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Carbon stocks and the use of shade trees in different coffee growing systems in the Peruvian Amazon

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Abstract

Agroforestry systems can play an important role in mitigating the effects of climate change given their capacity to increase tree diversity and to store more carbon than conventional farming. This study aims at assessing carbon stocks and the use of shade trees in different coffee growing systems in the Northeast Peruvian Amazon. Carbon stocks in trees were estimated by field-based measurements and allometric equations. Carbon stocks in dead wood, litter and soil (upper 60 cm) were determined using field sampling and laboratory analysis. The diversity analysis drew on the Shannon–Weiner diversity index, and focus groups were used to obtain information about the local use of shade trees. The total carbon stock in the polyculture-shaded coffee system was 189 t C/ha, while the *Inga*-shaded and unshaded systems totalled 146 and 113 t C/ha, respectively. The soil compartment contributed the largest carbon stock in the coffee growing systems and contained 67, 82 and 96% of the total carbon stock in the polyculture-shaded, *Inga*-shaded and unshaded coffee systems, respectively. The Shannon–Weiner index and tree species richness values were highest for the polyculture-shaded coffee system, with a total of 18 tree species identified as important sources of fodder, food, wood, firewood and medicine. Therefore, coffee agroforestry systems play a significant role in carbon storage, while promoting conservation of useful trees in agricultural landscapes in the Peruvian Amazon.

Introduction

The conversion of tropical forests has negative effects on biodiversity (Van Gemerden *et al.*, 2003) and causes significant depletion of terrestrial carbon (C) stocks, representing the second greatest source of anthropogenic carbon dioxide (CO_2) emissions to the atmosphere, after the burning of fossil fuels (Eaton and Lawrence, 2008). Consequently, there is a growing interest in learning how C stocks, forest structure, floristic composition, and species diversity vary with land-use changes (Donald, 2004; Jacobi *et al.*, 2014), in order to develop a pragmatic approach for managing agricultural landscapes and remnant forests in tropical ecosystems.

Forestry and agricultural practices, including afforestation, reforestation, natural regeneration of forests, silvicultural systems, and agroforestry can partially mitigate CO_2 emissions through C storage in long-lived C compartments (Soto-Pinto *et al.*, 2010; Jose and Bardhan, 2012). Such compartments include above- and belowground biomass, soil microorganisms, and relatively stable forms of organic and inorganic C in the soil (Nair *et al.*, 2009). These compartments are subject to gains and losses, depending on the rates of growth, mortality, and decomposition; affected by natural causes and anthropogenic activities (Parrota *et al.*, 2012).

Since the adoption of the Kyoto Protocol in 1997, agroforestry has gained attention as a strategy to store C in agricultural landscapes and mitigate the effects of climate change (Jose and Bardhan, 2012). Agroforestry systems are defined as land-use systems where woody perennials are managed together with crops and/or animals, and where ecological and economic interactions exist among the components as a result of spatial and temporal arrangements (Nair, 1993). The inclusion of trees within farming systems has been shown to improve soil properties and increase C storage (Ehrenbergerová *et al.*, 2016; Alegre *et al.*, 2017; Dollinger and Jose, 2018). Root growth supports the formation of soil aggregates and pores, and the production of litter and root exudates affects soil structure and chemistry (Frouz *et al.*, 2013). It is important to highlight that agroforestry systems can be both sinks and sources of C depending on the land-use systems that they replace: if replacing primary

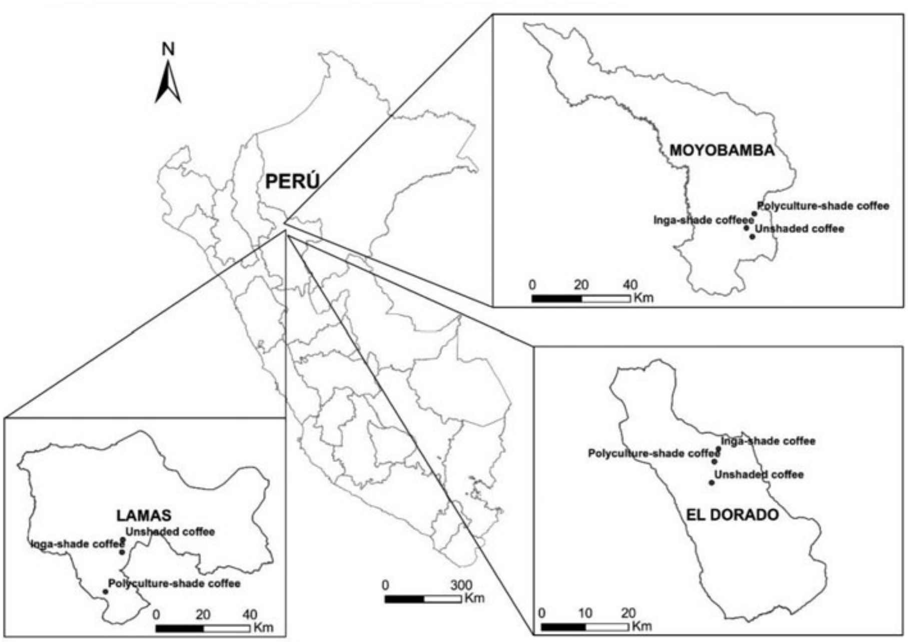

Fig. 1. Location of studied coffee plantations in San Martin, Peru.

