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Estimation of anthropogenic carbon dioxide emissions and aboveground carbon stocks in agroforestry cacao production systems in the southeastern Peruvian Amazon

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ABSTRACT

The increase in global climate variability due to greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2) has endangered both the environment and human health. In this context, it is important to quantify the carbon balance of anthropogenic activities, in terms of both carbon emission and carbon fixation. The aim of this study was to estimate the anthropogenic CO_2 emissions and aboveground carbon stocks in agroforestry systems of cocoa (*Theobroma cacao* L.) in the southern Peruvian Amazon, specifically in Madre de Dios. Nine agroforestry systems (AFS) of 4–7 years of age were selected, composed of *T. cacao* in association with timber, non-timber and fruit tree species. CO_2 emissions were estimates based on interviews with landowners, considering fuels, fertilizers, herbicides, and domestic use of firewood, charcoal, gas and electricity. To estimate carbon stocks, we calculate aboveground biomass, litter biomass and biomass of annual cocoa bean production. The density of *T. cacao* varied between 530–1160 individuals/ha with ten other associated species at lower densities. The aboveground carbon stock in AFS ranged from 7.7 to 13.7 Mg/ha and the carbon fixation rate ranged from 1.5 to 3 Mg/ha/year. Total emissions ranged from 0.12–2.15 Mg CO_2e/ha/yr, with fuel use being the main source of emissions (up to 98%). Fixation rates ranged from 12.8–23.8 Mg CO_2e/ha/year. Carbon dioxide emissions fixation rates were significantly higher than emissions in every AFS. The results suggest that AFS did not have a negative impact on the environment. The study highlights the importance of AFS within the context of climate change and the increasing environmental impact of conventional agricultural systems. The study shows that the assessed AFSs had a positive overall aboveground carbon balance. Emission rates were low, and fuel use was present in all the AFS and represented the largest source of CO_2 emissions. Therefore, by harboring tree species, the AFS would allow for climate change adaptation and mitigation strategies.

Keywords: agroforestry, aboveground biomass, carbon dioxide emissions, carbon fixation, carbon emission, Madre de Dios.

INTRODUCTION

The increase in global climatic variability due to greenhouse gas (GHG) emissions (IPCC, 2003), especially carbon dioxide (CO_2), has endangered both the environment and human health. This is because CO_2 is the primary GHG driving global warming, due to its high annual emissions, increased atmospheric concentration and longer persistence of the gas in the atmosphere. In addition, CO_2 is responsible for absorbing the thermal radiation emitted by the earth's surface and is considered the main driving factor that causes global warming (50%) (Jobbagy and Jackson, 2000). In the past, agriculture was the main source of CO_2 emissions into the atmosphere (Hernández et al., 2014). At present, the densely populated areas of the planet are considered to be the main responsible for CO_2 emissions into the environment, due to the exorbitant use of petroleum derivatives, deforestation and other anthropogenic effects (Waongo et al., 2015). Although agricultural activities and land use change also play an important role, as they are globally responsible for approximately 14% of GHG emissions (Bains et al., 2024; Johnson et al., 2007).

Thus human activities generate many negative effects on ecosystems, such as soil erosion, loss of biodiversity, deregulation of water flows through burning, which releases large quantities of CO_2 into the atmosphere (Clemente-Arenas, 2022; Lavelle et al., 2014). On a small scale, these impacts are exacerbated by the lack of technical and financial support available to smallholder farmers (Clemente-Arenas, 2022). For example, the agro-industrial cocoa sector is responsible for CO_2 emissions related to fertilizer application, production processes, plantation field operations, machinery supply and other small sources (Dianawati et al., 2023).

In the context of climate change, it is necessary to propose and implement initiatives to mitigate GHG emissions without threatening the environment sustainability and quality of life in the population (Johnson et al., 2007; Vallejos-Torres et al., 2024; van Rikxoort et al., 2014). Here agroforestry systems (AFS) emerge as a strategy to mitigate the effects of climate change, because they can absorb and store large amounts of CO_2 from the atmosphere through photosynthesis (Poveda et al., 2013). Tree species, shrubs or fruit trees in AFS are usually associated in the same area (Wahidurromdloni et al., 2025), which becomes a great strategy for productive, economic and environmentally friendly purposes and also helps to mitigate the effects caused by anthropic activities (Casanova-Lugo et al., 2011; Nair et al., 2009). Likewise, different species in AFS can interact and in this way achieve sustainable management, consolidating the optimization and diversification of production (Casanova-Lugo et al., 2011; Morales-Ruiz et al., 2025). Therefore, AFS can reduce GHG concentrations in the environment because they fix carbon in the plants (Umaña and Conde, 2013). Due to the AFS include shade trees with perennial crops, such as cocoa and coffee, which store carbon mainly in the woody component, where they can store between 12 and 228 Mg C/ha (Tito et al., 2022). However, it is important consider that the carbon capture capacity of AFS can be affected by species diversity, age, structure of the tree component, and vegetation density (Concha et al., 2007).

