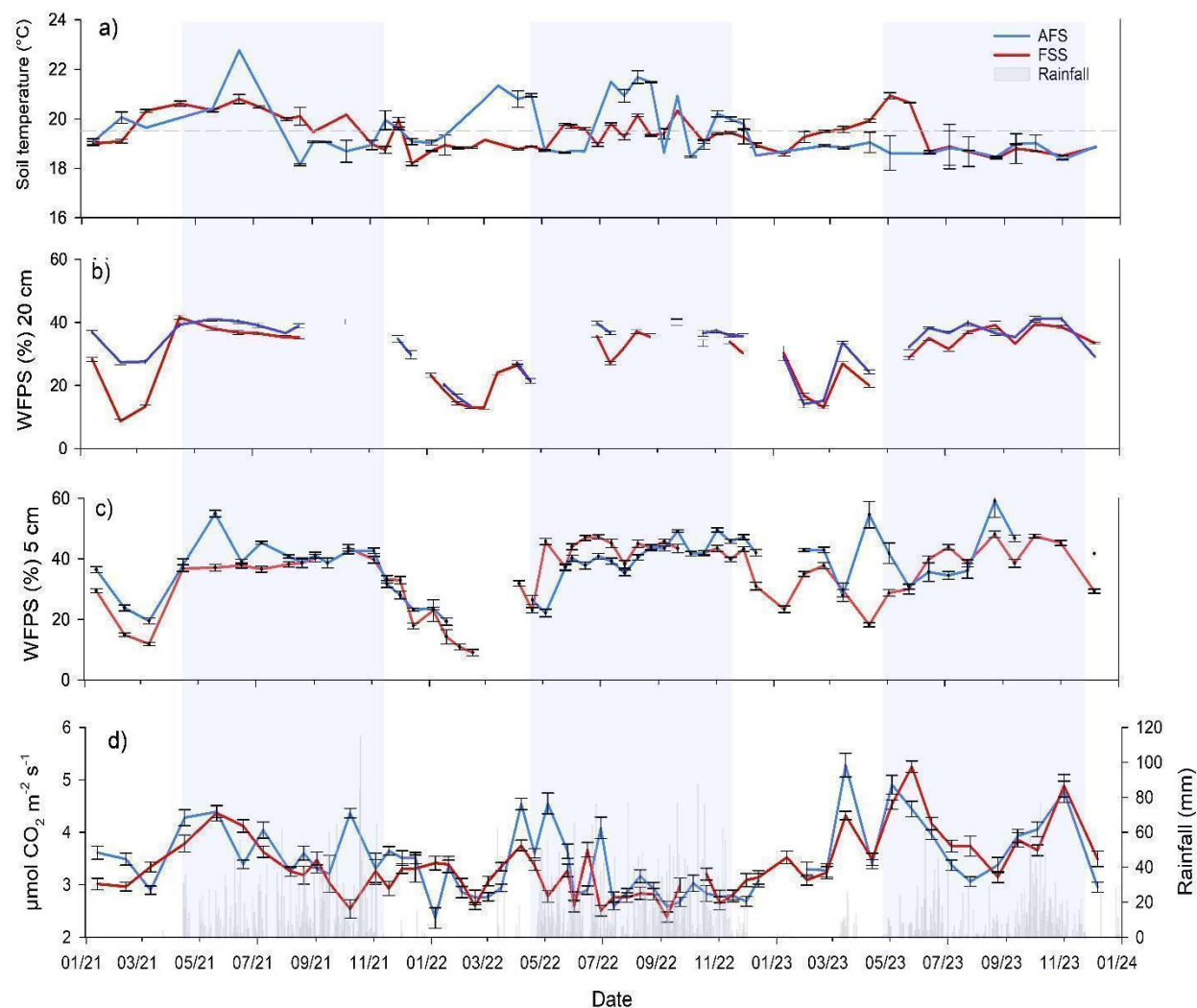


Figure 2. a) Soil temperature ($^{\circ}\text{C}$), b-c) Water-filled pore space at 20 cm and 5 cm, (%) and d) CO₂ flux ($\mu\text{mol CO}_2 \text{ m}_2 \text{ s}^{-1}$) and rainfall (mm) from 2021 to 2023 at La Hilda Farm, in full sun system (FSS = red solid line) and agroforestry system (AFS = blue solid line). Vertical lines represent standard error, $n = 20$.

Most of the CO₂ emissions were registered when soil temperature was between 18 and 22 $^{\circ}\text{C}$ (Figure 3b). CO₂ values ranged between 18 and 20 $^{\circ}\text{C}$ in FSS, and from 17 to 22 $^{\circ}\text{C}$ in AFS. In general CO₂

fluxes tended to be greater in AFS than in FSS, regardless of the soil temperature. Even though CO_2 emissions tended to increase with rainfall amount (Figure 3a) and WFPS, the results suggest a non-linear relationship among these variables, across all seasons for both land-use systems (Figure 3c and 3d). WFPS also does not show any linear relationship with respect to CO_2 , at both depths; 5 and 20 cm of depth (Figure 3c and 3d).