or secondary forests, they will generally accumulate comparatively lower amounts of biomass and C, but if established on degraded soils or treeless lands, the C accumulation is considerably increased (Montagnini and Nair, 2004). Therefore, promoting agroforestry on already deforested lands can be one of the strategies to mitigate land-use related CO_2 emissions to combat global warming (Schroth *et al.*, 2016).

Coffee is the most widely commercialized tropical crop on the international market (Da Silva and Leite, 2013) and represents an important source of income for millions of farmers (Donald, 2004). The use of shade trees in coffee plantations is common among farmers in the tropics (Dossa *et al.*, 2008), and associating tropical crops with trees offers the possibility of adding value to the land and obtaining future benefits. These include the provision of ecosystem services such as improvement of soil structure and water infiltration (Garrity *et al.*, 2010), an increase of C storage (De Stefano and Jacobson, 2018), enrichment of soil biota (Dollinger and Jose, 2018), improvement of soil fertility (Zake *et al.*, 2015), and conservation of biodiversity (Perfecto *et al.*, 2003).

The amount of C stored in agroforestry systems depends on biophysical conditions, system management, and the structure and diversity of trees, which are determined by environmental, social, and economic factors (Albrecht and Kandji, 2003; Nadège *et al.*, 2019). Oelbermann *et al.*, (2004) estimated that the potential to store C in aboveground components of agroforestry systems reached the value of 2.1×10^9 t C/year in tropical biomes. Likewise, the agroforestry systems of the humid tropics of South America have a C storage potential that ranges from 39 to 102 t C/ha (Albrecht and Kandji, 2003). Studies carried out in coffee plantations in the Peruvian Amazon reported that the total C stocks, including soil organic C (SOC) in the upper 30 cm, in systems shaded by *Pinus* spp., *Eucalyptus* spp., and *Inga* spp. were 178, 162, and 120 t C/ha, respectively and the C stock in unshaded coffee was 100 t C/ha (Ehrenbergerová *et al.*, 2016).

Some studies conducted in the Peruvian Amazon have analyzed the C distribution in different compartments, in agroforestry systems shaded by one predominant species (Ehrenbergerová *et al.*, 2016; Timoteo *et al.*, 2016). Moreover, just a few studies have so far reported the use and diversity of shade trees and their contribution at the species level to the aboveground C stock in polyculture-shaded agroforestry systems in this region (Vebrova *et al.*, 2014; Pizarro *et al.*, 2020). Consequently, the current study aims at assessing the differences in the C compartments as a result of management practices and the use of shade trees in different coffee growing systems, in the agricultural landscapes of the Northeast Peruvian Amazon. This study will contribute to information that is valuable for the implementation of sustainable projects using agroforestry systems as C sinks and ecosystem services providers.

Materials and methods

Study area

The study was carried out in three provinces of the San Martin region in Peru: El Dorado, Lamas, and Moyobamba (Fig. 1), between October 2015 and July 2016. The mean annual rainfall and temperature in these provinces are 1800 mm and 25°C, respectively, although there is a high variability associated with altitudinal gradients. The rainy season lasts from November to May.

Coffee production in the region is dominated by *Coffea arabica* and the varieties found in the study area were Typica, Catimor and Caturra. Three representative smallholder coffee growing systems were selected for this study: (1) Polyculture-shaded coffee: a coffee system with a dense shading polyculture in which the canopy mainly comprises different fruits and timber trees of different ages; (2) *Inga*-shaded coffee: it is the most typical coffee system in the study area and is associated with leguminous species (*Inga edulis* and *Inga ruiziana*) and (3) unshaded coffee (Table 1).

Each coffee growing system was evaluated in one farm in each province, thus totalling nine farms in the study area. The selected farms are organic and have been under coffee cultivation between 7 and 12 years (Table 1), with similar management practices and

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Table 1. Characteristics of the selected coffee growing systems.