On the other hand, despite being a potential approach for mitigating the effects of climate change, AFS can also be a source of emissions due to poor management. This highlights the importance of assessing the balance of GHG emissions in AFS. This information will allow us to assess the impacts of AFS in the context of climate change and promote the use of this strategy for biodiversity conservation (Caicedo-Vargas et al., 2022; Nugroho et al., 2023). Moreover, considering that in the context of climate change, the rising temperature, variations in rainfall and water stress had a negative effect on ability of plants to absorb CO_2 from atmosphere (Chaudhry and Sidhu, 2022; Grosse-Heilmann et al., 2024; Vicca et al., 2022). Because, rising temperatures affect many physiological processes, including photosynthesis and respiration, and alter the nutritional factor in plants and many nutrient cycles in nature (Elbasiouny et al., 2022).

Similar to several regions in the Peruvian Amazon, Madre de Dios has large areas that have been overexploited and abandoned due to deforestation for cattle ranching and shifting cultivation (Clemente-Arenas, 2022; Perz et al., 2005). In this context, AFS is an option for the rehabilitation, management of these degraded areas, prevent deforestation and degradation of natural forests. Due to AFS are similar to natural forests, they have great potential as carbon sinks (Casanova-Lugo et al., 2011; Poveda et al., 2013), promote the conservation of biodiversity, reduce soil erosion, increase soil organic matter uptake, and restore degraded areas (Nair et al., 2009; Rügnitz et al., 2009).

Despite the importance of AFS, there are few studies analyzing carbon fixation and CO_2 emissions of AFS in the Peruvian Amazon. Although, there are studies that assess the sustainability and above-ground and soil carbon reserves in AFS (Arevalo et al., 2002; Concha et al., 2007; Lapeyre et al., 2004). The present study highlights the importance of AFS in the context of climate change by estimating their carbon stock and CO_2 emissions in the southern Peruvian Amazon and will serve as a baseline for future research. Since AFS in Madre de Dios have the potential to offer an alternative approach to development and conservation (Clemente-Arenas, 2022). The study aimed to estimate the anthropogenic CO_2 emissions and aboveground carbon stocks in agroforestry systems of cocoa (*Theobroma cacao* L.) in the southern Peruvian Amazon, Inambari, Madre de Dios. To this purpose, the sources of CO_2 emissions and fixation during the production process of *T. cacao* have been quantified.

MATERIAL AND METHODS

Study area

The study was conducted in agroforestry systems (AFS) with *Theobroma cacao* L. (cocoa) located in three sectors of the Inambari district, in the southern Peruvian Amazon (Figure 1). The study area is located 140 km from the city of Puerto Maldonado, at an average altitude of 359 m a.s.l. The climate of the study area is hot and humid, with temperatures ranging from 25 °C to 37 °C. Annual precipitation ranges from 1413 to 3734 mm (2257 mm average for the period 1970–2023) (Aucahuasi-Almidon, et al., 2024).

Study design

Three sectors of the Inambari district were selected from the list of Agrobosque cooperative members (Nueva Generación, Santa Rita Alta and Puerto Trujillo). In each sector, three AFS were selected (nine in total). The age of establishment of the AFS ranged from 4 to 7 years, and farm size varied from 1.5 to 9 ha (Table 1). Table 1 and Figure 2 show all the species found in each AFS.

Vegetation sampling

In each AFS, a plot of 1000 m^2 (20 × 50 m) was established. All trees, shrubs and fruit trees in each plot were identified. The diameter and height of each individual were measured using a diameter tape and a clinometer, respectively. For cocoa and small plants, diameter was measured at 30 cm above ground, and for trees, diameter at breast height (DBH) was measured at 1.30 m above ground.

Above ground biomass

The aboveground biomass of all the individuals recorded in the plots was estimated using specific and general allometric equations (Table 2).

Litter biomass

In each vegetation plot, litter was collected in four subplots of 0.25 m^2 (50 × 50 cm) (Hernandez