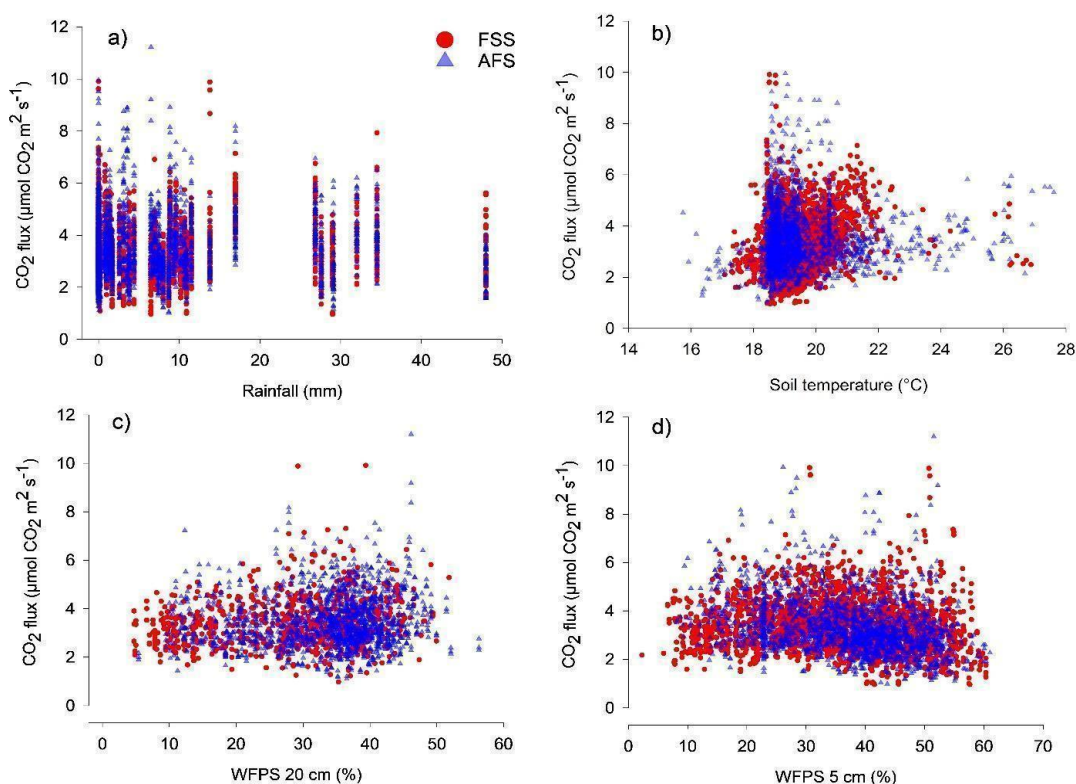


Figure 3. Relation between CO_2 fluxes and a) rainfall (mm), b) soil temperature ($^{\circ}\text{C}$), c) water-filled pore space (%) at 20 cm and d) water-filled pore space (%) at 5 cm from 2021 to 2023 at La Hilda Farm, in full sun system (FSS = red dots) and agroforestry system (AFS = blue triangles).

To further explore the relationship between CO_2 fluxes and WFPS, data was analysed seasonally, however no significant differences were observed among these two variables. despite WFPS increasing

throughout the season (Figure 4a, 4b and 4c). Almost all CO_2 values fluxes ranged from 2 to 6 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$.

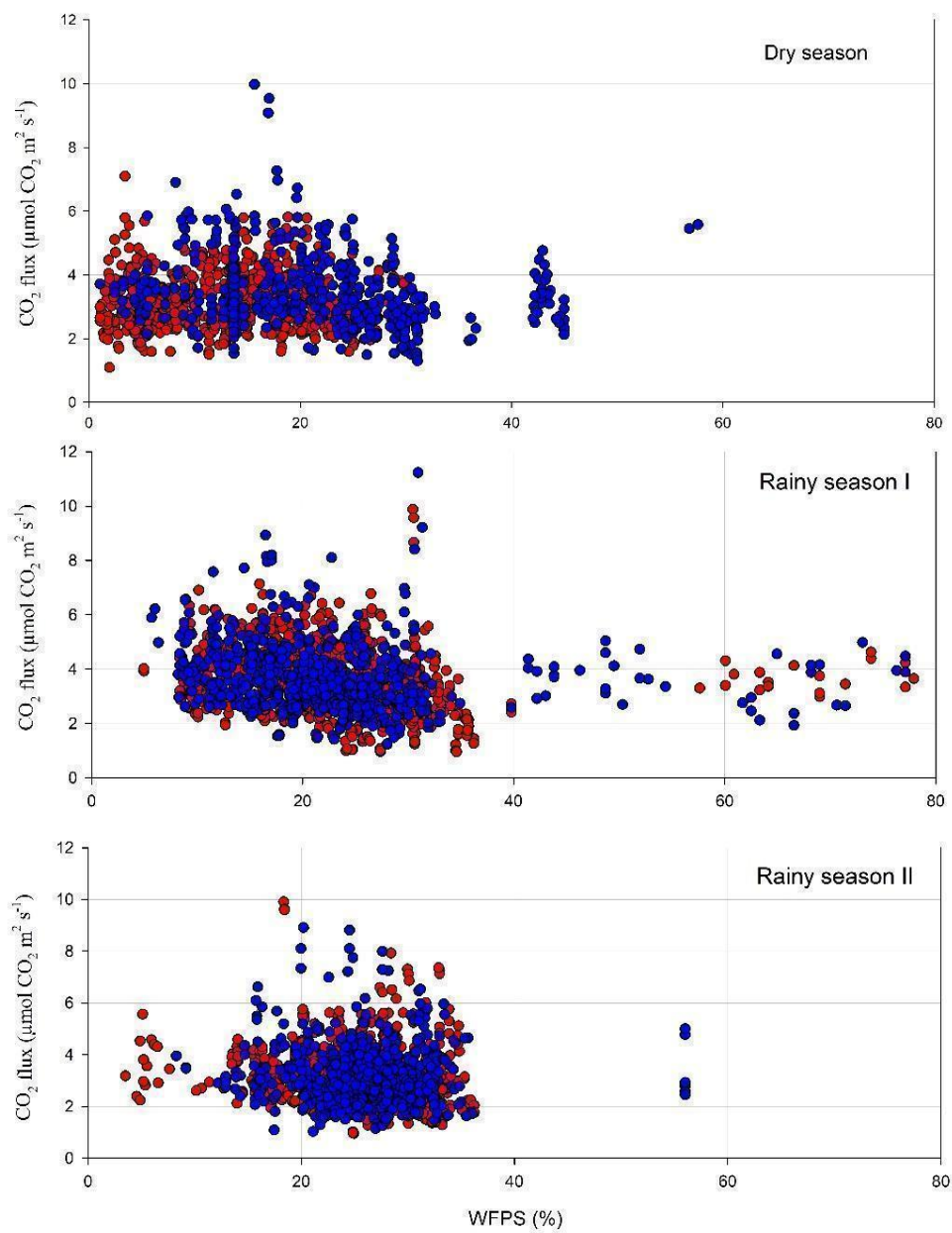


Figure 4. Relation between CO_2 fluxes and water-filled pore space (%) at 5 cm of soil depth in a) dry season from December to March, b) First rainy season from April to July and c) second rainy season from

August to November, from 2021 to 2023 at La Hilda Farm, in full sun system (FSS = red dots) and agroforestry system (AFS = blue dots).

Influence of climatic variables on CO₂ fluxes

Principal component analysis (PCA) showed that for CO₂ flux variation in the AFS, the first two components explain 74.63 % of the total variance. Component 1 had higher loading of RH (0.46), VPD (-0.43), ET (-0.41) whilst Component 2 was more influenced by soil humidity at 5 cm (0.46), AT (0.45) and rainfall (0.45) (Figure 5a). For the PCA in FSS, the first two components explained up to 60.86% with VPD (0.50), AT (0.43) and AP (0.36) being more relevant in the loadings (Figure 5b). However, for FSS as the first two axis explain less than 80% this suggest that the variability of the data is due to a high amount of variables.