Coffee growing system	Province	Previous land-use	Altitude (m.a.s.l.)	Age (years)	Shade trees density (trees/ha)	Mean annual yield (t/ha)	Coffee farm area (ha)
Polyculture-shaded coffee	El Dorado	Secondary forest	960	9	700	1.7	2
Polyculture-shaded coffee	Lamas	Secondary forest	1040	8	600	1.7	3
Polyculture-shaded coffee	Moyobamba	Secondary forest	1050	9	700	1.7	3
Inga-shaded coffee	El Dorado	Maize and banana	1000	10	550	2.2	2
Inga-shaded coffee	Lamas	Maize and banana	850	12	800	1.4	2
Inga-shaded coffee	Moyobamba	Maize	1100	12	800	2.2	3
Unshaded coffee	El Dorado	Maize	480	8	–	2	2
Unshaded coffee	Lamas	Maize and banana	980	7	–	2.2	1.5
Unshaded coffee	Moyobamba	Secondary forest	1210	7	–	2	1

inputs. Coffee plants reach their maximum vegetative development from 6 to 8 years after sowing (Arcila, 2007), so the variation in the age of the coffee plants is not likely to have an impact on the C storage in these. The approximate distance between rows is 1.5 m with 1 m between coffee plants, resulting in a total of approximately 6650 coffee plants/ha. Pruning of coffee plants is carried out approximately every 2 years at a height of 0.3–0.5 m, eliminating unproductive branches to renew the plants. The organic material from pruning is left on the ground for decomposition. Weeds are removed using machetes. Organic amendments and manure are applied every 1 or 2 years, depending on the finances of farmers.

Field sampling

In this study, a nested plot design was used. The central point of the sampled plots was located at a minimum distance of 50 m from the edge of the coffee farm, and the slopes of the plots ranged from 0° to 15°. To estimate aboveground biomass, one plot of 16 m × 25 m was established in each sampled farm and this plot was divided into four sub-plots of 4 m × 25 m to facilitate the evaluation of trees and coffee shrubs. The total result per plot was used in the analysis. In these plots, the height and diameter at 15 cm above the ground (d15) of coffee plants were measured, and the height and diameter at 1.3 m above the ground (DBH = diameter at breast height) of the shade trees were also measured. An additional sub-plot of 1 m × 25 m was established in each one of the four sub-plots of 4 m × 25 m to measure dead wood. Subsequently, at the center of the 1 m × 25 m sub-plot, another 50 cm × 50 cm sub-plot was established to measure litter (Arévalo *et al.*, 2003). Dead wood and litter (leaves, branches, flowers and fruits) were carefully removed by hands (protected by leather gloves) from the soil surface. Soil was sampled from soil pits located at the center of each 4 m × 25 m sub-plot, with four replicates. Volume-specific soil samples were collected from three depths (0–10 cm, 10–30 cm and 30–60 cm) using a cylinder. This procedure resulted in a total of 108 soil samples. The soil samples were oven-dried (at 105°C for 72 h) for weight determination.

Metrics and use of shade trees

A diversity analysis was performed at the species level in the different coffee growing systems. Species diversity was assessed using the Shannon–Weiner diversity index:

$$H = -\sum_{i=1}^{S} pi \ln(pi),$$

where S is the number of categories in the habitat, pi is the relative abundance of species i on a farm.

Information about the use of shade trees in the coffee systems was collected through focus group interviews with coffee farmers. This activity encompassed 23 men and 12 women farmers, distributed in four groups. On average, nine farmers participated in each group, of which three were women and the rest were men. The farmers were selected as participants based on their specific knowledge about different uses of plants, in addition, the owners of the coffee plantations in which the C stocks were studied also participated in the focus groups. During the focus groups, the participants were asked to discuss the use of each shade tree identified in the coffee systems and the outcomes of the discussions were recorded.

Above- and belowground carbon estimation

Allometric models were used to estimate aboveground biomass based on the measured DBH (Table 2). The wood density value for each identified species was obtained from the 'Global Wood Density Database' (Zanne *et al.*, 2009). In cases where data were not available in the database, density values of the genus or family were used. Root biomass was estimated using the regression equations developed by Cairns *et al.* (1997) (Table 2). The biomass values obtained for each tree within the same plot were used to calculate the total tree biomass of the plot and the resulting value was extrapolated to obtain the biomass stock of 1 ha. For measuring dead wood, a sample of approximately 500 gr was collected and the wet weight was measured. Subsequently, the

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Table 2. Allometric equations used to estimate above- and belowground biomass in different coffee growing system.