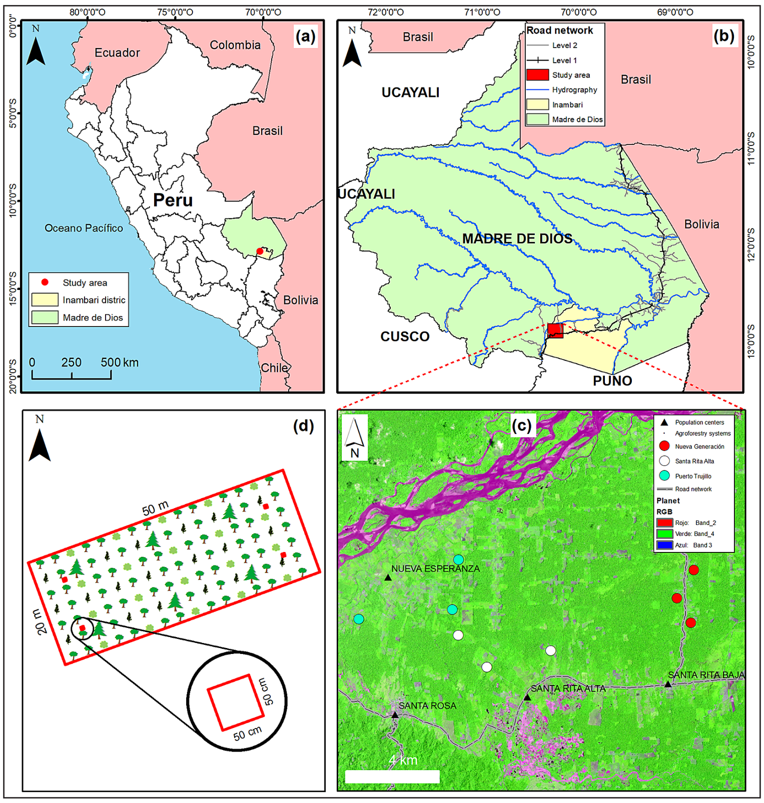

Figure 1. Map of the location of the agroforestry systems in the study area (d), with reference to Peru (a) and Madre de Dios (b), (c) illustration of a plot implemented in each agroforestry system

Table 1. The age, the area and species present in each agroforestry system

Sector	Agroforestry system (AFS)		AFS age (year)	Area (ha)
	Code	Species		
Nueva Generación	AFS-1	*Theobroma cacao* L. [cocoa], *Jacaranda copaia* (Aubl.) D.Don [achihua], *Cedrela odorata* L. [cedro], *Averrhoa carambola* L. [starfruit], *Citrus sinensis* (L.) Osbeck [orange] y *Citrus limon* (L.) Osbeck [lemon]	5	2
	AFS-2	*Theobroma cacao* L. [cocoa], *Musa paradisiaca* L. [banana], *Jacaranda copaia* (Aubl.) D.Don [achihua] y *Citrus limon* (L.) Osbeck [lemon]	7	2
Santa Rita Alta	AFS-3	*Theobroma cacao* L. [cocoa] y *Jacaranda copaia* (Aubl.) D.Don [achihua]	5	5
	AFS-4	*Theobroma cacao* L. [cocoa], *Musa paradisiaca* L. [banana] y *Solanum sessiliflorum* Dunal. [peach tomato]	4	1.5
	AFS-5	*Theobroma cacao* L. [cocoa]	5	9
	AFS-6	Theobroma cacao L. [cocoa] y *Bertholletia excelsa* Bonpl. [brazil-nut]	4	5
Puerto Trujillo	AFS-7	*Theobroma cacao* L. [cocoa], *Musa paradisiaca* L. [banana], *Citrus reticulata* Blanco. [tangerine], *Cedrela odorata* L. [cedro] y *Matisia cordata* Humb. [sapote]	5	5
	AFS-8	*Theobroma cacao* L. [cocoa] y *Musa paradisiaca* L. [banana]	5	4
	AFS-9	*Theobroma cacao* L. [cocoa], *Artocarpus altilis* (Parkinson) [breadfruit], *Musa paradisiaca* L. [banana] y *Citrus limon* (L.) Osbeck [lemon]	5	3

Note: the common names for each species are given in square brackets.