Regarding to the correlation matrix, in AFS the CO₂ flux showed a positive correlation un the ET (0.33), AT (-0.47) and soil humidity at 5 cm (-0.45). In FSS, AP (0.41) and ST at 5 cm depth (0.34), variables that positively correlated, whereas ET (-0.27) and WFPS at 5 cm (-0.17) exhibited strong negative correlations (Detail in Supplementary Material Table 1). The variables soil humidity at 20 cm (20) and RH showed a low correlation with CO₂ in both systems. In both systems, rainfall and WFPS at 5 cm seemed to be inversely proportional to CO₂ emissions, indicating that wetter soils tend to emit less CO₂.

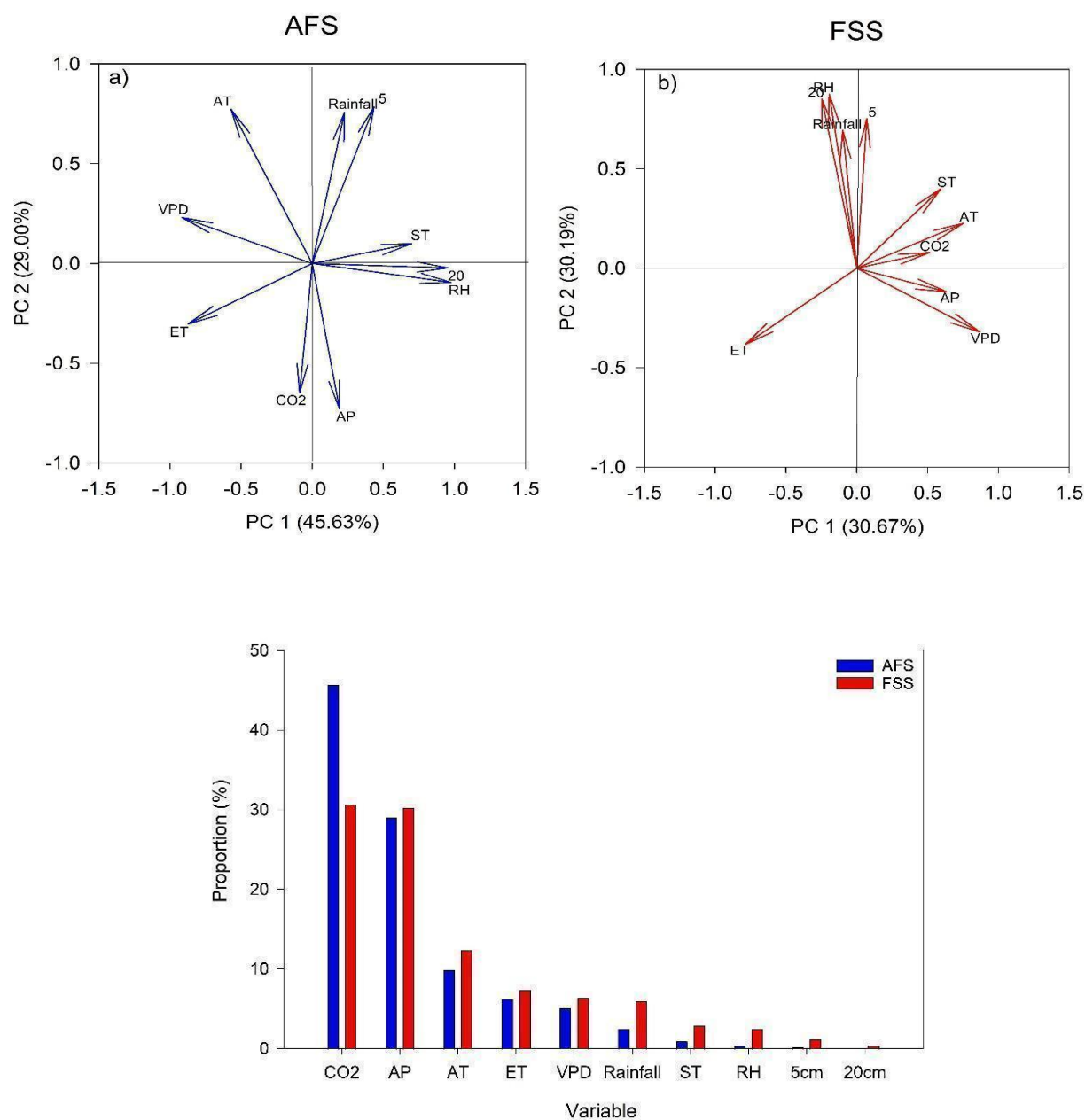


Figure 5. a) Biplot in Coffee Agroforestry system (AFS), b) Biplot Coffee at Full Sun System (FSS), and c) Accumulated variance (%) of Principal components analysis (PCA) for CO₂ fluxes and climatic variables for a period of three years at La Hilda Farm, Alajuela, Costa Rica. AP=air pressure, AT= air temperature, ET=evapotranspiration, VDP= vapor deficit pressure, ST = soil temperature at 5 cm depth, RH= relative humidity, 20= WFPS at 20 cm depth, 5= WFPS at 5 cm depth.

Spatial variability of CO₂ fluxes

The CO₂ flux spatial distribution tended to be higher in the northern section of the plots in both AFS and FSS and varied throughout the study (Figure 6). The spatial variation in the soil CO₂ efflux (expressed as the coefficient of variation – CV) was higher in AFS than in FSS during the three years of the study. FSS showed values of 27, 30 and 30 % while AFS exhibited CV values of 29, 34 and 32 % for 2021, 2022 and 2023 respectively. The year 2021 showed the lowest variability data compared with 2022 and 2023, during these years data variability was moderate to high.

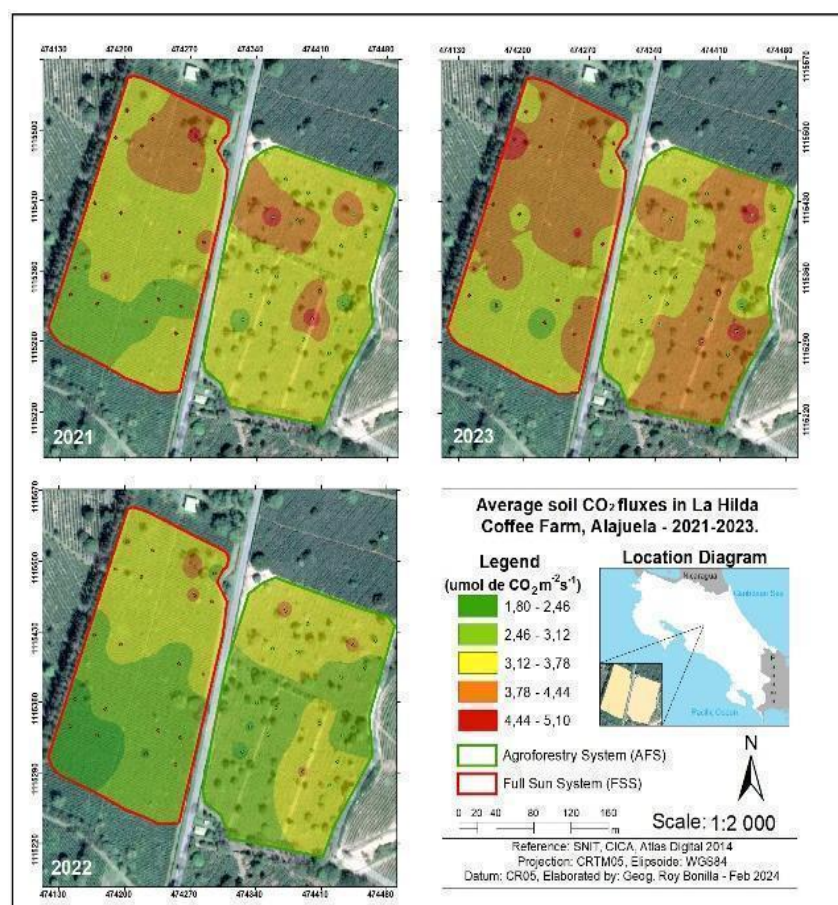


Figure 6. Annual average soil CO₂ flux dynamics ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) by year from 2021 to 2023 in full sun system (FSS = left plot) and agroforestry system (AFS = right plot) at La Hilda Coffee Farm.

Discussion

Climatic drivers of CO₂ fluxes

Our study period (2021-2023) was subject to important variations in the ENSO phenomenon; however, this did not translate into high inter-annual variability in CO₂ fluxes (Figure 3d) except in 2023 although it was not statistically significant. The findings did not support our initial hypothesis, since no significant differences in soil CO₂ flux were observed in any of the coffee systems (FSS or AFS) despite the substantial influence of ENSO on regional precipitation, with El Niño typically leading to decreased rainfall and heightened drought risk along the Pacific coast of Central America, where our study area is located (Pascale et al., 2021; Sánchez-Murillo et al., 2017; Sánchez-Murillo et al., 2023), and with la Niña generating conditions often associated with increased precipitation in the region (Quesada-Román et al., 2021; Huguenin et al., 2023).

In both coffee systems, CO₂ emissions exhibited a clear seasonal pattern that increased with the onset of rainfall and decreased when the rain season was established (Figure 4). CO₂ fluxes were significantly influenced by climatic factors, particularly soil moisture and temperature, which are closely tied to precipitation, but specially regulated by WFPS (Costa et al., 2018).

Although our study period may have been too short to observe notable changes in soil CO₂ fluxes related to ENSO, it's well-established that soil carbon dynamics can be more responsive to climate change in areas experiencing more extreme climate shifts. For instance, regions undergoing rapid warming or significant alterations in precipitation patterns often exhibit more pronounced changes in soil CO₂ emissions.

While temperate zones undergo substantial seasonal temperature fluctuations, tropical regions maintain a relatively stable climate, with average temperatures ranging from 16 to 26 °C, creating a stable environment. Furthermore, short dry seasons of only five months and frequent rainfall throughout the year contribute to consistent climatic patterns. As a result, CO₂ emissions exhibit less variability

compared to temperate zones with more pronounced seasonal changes. As Davidson et al., (2000) indicate, the temperature effect over CO₂ fluxes is often more pronounced than the water effect, especially in temperate and boreal regions. The sensitivity of heterotrophic respiration to climate variability differs across climate zones, suggesting that carbon loss rates from heterotrophic respiration vary by region (Tang et al., 2020).

Soil CO₂ emissions are generally considered as instantaneous soil respiration. While this holds true in the long term, short-term fluctuations can occur due to changes in CO₂ storage within the soil pore space. This pore space acts as a “buffer” or reservoir for CO₂, influencing the observed emissions (Maier et al., 2011). Pre-dry season rainfall events can stimulate biological activity, leading to increased CO₂ efflux. However, as the rainy season progresses, waterlogging can reduce topsoil diffusivity, hindering CO₂ diffusion and causing it to accumulate within the soil (Maier et al., 2011; Yu, 2020). This stored CO₂ may be subsequently released during dry periods, potentially explaining the CO₂ emission peak observed in 2023, which followed a year of increased rainfall in 2022 (Figure 2).

Soil respiration originates primarily from two sources: autotrophic respiration (from roots) and heterotrophic respiration (from decomposers). However, distinguishing between the two remains challenging (Hanson et al., 2000; Zheng et al., 2021). An increase in CO₂ flux with rising soil moisture typically indicates that heterotrophic respiration by soil microorganisms is the dominant source. This is because soil moisture levels above 60 % WFPS have been identified as a threshold for optimal microbial activity; beyond this threshold, reduced oxygen availability inhibits microbial processes, leading to decreased activity (Zheng et al., 2021). In our study, the 60 % WFPS threshold was only reached during the initial phase of the rainy season. However, this did not significantly affect CO₂ emissions, suggesting other factors influencing soil respiration during this period.

Climatic factors play a significant role in regulating soil CO₂ fluxes by influencing the rate at which this gas is released into the atmosphere (Smith et al., 2018). In addition to soil moisture and air temperature (previously discussed), additional factors such as vapor pressure deficit (VPD), atmospheric pressure (AP), air humidity, evapotranspiration (ET), and wind speed are key drivers of soil respiration. These factors crucially regulate soil moisture content, which directly impacts microbial activity and carbon mineralization processes. Although VPD, AP, and AT were higher in FSS as compared with AFS, the differences were not reflected in soil CO₂ flux measurements. However, at the ecosystem level, VPD plays a pivotal role in C cycle dynamics by mediating soil-plant-atmosphere interactions. VPD is closely linked to soil water content and water use efficiency (Wang et al., 2024), both of which can be significantly influenced by the microclimate condition present in agroforestry systems.

Although soil moisture is directly affected by rain, it does not always respond proportionally, since there are other factors that can mediate in this reaction, such as soil physical properties, vegetation structure, and soil cover (Yu, 2020). Particularly, soil texture plays a crucial role in CO₂ fluxes, since it affects water retention capacity by influencing pore size distribution and organic matter retention. The relative proportions of clay, sand, and loam control the rate of gas diffusion, contributing to creation of CO₂ concentration gradients within the soil profile (Yang et al., 2018). In La Hilda, the soils are Andisols with deep profiles, high sand content (60-80 %), good structure and porosity and high infiltration rates, which result in an adequate drainage with little to no waterlogging, which explains the similar WFPS values and similar CO₂ fluxes observed in both sites (Monge-Muñoz et al., 2025).