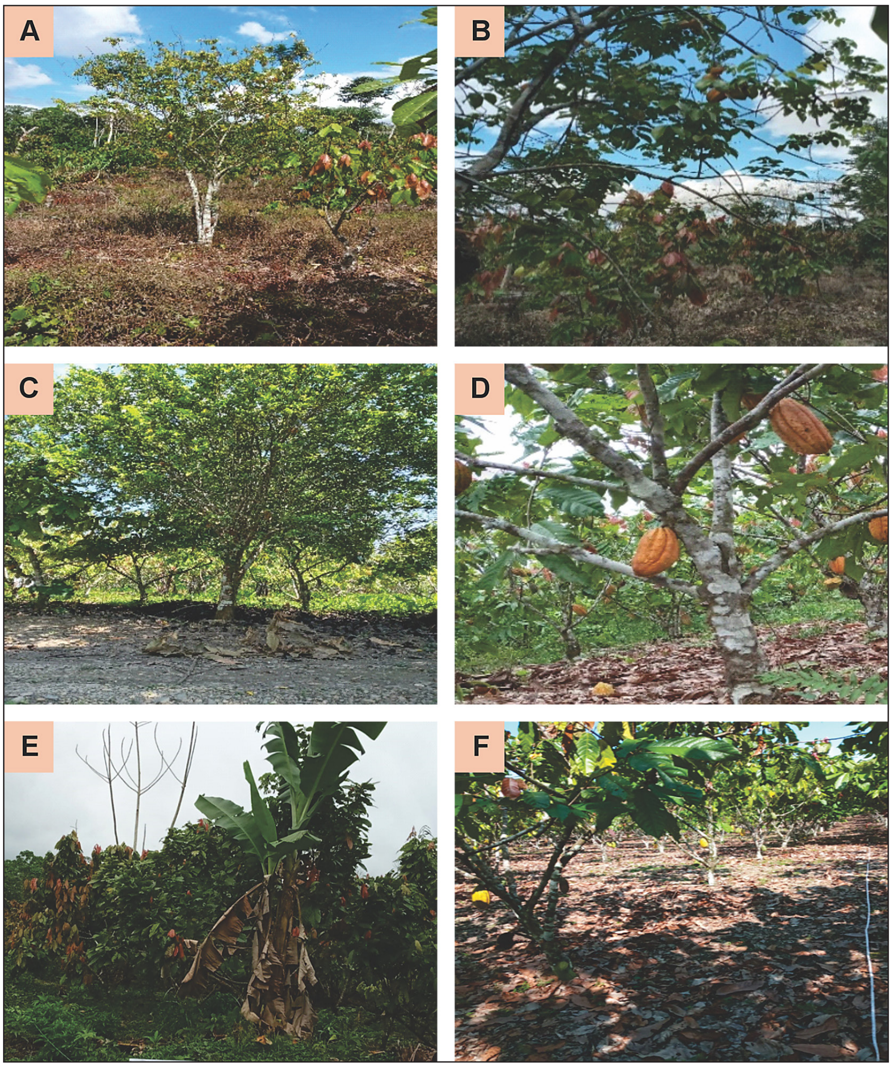

Figure 2. Photographs of agroforestry systems with cacao (*Theobroma cacao*). (A) *T. cacao* + *Averrhoa carambola*. (B) *T. cacao* + *Cedrela odorata*. (C) *T. cacao* + *Citrus reticulata*. (D) *T. cacao* + *Citrus limon*. (E) *T. cacao* + *Musa paradisiaca. (F) T. cacao* + *Bertholletia excelsa*

et al., 2021). We stored each leaf litter sample in appropriately coded paper bags and then dried it in an oven at 70 °C to a constant weight. To obtain total carbon, litter biomass had to be multiplied by the carbon fraction (0.5) (Hernandez et al., 2021; Poveda et al., 2013; Rügnitz et al., 2009).

Determination of CO_2 emissions

To determine the sources of CO_2 emissions, semi-structured interviews were carried out with the owners of the AFS (Canal and Andrade, 2019). The quantity of product used in AFS was quantified in order to subsequently perform the transformations with the emission factors generated according to different products. (IPCC, 2006). The items included in the surveys were (1) fuel use, (2) nitrogen fertilizer use, (3) herbicide use, (4) household resource use (firewood use, coal use, and gas use), and (5) electricity (Marín, 2016). For the AFS emissions, the sum of all reported emission sources has been considered in CO_2e units (Equation 1).

$$E(CO_2e) = E_{Fertilizer} + E_{Herbicide} + E_{Fuel} + E_{Transport} + E_{Firewood} + E_{Coal} + E_{Gas} \quad (1)$$

where: E – Emissions of CO_2e.

Determination of CO_2 fixations

For the estimation of CO_2 fixation, the aboveground biomass, the litter biomass and the biomass of the annual production of cocoa beans were quantified. The aboveground biomass obtained was multiplied by the carbon fraction 0.5 to calculate the carbon stock stored by the vegetation and litter in AFS (IPCC, 2003). Carbon storage in total biomass was divided by the age of each AFS to determine the carbon fixation rate for cocoa trees, shrubs, timber forest trees, and fruit trees (Marín, 2016). In order to quantify the rate of fixation in terms of CO_2e, the carbon values obtained have been multiplied by a constant of 3.67 (IPCC, 2006; Vallejos-Torres et al., 2024). To quantify the carbon fixation of AFS, the sum of all reported fixation sources was considered (Equation 2).

$$F(CO_2e) = F_{Aboveground} + F_{Litter} + F_{beans-cocoa} \quad (2)$$

where: F – fixation of CO_2e.

Data analysis

Analysis of variance (ANOVA) was used to compare carbon fixation and CO_2 emissions among the three sectors studied at a significance level of 0.05. Pearson's correlation coefficient was used to analyze the relationship between the age of the AFS, the carbon stock and the carbon fixation. All analyses were performed using the SigmaPlot 16 statistical package and the GG Plot 2 package of R version 2023.09 in an R-Studio environment.

RESULTS AND DISCUSSION

Table 3 shows all species recorded in the nine AFS evaluated. In general, the density of plants per AFS varied between 620 and 1170 individuals/ha. *T. cacao* (530–1160 plants/ha) was the most abundant species in the AFS. Species other than *T. cacao* were identified at low densities (10–180 plants/ha). Fruit plants such as *M. paradisiaca* (10–80 plants/ha) and species of the genus Citrus

Table 2. Allometric equations for estimating aboveground biomass of species in the nine cacao agroforestry systems in Inambari District, Madre de Dios, Peru

Species	Allometric equation	Source
Theobroma cacao L. (cocoa)	$AGB = 3.3973 \times D^{-4.8961}$	(Brancher, 2010)
Tree species (DAP < 5 cm)	$AGB = \exp(-1{,}9968 + 2{,}4128\ ln(D))$	(Nelson et al., 1999)
Tree species (DAP > 5 cm)	$AGB = 0.0559(\rho \times D^2 \times H)$	(Chave et al., 2014)
Shrub species	$AGB = 0.1184 \times D^{2.53}$	(Arevalo et al., 2002)
Musa paradisiaca L. (banana)	$AGB = 0.0303 \times D^{2.1345}$	(Hairiah et al., 2010)
Citrus fruits	$AGB = -6.64 + 0.279 \times BA + 0.000514 \times BA^2$	(Schroth et al., 2002)
Bertholletia excelsa Bonpl. (brazil-nut)	$AGB = -18.1 + 0.663 \times BA + 0.000384 \times BA^2$	(Schroth et al., 2002)

Note: AGB (kg) – aboveground biomass; D (m) – diameter (1.30 m) (30 cm); H (m) – height; ρ (mg/cm^3) – wood density; BA (cm^2) – basal area.

Table 3. Abundance of species found in the agroforestry systems evaluated

Sector	AFS	Species	Abundance (plants/ha)	Total (plants/ha)
Nueva Generación	AFS-1	*Jacaranda copaia*	30	900
		Theobroma cacao	810	
		Averrhoa carambola	20	
		Cedrela odorata	10	
		Citrus limon	10	
		Citrus sinensis	20	
	AFS-2	*Jacaranda copaia*	10	1090
		Theobroma cacao	1060	
		Citrus limon	10	
		Musa paradisiaca	10	
	AFS-3	*Jacaranda copaia*	10	890
		Theobroma cacao	880	
Santa Rita Alta	AFS-4	*Theobroma cacao*	530	620
		Solanum sessiliflorum	10	
		Musa paradisiaca	80	
	AFS-5	*Theobroma cacao*	880	880
	AFS-6	*Theobroma cacao*	1160	1170
		Bertholletia excelsa	10	
Puerto Trujillo	AFS-7	*Theobroma cacao*	780	1040
		Cedrela odorata	10	
		Citrus reticulata	60	
		Musa paradisiaca	180	
		Matisia cordata	10	
	AFS-8	*Theobroma cacao*	880	890
		Musa paradisiaca	10	
	AFS-9	*Theobroma cacao*	770	960
		Citrus limon	50	
		Artocarpus altilis	50	
		Musa paradisiaca	90	

(*C. reticulata*, *C. sinensis* and *C. limon*, between 10–60 plants/ha) were the most abundant species. While species with forestry potential (timber and non-timber) were found at lower densities. *J. copaia* was the species with the highest density (30 trees/hectare), followed by other forest species at lower densities (10 trees/ha, *Cedrela odorata* and *Bertholletia excelsa*).

Above ground biomass

Table 4 shows the results of the carbon stock and the estimated carbon fixation rate. The carbon stock in the AFS varied between 7.7 and 13.7 Mg/ha, and the carbon fixation rate varied between 1.5 and 3 Mg/ha/year. No significant differences were found in AFS carbon stocks by sector (ANOVA, $p > 0.05$). Low stock and carbon sequestration values in AFS are associated with low *T. cacao* densities and the absence of forest species (e.g., AFS-5 and AFS-8). On the other hand, no significant correlations were found between AFS age and carbon stock ($r = 0.45$; $p = 0.22$) and carbon fixation ($r = -0.34$; $p = 0.37$).

Traditional polycultures can have significantly higher carbon reserves compared to monocultures (Canal and Andrade, 2019). Agroforestry is considered an important strategy for carbon sequestration due to the storage potential of plant species and soil. However, the storage capacity can vary depending on the species used in the AFS and the characteristics of the site (Goñas et al., 2022). The carbon stocks found in the present study were lower than those reported by previous

Table 4. Results of estimates of aboveground biomass and carbon fixation in agroforestry systems

Sector	Aboveground biomass (Mg/ha)	Carbon (Mg/ha)	Carbon fixation (Mg/ha/year)	Mean carbon fixation by sector (Mg/ha/year)
Nueva Generación	25.5	12.7	2.5	2.0 a
	27.3	13.7	2.0	
	15.4	7.7	1.5	
Santa Rita Alta	16.8	8.4	2.1	2.4 a
	21.9	11	2.2	
	23.9	12	3.0	
Puerto Trujillo	23.4	11.7	2.3	2.1 a
	15.5	7.7	1.5	
	23.3	11.6	2.3	

Note: means within a column followed by the same letter are not significantly different according to ANOVA.