Another important soil property that regulates CO₂ flux is C content. Although there were no CO₂ flux differences among plots (Figure 2d), there is a trend towards greater CO₂ fluxes in the AFS, which suggests the presence of faster C recycling process that translates into shorter residence of C in soil. This is consistent with the low content of soil carbon stock at 0-30 cm of depth in AFS ($138 \pm 4 \text{ Mg C ha}^{-1}$) as

compared with FSS ($169 \pm 4 \text{ Mg C ha}^{-1}$) (Monge-Muñoz et al., 2025). A similar result was reported by Lopes et al., (2024), who found lower C concentrations in an AFS as compared with FSS.

Similarly to our findings, Gomez, et al. (2016) and Lopes et al., (2024) did not report differences in mean soil CO_2 flux when comparing AFS vs. FSS in a coffee plantation. They reported values from 2.39 to $8.95 \mu\text{mol CO}_2 \text{ m}^2 \text{ s}^{-1}$ and 1.5 to $3.12 \mu\text{mol CO}_2 \text{ m}^2 \text{ s}^{-1}$ respectively for the two systems, comparable to our findings (1.69 to $6.42 \mu\text{mol CO}_2 \text{ m}^2 \text{ s}^{-1}$). Both studies found a positive correlation between CO_2 and soil temperature and negative correlation with total organic carbon, while our study only showed a positive correlation between CO_2 and ST at the 5cm depth in the FSS.

Also, consistent with previous research (Courtois et al., 2018; Qiu et al., 2020), in our study we found that soil CO_2 fluxes exhibited high spatial variability, with a coefficient of variation (CV) ranging from 23 % to 34 %. Despite this variation, the CO_2 fluxes were similar between the two plots analyzed. The spatial distribution of soil CO_2 fluxes (Figure 6) revealed distinct hotspots, which were strongly associated with areas of consistently higher soil moisture, particularly during drier years (2021 and 2022)

Topography and altitude also influenced soil CO_2 efflux. Higher altitudes are generally correlated with reduced soil CO_2 emissions (Wang et al., 2011; Kopp et al., 2023). In this study, altitude ranged from 1215 m in FSS to 1192 m in AFS, with a 23-meter difference observed from northwest to southeast across the plots. This variation in altitude and slope likely contributed to the observed spatial heterogeneity, as complex terrain can rapidly alter the distribution of soil moisture through preferential flow paths that redistribute rainwater (Supplementary Material Figure 2).

Additionally, complex terrain influences other factors such as soil temperature, lateral movement of water, and redistribution of sediments, nutrients, and C. These processes, in turn, affect soil CO_2 flux. Kopp et al., (2023) found significant relationships between topography and soil organic C

storage; these findings link topography to the spatial distribution of C fluxes and the dynamics of soil C storage.

Finally, an important factor to consider in AFS is the density, development, canopy arrangement, and age of the trees. In this study, tree density was relatively low, approximately 30 trees ha⁻¹, likely resulting in lower shade cover, a factor not explicitly evaluated in this research.

CO₂ fluxes in the agroecological concept

Structural configuration of the agroecosystems; type of plantation and management (AFS or FSS), influence CO₂ soil fluxes and vegetation's response to moisture fluctuations; drought stress may limit soil heterotrophic respiration by reducing the spread of organic solutes from soil to microbial community and the number and size of soil microbial populations. AFS, with their diverse plant communities, can enhance soil moisture regulation through processes like litter input and deeper root systems. Additionally, factors such as underground biomass and soil moisture directly influence soil respiration rates (Zheng et al., 2021).

The quantity and quality of litterfall, influenced by plant diversity in AFS, can significantly impact soil C dynamics. A diverse plant community can provide a continuous supply of fresh organic matter by litter deposition, reducing the pressure on soil microbial communities to decompose recalcitrant soil organic C reserves. By utilizing the readily available fresh organic matter, microbes can maintain their activity without depleting the more stable soil organic C pool. This mechanism becomes particularly important during drought stress, when high temperatures and water scarcity can lead to microbial mortality and reduced soil respiration. Dry conditions also induce osmotic stress in soil microbial communities, which restricts the production of extracellular enzymes necessary for organic matter decomposition, thereby further reducing CO₂ emissions (Costa et al., 2018). Additionally, the reduction in

topsoil diffusivity during dry periods limits oxygen availability, which is essential for bacterial decomposition and CO₂ release.

Under such conditions, the temperature sensitivity of soil organic C decomposition may increase as microbes are forced to rely on more recalcitrant C sources. When precipitation events occur, surviving microbes can quickly resume activity, resulting in a surge in heterotrophic soil respiration. This dynamic underscores the complex interactions between drought, microbial activity, C cycling, and CO₂ fluxes, particularly in ecosystems subjected to seasonal rainfall variability (Kruse et al., 2013).

Although no significant differences were found among sites in CO₂ fluxes, differences in above ground biomass could also play an important role in our results as C fixation rates by plants and this is reflected in an increased production of both above- and below-ground biomass. Roots, by growing and releasing exudates, stimulate soil microbial activity, favoring the decomposition of organic matter and the formation of stable aggregates, which in turn increases the soil's capacity to sequester C (Nair et al., 2015). In this study leaf area index (LAI) was used as a proxy for biomass, as higher LAI translates into a greater photosynthetic capacity, allowing plants to capture more CO₂ from the atmosphere. LAI tended to be higher in FSS (from 4 to 6) compared to AFS (0.8 to 5) (Montero, 2022), likely due to the age and vigor of the coffee plantations. FSS plantations were younger (Sarchimor T-5296, year 2016) and more vigorous than AFS plantations (Catuaí, year 1991), this is further supported by higher soil C content in FSS (Monge-Muñoz et al., 2025), although as previously discussed there are many mechanisms that interfere in how fixed CO₂ by plants eventually transforms in respired CO₂ (Nair et al., 2015).

In a climate change context, altered precipitation and evapotranspiration patterns can significantly influence microbial activity and soil C dynamics. More frequent and intense drying-wetting cycles can accelerate the decomposition of labile organic matter, potentially leading to a loss of soil C. However, microclimates created by agroforestry systems, with their diverse vegetation and complex

structure, can help mitigate these effects by providing more stable moisture conditions and promoting the formation of physically and chemically protected soil C pools (Kruse et al., 2013; Zheng et al., 2021). In fact, in this study soil moisture tended to be higher on average in AFS compared with FSS (24 % and 21.3 % at 20 cm depth, respectively) (Monge-Muñoz et al., 2025), highlighting the potential of these systems to buffer soil against the adverse impacts of altered hydrological cycles.