studies in AFS of the Peruvian Amazon (Concha et al., 2007; Díaz Pablo et al., 2024; Goñas et al., 2022; Tito et al., 2022; Vela Alvarado et al., 2024) and in Madre de Dios (Clemente-Arenas, 2021, 2022; Surco-Huacachi and Garate-Quispe, 2022), for AFS with similar ages. In Madre de Dios, carbon stocks of 20–116 Mg/ha have been reported for AFS between 4 and 7 years of establishment (Clemente-Arenas, 2021, 2022; Surco-Huacachi and Garate-Quispe, 2022). These differences with our study may be due to (1) higher density of *T. cacao,* (2) higher density of forest species (*J. copaia*, C. *odorata*, *B. excelsa*, *A. altilis* and Dipteryx species), and (3) better management of AFS. Because the abandonment of AFS can have a negative impact on the accumulation of carbon in vegetation, and because cocoa AFS, which include forest, fruit, timber and industrial species, are the most effective at sequestering carbon compared to conventional land use systems (Concha et al., 2007; Segura-Elizondo and Moya, 2021).

On the other hand, carbon stock in cocoa AFS in the Peruvian Amazon can vary from 2.9–4.4 Mg/ha in the first year of establishment to 27–169 Mg/ha in AFS at age 10–20 years (Tito et al., 2022; Vela Alvarado et al., 2024). This high variability in the carbon stock of the cacao AFS is due to trees species (Tito et al., 2022), vegetation structure (Hernandez et al., 2021; Ruiz-Russi et al., 2023), soil physicochemical characteristics that may affect AFS productivity (Culqui et al., 2025), and the management of AFS (Silva-Parra, 2018). However, most studies report the presence of tree species and their size as the main factors influencing the variability of AFS carbon accumulation (Clemente-Arenas, 2021). Because tree vegetation can represent between 48–80% of the carbon stored in AFS (Alexander et al., 2025; Goñas et al., 2022; Hernandez et al., 2021; Vela Alvarado et al., 2024), and this proportion increases as the age of the AFS increases (Goñas et al., 2022; Kouadio et al., 2025).

Previous studies have demonstrated that AFS increase carbon fixation rates and promote the conservation of ecosystems degraded by anthropogenic activities, which can be considered as a strategy to mitigate climate change (Hernandez et al., 2021; Morales-Ruiz et al., 2025). The carbon fixation rates found in this study were similar to the mean values reported for AFS in the tropics (2.1 Mg/ha/year) (Clemente-Arenas, 2021; Mena-Mosquera and Andrade C, 2021; Singh et al., 2024), which can vary between 0.29 and 17.6 Mg/ha/year (Poveda et al., 2013; Segura and Andrade, 2012; Sow et al., 2024), due to site characteristics, land use, species composition, age of the AFS, and forest management practices (Chirwa et al., 2022; Sow et al., 2024). Values found in the study were also similar to those reported for cacao AFS in the Peruvian Amazon (1.48 to 2.64 Mg/ha/year) (Rojas, 2022; Silva-Parra, 2018). Our results demonstrate that AFS have the potential for carbon sequestration and climate change mitigation (Chirwa et al., 2022).

Litter biomass

The carbon content in the litter of the AFS varied between 9.6–20.3 Mg/ha (Table 5). The sectors evaluated showed no differences in the carbon content of the AFS' litter (ANOVA, $p > 0.05$). Although AFS in the Puerto Trujillo sector had the highest average litter carbon content (Table 5).

Litter carbon stock assessment is important because its nutrient-rich decomposition and interaction with microorganisms promote more

Table 5. Results of estimates of litter biomass and carbon fixation in agroforestry system

Sector	AFS	Biomass (Mg/ha)	Carbon (Mg/ha)	Mean litter carbon by sector (Mg/ha)
Nueva Generación	AFS-1	19.10	9.55	13.48 a
	AFS-2	21.30	10.65	
	AFS-3	40.50	20.25	
Santa Rita Alta	AFS-4	32.2	16.1	13.15 a
	AFS-5	18.9	9.45	
	AFS-6	27.8	13.9	
Puerto Trujillo	AFS-7	34.8	17.4	17.43 a
	AFS-8	33.6	16.8	
	AFS-9	36.2	18.1	
Mean		26.97	13.48	14.69

Note: means within a column followed by the same letter are not significantly different according to ANOVA.

efficient nutrient cycling in AFS (Nugroho et al., 2023), creating conditions for vigorous and sustained vegetation growth (Wahidurromdloni et al., 2025), improving system productivity and reducing dependence on external fertilizers, all of which are critical to the sustainability of AFS (Culqui et al., 2025; Segura-Elizondo and Moya, 2021). Our results for litter carbon were similar to those reported for AFS in Madre de Dios (7.3–22 Mg/ha) (Surco-Huacachi and Garate-Quispe, 2022). In addition, litter carbon levels were higher than those reported for primary forests in Madre de Dios (1.6–3.4 Mg/ha) (AIDER, 2012) and those reported in cocoa AFS in Peru and the Amazon (Concha et al., 2007; Díaz Pablo et al., 2024; Leiva-Rojas and Ramírez-Pisco, 2021; Vallejos-Torres et al., 2024). These differences may be due to greater dynamics in litter decomposition and greater input of carbon and nutrients to the soil through mineralization in forests than in AFS (Leal et al., 2023), since Amazonian forests have high soil carbon stocks (25–60 Mg/ha) (AIDER, 2012; Cardozo et al., 2022; Dalmo et al., 2016). Other factors such as tree density, species composition, phenology, and land management practices would also influence higher carbon content in litter (Ratna et al., 2022).