Conclusions

The CO₂ efflux was similar in the Agroforestry (AFS) and Full sun system (FSS) coffee systems, the shade provided by then incipient AFS, with low tree density did not have an impact in the soil CO₂ efflux.

A deep understanding of the complex interactions between climate and land-use systems is essential for accurately modeling soil CO₂ fluxes, predicting the global carbon cycle, and assessing the impacts of climate change.

The length and frequency of precipitation events can be as influential as, or even more than, seasonal variations in total rainfall in regulating soil CO₂ flux and other aspects of the carbon cycle, underscoring the complexity of ecosystem responses to climate change.

The absence of clear differences in soil respiration between AFS and monocultures suggests that other factors, such as microbial community composition or soil organic carbon stability, might be more sensitive to management practices. The fact that no statistical differences in soil respiration between systems were found does not invalidate the complexity and heterogeneity of the processes occurring in these systems. Agroforestry offers a multitude of species interactions and ecosystem processes that can influence other aspects of the carbon cycle and soil health beyond respiration rate. The multifunctional benefits of these systems make them a key strategy for sustainable natural resource management.

The relatively short duration of our study likely limited our ability to detect significant changes in soil CO₂ fluxes in response to the interannual variability of the ENSO. Detecting such subtle responses often requires long-term monitoring efforts that capture multiple ENSO cycles, allowing for a more

robust assessment of the influence of this climate phenomenon on the relatively short duration of our study likely limited our ability to detect significant changes in soil CO₂ fluxes.

Acknowledgments

We thank José Miguel Araya, Cristian Porras, Eddy Valle, Federico Montero, Raquel Ramírez and other staff at the Fabio Baudrit Experiment Station; and Giovanni Mora, Yamilka Corrales, Roy Bonilla, Jorge Mora, Grattia Corrales, for the support in the measurements. Special thanks to Mariano Vargas and Grupo Santa Eduvigis for their field support. The authors acknowledge the support of the UCR special grant for research groups under project C0454, C2059, C3651 and the Vice Chancellor Office of Research and of Administration for additional support for equipment installation in the field.

Statements and Declarations

Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be constructed as a potential conflict of interest.

Data Availability Statement

The datasets generated throughout this study are available from the corresponding author by request.

Funding

Universidad de Costa Rica, Vicerrectoría de Investigación. Project C0454: Flujos de carbono y eficiencia en el uso del agua en agroecosistemas cafetaleros innovadores. Project C2059 CARBOSEC: Evaluación del efecto de tres formas de manejo contrastantes de un cultivo de café en la actividad

biológica y la capacidad de secuestro de carbono del suelo. Project C3-651 DIC2AFE: Dinámica de la captura de carbono en agroecosistemas cafetaleros innovadores.

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Capítulo V: Conclusiones y Recomendaciones

Conclusiones

Este estudio resalta la complejidad de la acumulación de carbono en el suelo, en la que interactúan múltiples factores como la densidad de siembra del cultivo y el arreglo espacial del sistema agroforestal, las especies que conforman el SAF, la calidad y cantidad de hojarasca, las propiedades del suelo, el historial de uso del suelo y las condiciones ambientales. Algunas de las conclusiones más relevantes del estudio son:

1. La diversificación de árboles de sombra en los sistemas agroforestales ofrece numerosos beneficios ambientales (como reducción de la erosión del suelo, la regulación del microclima, y el aumento de la biodiversidad, entre otros), pero la selección de árboles debe considerar cuidadosamente sus propiedades de descomposición. Las tasas de entrada de hojarasca y las relaciones C/N influyen significativamente en la acumulación de carbono del suelo, demostrando la importancia de comprender estos mecanismos de retroalimentación.
2. Si bien los contrastantes historiales de manejo de los sitios de estudio pueden haber limitado la detección de diferencias significativas en los reservorios de carbono del suelo, la ausencia de diferencias inmediatas destaca el potencial de cambios a largo plazo en la acumulación de carbono del suelo bajo diferentes sistemas de manejo.
3. Nuestros resultados resaltan la importancia de considerar múltiples factores más allá de la presencia de árboles para comprender la dinámica del carbono del suelo en sistemas agroforestales.
4. Aunque no se encontraron diferencias significativas en los flujos de CO₂ del suelo entre los dos sistemas, este hallazgo resalta la complejidad y de los sistemas agroforestales. La etapa inicial de desarrollo de los sistemas agroforestales, con baja densidad de árboles, no tuvo un impacto

significativo en el flujo de CO₂ del suelo en comparación con los sistemas a pleno sol, pero la modulación observada en algunas de las propiedades evaluadas (CO₂, humedad del suelo y temperatura) subraya la importancia de los SAF para la mitigación del cambio climático, la conservación del suelo y los servicios ecosistémicos a largo plazo. Además, el estudio demuestra la necesidad de monitoreos a largo plazo para capturar las respuestas de los flujos de CO₂ del suelo a la variabilidad climática, como las impulsadas por la Oscilación Sur del Niño.

5. El período de análisis, que abarcó fases contrastantes de ENSO, proporcionó valiosos conocimientos sobre cómo estos eventos climáticos a gran escala pueden influir en la dinámica del carbono dentro de los sistemas agroforestales y los sistemas a pleno sol. Esto subraya la importancia de comprender cómo las variaciones locales en precipitación y temperatura interactúan con las prácticas de manejo sobre la dinámica del carbono del suelo.

Recomendaciones

1. Para garantizar una comparación sólida estadísticamente, los sistemas de manejos del café idealmente deberían iniciarse bajo condiciones similares.
2. Para obtener una comprensión más completa de los procesos de descomposición de la hojarasca, futuros estudios deberían investigar la diversidad funcional y la abundancia de organismos descomponedores, lo que podría proporcionar información valiosa sobre sus roles en la descomposición de la hojarasca y sus posibles impactos en la dinámica del carbono del suelo.
3. La duración relativamente corta de nuestro estudio probablemente limitó nuestra capacidad para detectar cambios significativos en los flujos de CO₂ del suelo en respuesta a la variabilidad interanual de ENSO. La detección de estas respuestas a menudo requiere

esfuerzos de monitoreo a largo plazo y con una mayor frecuencia que capturen múltiples ciclos de ENSO, permitiendo una evaluación más robusta de la influencia de este fenómeno climático.

4. El empleo de técnicas de isótopos estables, como el uso de ^{13}C , puede proporcionar información valiosa sobre los efectos a largo plazo de diferentes prácticas de manejo sobre los reservorios de carbono del suelo. Este enfoque puede ayudar a dilucidar los impactos acumulativos de estas prácticas a lo largo del tiempo, por ejemplo, para rastrear las fuentes de carbono, el movimiento y el almacenamiento de carbono en el suelo.

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Anexos

Anexo 1. Supplementary Information. Litter dynamics and soil carbon stock in a coffee agroforestry system in Costa Rica

Table 1. Tree species in the coffee agroforestry system at Finca La Hilda, Poás, Alajuela.

Common name	Scientific name	Family
Aguacatillo	<i>Persea caerulea</i>	Lauraceae
Aguacatillo ascá	<i>Ocotea insularis (Meisn.) Mez.</i>	Lauraceae
Anono	<i>Annona squamosa</i>	Annonaceae
Cedro	<i>Cedrela sp.L</i>	Meliaceae
Chapermo	<i>Lonchocarpus costaricensis</i>	Fabaceae
Dantisco	<i>Mauria heterophylla</i>	Sapindaceae
Guarumo	<i>Cecropia peltata L.</i>	Urticaceae
Guayaba	<i>Psidium sp</i>	Myrtaceae
Híguito	<i>Ficus pertusa</i>	Moraceae
Jinocuabe blanco	<i>Bursera sim aruba</i>	Burseraceae
Laurel Blanco	<i>Cordia alliodora(Ruiz y Pav.) Oken</i>	Boraginaceae
Limón mandarino	<i>Citrus x limonia Osbeck (Pro SP.)</i>	Rutaceae
Llama del bosque	<i>Spathodea campanulata P. Beauv.</i>	Bignoniaceae
Lorito	<i>Cojoba arborea</i>	Fabaceae
Naranja malagueña	<i>Citrus Xsinensi (L.)</i>	Rutaceae
Poró real	<i>Erytnnina poeppiguiana</i>	Meliaceae

Table 2. Soil chemical characterization of coffee plots in the full sun system (FSS) and agroforestry system (AFS), at Finca La Hilda (n=1, composite sample). November 2021.

Soil characteristics	FSS	AFS
pH	5.3	5.2
Acidity	0.74	0.47
Ca (cmol+)/L	2.42	2.65
Mg (cmol+)/L	0.59	0.77
K (cmol+)/L	0.25	0.36
CICE (cmol+)/L	4.00	4.25
SA %	19	11
P mg/L	3	2
Zn mg/L	4.7	1.9
Cu mg/L	9	7
Fe mg/L	93	86
Mn mg/L	14	11
CE (mS/cm)	0.2	0.3

Table 3. Soil physical characteristics at tree depth in full sun system (FSS) and agroforestry system (AFS) plots at La Hilda Farm. n=5. $\pm$ represent the standard error.

Soil characteristics	Depth	FSS	AFS
Bulk density (g cm ⁻³)	0-5	0.62 $\pm$ 0.007	0.64 $\pm$ 0.009
	5-15	0.66 $\pm$ 0.02	0.65 $\pm$ 0.02
	15-30	0.65 $\pm$ 0.02	0.63 $\pm$ 0.02
Porosity (%)	0-5	72.32 $\pm$ 0.43	75.40 $\pm$ 0.30
	5-15	71.17 $\pm$ 0.34	71.92 $\pm$ 0.32
	15-30	71.88 $\pm$ 0.89	72.50 $\pm$ 0.31
WFPS	0-5	61 $\pm$ 1.13	62 $\pm$ 0.46
	5-15	64 $\pm$ 1.02	60 $\pm$ 0.83
	15-30	62 $\pm$ 0.66	62 $\pm$ 0.68

Table 4. Litterbags decomposition rate (k) (g d^{-1}) of *C. arabica* and *O. insularis* in 2022 and 2023 at La Hilda Farm in full sun system (FSS) and agroforestry system (AFS). $\pm$ represent standard error. Different letters indicate significant differences by Tuckey test ($p < 0.05$) between leaves of the same season.

Decomposition rate (k)	2022		2023	
	Dry season (g d^{-1})	Rainy season (g d^{-1})	Dry season (g d^{-1})	Rainy season (g d^{-1})
<i>C. arabica</i> - FSS	$0.004 \pm 0.0003a$	$0.007 \pm 0.0001b$	$0.002 \pm 0.0004a$	$0.005 \pm 0.0003a$
<i>C. arabica</i> - AFS	$0.003 \pm 0.0002b$	$0.006 \pm 0.0004b$	$0.004 \pm 0.0003b$	$0.007 \pm 0.0004b$
<i>O. insularis</i> - AFS	$0.003 \pm 0.0003ab$	$0.003 \pm 0.0003a$	$0.004 \pm 0.0002ab$	$0.004 \pm 0.0005a$

Table 5. Lignin, carbon, and nitrogen content of *C. arabica* and *O. insularis* at 0 and 90 days of decomposition in full sun system (FSS) and agroforestry system (AFS), at La Hilda Farm, 2022. (Lignin: $n=3$, C and N: $n=1$).

Specie - Plot	% Lignin ($n=3$)	% C	Day 0		Day 90		
			% N	C/N	% C	% N	C/N
<i>C. arabica</i> - FSS	2.72 ± 0.16	47.7	2.9	16	39.3	3.7	10
<i>C. arabica</i> - AFS	2.40 ± 0.56	48.6	2.7	18	49.0	5.2	9
<i>O. insularis</i> - AFS	2.67 ± 0.08	49.6	2.3	21	48.7	3.2	15

Table 6. Microbial biomass (mg C/kg soil) at La Hilda Farm in full sun system (FSS) and agroforestry system (AFS) in July and November. $n=5$. $\pm$ represents the standard error.

Month	FSS (mg C/kg soil)	AFS (mg C/kg soil)
Jul	298 ± 13	294 ± 16
Nov	386 ± 28	264 ± 14

Anexo 2. Supplementary Information Dynamics of soil CO₂ flux of coffee agroforestry and full-sun coffee tropical systems