CO_2 emissions

The total CO_2 emissions in the AFS varied between 0.12 to 2.15 Mg CO_2e/ha/year (Table 6), and they had a high variability (95% coefficient of variation). Fuel consumption was present in all AFS and was the largest source of CO_2 emissions (up to 98%). The use of gas, firewood and fertilizer contributed less to CO_2 emissions (0.4–29%). Gas and coal were the least frequent sources of emissions, being present in only two AFS. No significant differences in CO_2e emissions were found among sectors (ANOVA, $p > 0.05$). While AFS in Puerto Trujillo had the lowest average emissions (0.44 Mg CO_2e/ha/year), while the Santa Rita Alta sector had the highest average and variability of emissions (0.94 Mg CO_2e/ha/year) (Figure 3). This high variability in emissions is due to differences in the use of fuel and coal for domestic use and fuel for transport according to AFS.

The characterization of each resource use and its emissions in the AFS allows us to quantify their impacts (Dianawati et al., 2023). Our results are consistent with previous studies reporting that fuel use is the main source of CO_2 emissions in AFS (Umaña and Conde, 2013). Therefore, CO_2 emissions would play an important role in maintaining the environmental benefits of the cocoa production process (Pérez-Neira et al., 2020). However, our emissions results are lower than those found by the AFS for coffee and cocoa (0.5–1.3 Mg CO_2e/ha) in the Amazon region of Colombia and Brazil (Ortiz-Rodríguez et al., 2016; Segura and Andrade, 2012). On the other hand, the proportion of emissions from fertilizer use in our study was low (between 3.8–28%), which is different from what was reported by a study in the Amazon, which found that fertilizer use (30–35%) and transport (45–57%) were the main sources of emissions (Ortiz-Rodríguez et al., 2016; Pérez-Neira et al., 2020; van Rikxoort et al., 2014).

CO_2 fixations

The fixation rates of the AFS in the study varied between 12.8 to 23.8 Mg CO_2e/ha/year. At the

Table 6. Results of the estimation of CO_2 emissions in the agroforestry system

Source of emission	Sector								
	Nueva Generación			Santa Rita Alta			Puerto Trujillo		
	AFS-1	AFS-2	AFS-3	AFS-4	AFS-5	AFS-6	AFS-7	AFS-8	AFS-9
Fertilizers (Mg CO_2/ha/year)	-	0.146	-	0.083	0.029	-	0.042	-	0.214
Herbicides (Mg CO_2/ha/year)	0.046	0.138	-	-	0.348	-	0.017	-	-
Fuel (Mg CO_2/ha/year)	0.196	0.342	0.098	0.978	0.109	0.078	0.196	0.196	0.391
Fuel for transportation (Mg CO_2/ha/year)	0.098	0.196	0.039	0.196	0.065	0.039	0.059	0.049	0.130
Firewood (Mg CO_2/ha/year)	-	0.038	-	0.008	-	-	0.018	0.018	0.002
Coal (Mg CO_2/ha/year)	0.470	-	-	0.882	-	-	-	-	-
Gas (Mg CO_2/ha/year)	-	-	0.002	-	0.001	-	-	-	-
Total emissions (Mg CO_2e/ha/year)	0.81	0.86	0.14	2.15	0.55	0.12	0.33	0.26	0.74
Mean (Mg CO_2e/ha/year)	0.60 a			0.94 a			0.44 a		

sector level, no significant differences were found in the average CO_2 fixation in the AFS (ANOVA, $p > 0.05$). Although the highest CO_2 fixation values were found in Santa Rita Alta and Puerto Trujillo, this is due to a balance between carbon storage in aboveground biomass and leaf litter. The high rate of CO_2 fixation in the AFS is consistent with previous studies, which suggest that cocoa AFS can store a large quantity of carbon (Umaña and Conde, 2013). On the other hand, the CO_2 fixation results are consistent with those reported in previous studies on AFS with *T. cacao* (14-22 Mg CO_2e/ha/year) (Cabezas-Andrade et al., 2024; Canal and Andrade, 2019). Our results show