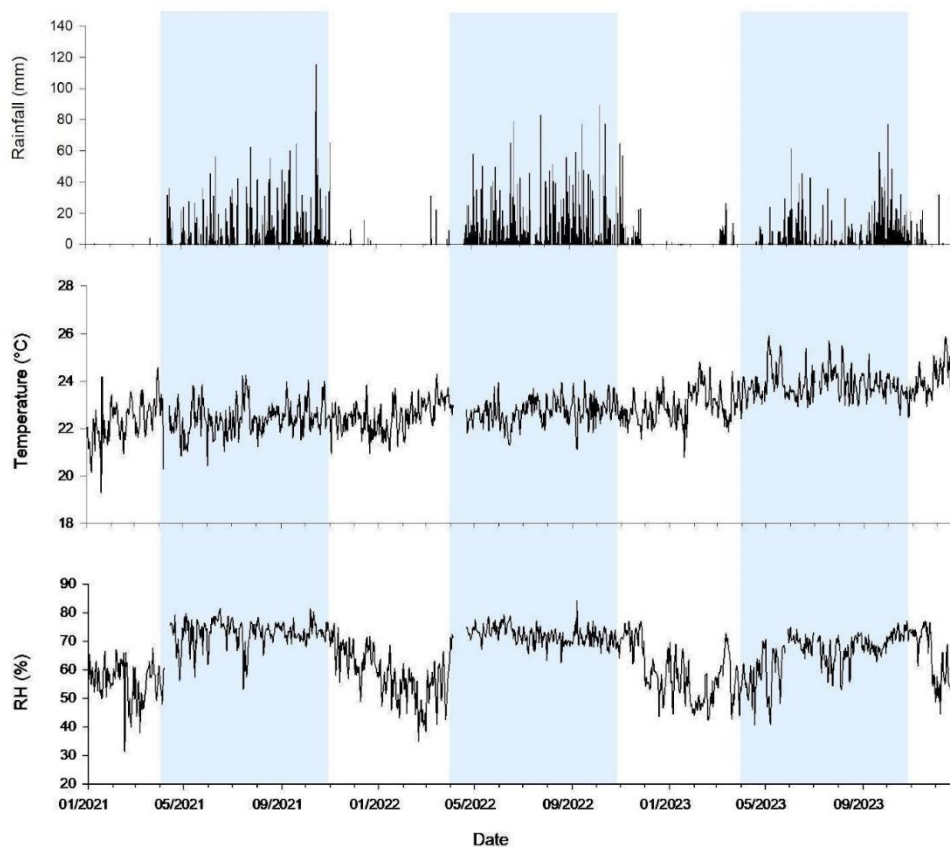


Figure 1. Daily rainfall (mm), air temperature (°C) and relative humidity (%) at La Hilda Farm, Alajuela.

Data from Jan 2021 to December 2023. Shared areas represent the rainy season. Data from 2022 to 2023 was describe by Monge et al., (2024).

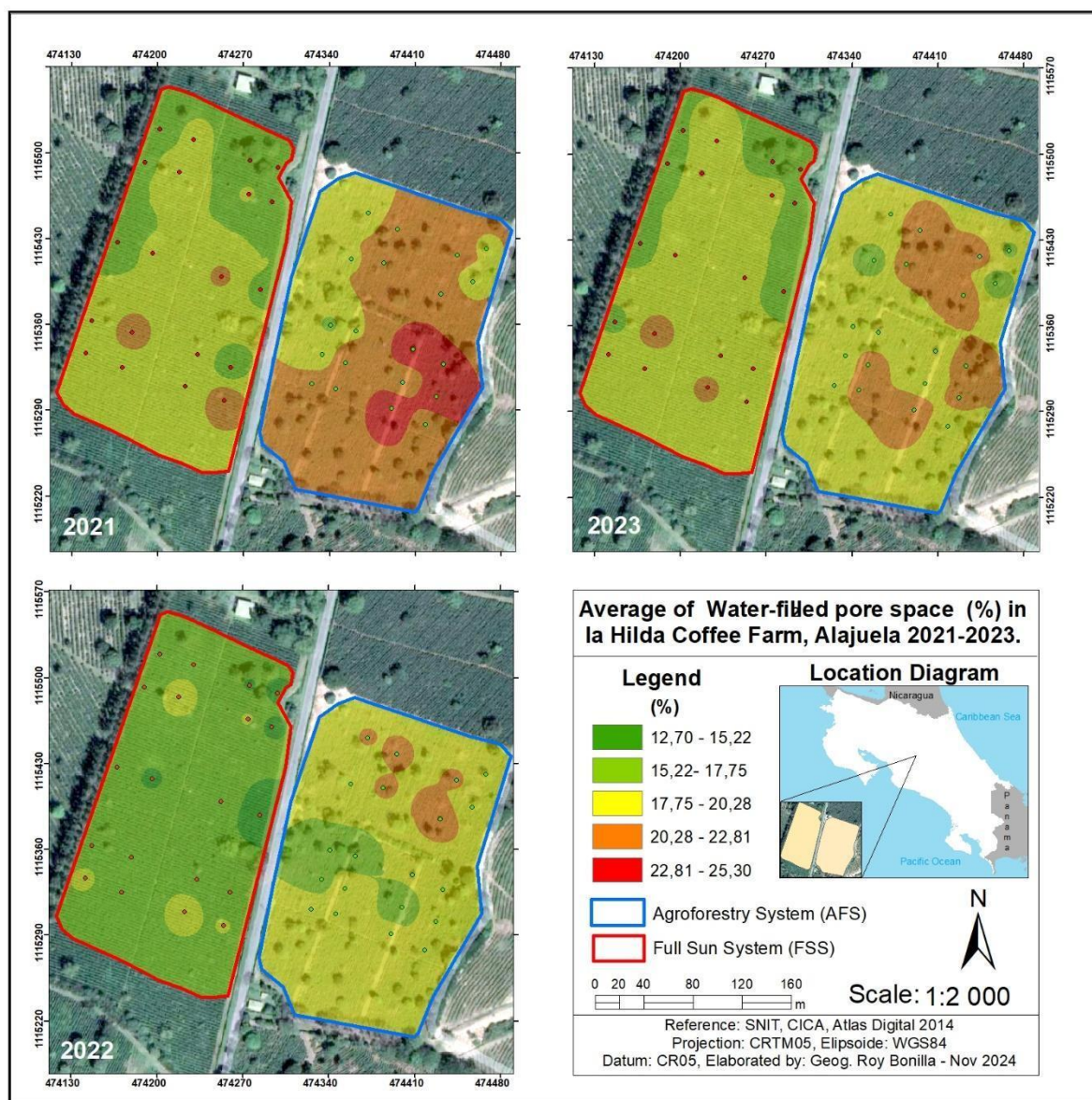


Figure 2. Annual average soil water-filled pore space (%) by year from 2021 to 2023 in full sun system (FSS) and agroforestry system (AFS) at La Hilda Coffee Farm.

Table 1. Correlation Matrix of CO₂ and environmental variables in in full sun system (FSS) and agroforestry system (AFS) at La Hilda Coffee Farm.

Variable	CO ₂ - AFS	CO ₂ - FSS
AP	0.18	0.41
AT	-0.47	0.22
ET	0.33	-0.27
VPD	-0.03	0.32
Rainfall	-0.39	-0.02
ST	0.12	0.34
RH	-0.09	0.10
WFPS 5 cm	-0.46	-0.17
WFPS 20 cm	-0.08	0.09