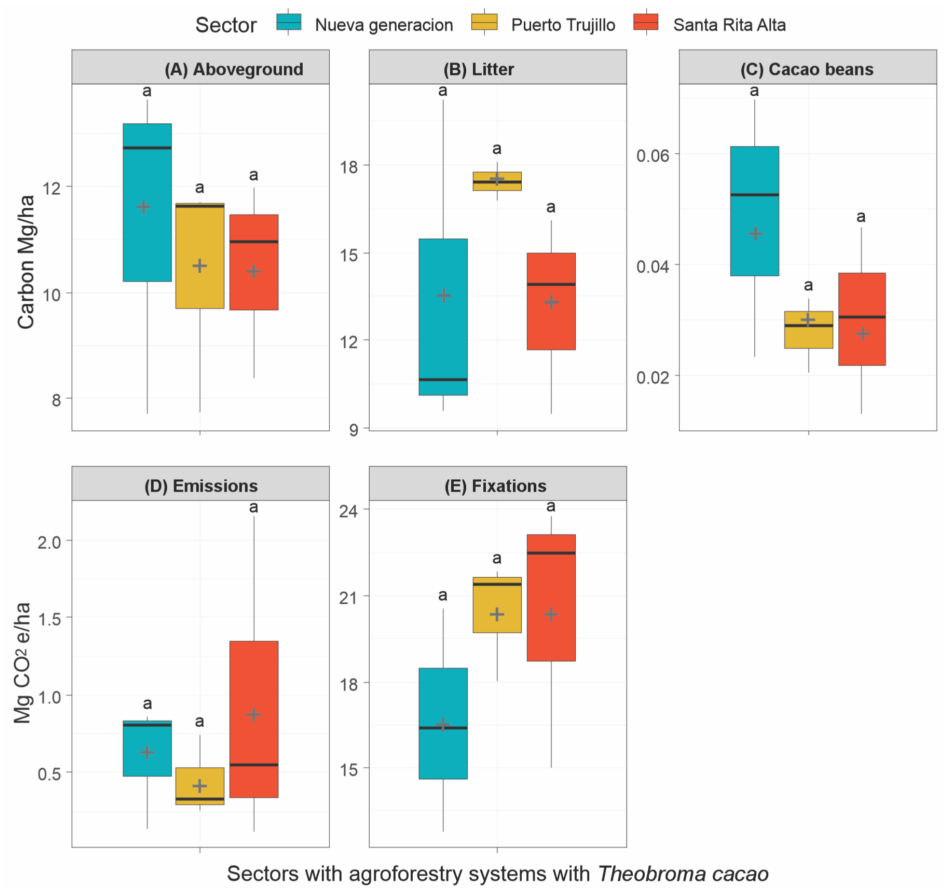

Figure 3. Box plots comparing stored carbon (aboveground, litter and cacao beans), emissions and fixations of CO_2e by agroforestry system sector in the Peruvian Amazon. The gray cross (+) represents the average. Lowercase letters above boxplots indicate non-significant differences among sectors

that AFS can be considered in a climate change mitigation strategy due to their great potential to reduce GHG emissions, promote strategies to conserve native biodiversity, and also provide socio-economic benefits to local populations (Canal and Andrade, 2019; Silva-Parra, 2018), unlike monocultures (Cabezas-Andrade et al., 2024; Pérez-Neira et al., 2020).

Our results show that all AFS in the study had a positive carbon balance (12–23.5 Mg CO_2e/ha/year) (Figure 3F), because the CO_2 fixation rates (Figure 3E) were much higher than the emission rates (Figure 3D). Agricultural production has a significant impact on the environment and is considered one of the main sources of GHG emissions (Bains et al., 2024). In this context, agroforestry is emerging as an alternative to traditional agriculture in the Amazon, as a dynamic and ecological natural resource management system that provides greater social, economic and environmental benefits than agriculture and plantations (Dianawati et al., 2023; Ruiz-Russi et al., 2023). Since we found a positive net carbon sequestration, our results suggest that AFS did not have a negative impact on the environment (Nguyen-Duy et al., 2018). This is consistent with previous studies on AFS with *T. cacao*, *Coffea arabica* and *Cordia alliodora* in the Colombian Amazon (Canal and Andrade, 2019; Umaña and Conde, 2013). Therefore, our results show that cocoa production management can be environmentally sustainable (Pérez-Neira et al., 2020; Ruiz-Russi et al., 2023), have less environmental impact, can be economically viable in terms of return on investment, energy or GHG intensity (Caicedo-Vargas et al., 2022). Our results highlight the importance of AFS in the context of climate change (Canal and Andrade, 2019) and the increasing environmental impacts of traditional agricultural systems (Pérez-Neira et al., 2020). Considering the tree structure and how AFS are managed, they tend to store more carbon. Furthermore, AFS can harbor several tree species and can promote strategies for climate change adaptation and mitigation. Therefore, it is clear that AFS can be useful in addressing climate change (Canal and Andrade, 2019).

CONCLUSIONS

Our results show that the AFS in the study had a positive carbon balance. The aboveground carbon stock in the AFS varied between 7.7 and 13.7 Mg/ha. The emission CO_2 rates were low. However, fuel use emerged as the primary source of CO_2 emissions across all AFS. Therefore, by providing habitat for diverse species, AFS would enable strategies to adapt to and mitigate climate change. These findings are valuable for informing sustainable public policies and aligning them with low-carbon objectives, enhancing the economic and environmental resilience of areas degraded or abandoned by traditional agricultural practices in the Amazon.

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