Species group	Allometric model	n	r^2	DBH range (cm)	References
Trees in moist tropical forest	$AGB = \exp(-1.7689 + 2.377 \times Ln(DBH))$	40	0.96	$2 \leqslant DBH < 5$	Nascimento and Laurance (2002)
Trees in moist tropical forest	$AGB = 0.0673 \times (\rho \times DBH^2 \times H)^{0.976}$	4004	–	$DBH \geqslant 5$	Chave *et al.* (2014)
Inga species	$AGB = 0.01513 \times DBH^{3.0054}$	32	0.83	$10 \leqslant DBH \leqslant 29$	Castellanos *et al.* (2010)
Coffea arabica	$Ln(AGB) = -2.39287 + 0.95285 \times Ln(d_{15}) + 1.2693 \times Ln(H)$	69	0.63	$0 \leqslant d_{15} \leqslant 9$	Suarez (2004)
Roots	$Y = \exp(-1.0587 + 0.8836 \times Ln(AGB))$	–	0.84	–	Cairns *et al.* (1997)

AGB, aboveground biomass; Y, Root biomass; DBH, diameter at breast height; d_{15}, diameter at 15 cm aboveground; H, height; ρ, wood density.

samples were taken to the laboratory and dried at 70°C for dry weight determination. With such information, the moisture content and dead wood biomass were determined by means of the following equations:

$$\text{Moisture content} = \frac{(\text{Sample wet weight} - \text{Sample dry weight})}{\text{Sample wet weight}}.$$

$$\text{Dead wood biomass} = \sum_{i=1}^{n} (\text{Total wet weight} - (\text{Total wet weight} \times \text{moisture content}))$$

Litter biomass was determined in the same way as that of dead wood biomass. The C present in biomass was assumed to be 50% (IPCC, 2003). The C stock obtained each compartment of each plot were extrapolated to estimate the C stock per hectare.

Soil organic carbon estimation

The cylinder method was used to calculate soil bulk density. It was determined through the following formula:

$$\text{BD}: \frac{W_d}{V}$$

where BD is bulk density (g/cm^3), W_d is the weight of the oven-dried soil sample (g) and V is the volume of the soil sample (cm^3).

Therefore, SOC was determined using the method developed by Walkley and Black (1934) in the soil laboratory of the Universidad Nacional Agraria La Molina, Lima, Peru. Soil inorganic C was not measured.

Soil organic carbon was calculated using the formula:

$$\text{SOC } (tC/\text{ha}) = \text{CC} \times D_s \times \text{BD}$$

where CC is the organic carbon content in the soil (%), D_s is the depth of the sampling zone (cm) and BD is bulk density (g/cm^3).

As differences in soil bulk density between the different systems were small and non-significant in all soil layers sampled, we used the fixed-depth approach to calculate the SOC stocks (Rahman *et al.*, 2018).

Data analysis

Statistical analyses were performed using R version 3.4.1. (R Core Team, 2019). The normality of the different variables related to C stock was checked using the Shapiro–Wilk's test ($P < 0.05$). ANOVA was used for multi-comparisons and Tukey's test, at a 0.05 significance level was used to compare the means. Pearson's correlations (r) were used to assess interrelations between the total aboveground C stocks and the dendrometric and diversity parameters.

Results

Metrics and use of shade trees

The diversity of perennial plant species varied between locations and types of coffee growing systems. A total of 174 individual shade trees were recorded across all the study sites and these comprised 24 different species from 12 families. In the polyculture-shaded coffee farms, 12 families, 22 species and two morphospecies were registered. The richest species families included Fabaceae and Meliaceae with six and three species, respectively. Polyculture-shaded coffee growing systems from Lamas showed the highest floristic richness (12 of 22 species), followed by El Dorado (10 of 22 species) and Moyobamba (9 of 22 species). The polyculture-shaded systems from El Dorado and Moyobamba showed a greater contrast in their structure, with a high predominance of *Cedrela odorata* and *Acrocarpus fraxinifolius*, respectively; while the polyculture-shaded system from Lamas had a more homogeneous distribution of species (Table 3). According to farmers, most of the shade trees in the polyculture-shaded coffee systems were selectively left on farmlands during land preparation and nurtured during coffee establishment. Furthermore, only one family and two species (*Inga edulis* and *Inga ruiziana*) were registered in the *Inga*-shaded coffee system.

The basal area (25.40 m^2/ha), tree height (10.02 m) and DBH (16.72 cm) values were highest in polyculture-shaded coffee in comparison to *Inga*-shaded coffee (basal area: 19.16 m^2/ha, tree height: 8.71 m, DBH: 13.91 cm). The Shannon–Weiner diversity index H' for polyculture-shaded coffee was higher than for *Inga*-shaded coffee, with values of 0.58 and 0.30, respectively. The present study determined relationships between tree metrics, the Shannon–Weiner diversity index H' and total aboveground C stocks aiming to understand how these parameters can affect C accumulation in shaded-coffee systems. Significant linear relationships were found between aboveground C stocks and mean tree height (r: 0.7404; R^2: 0.5482), aboveground C stocks and mean

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Table 3. Relative abundance of plant species in polyculture-shaded coffee farms.

Agroforestry system	Species	Family	Relative abundance (%)	Average no. trees/ha
Polyculture-shaded coffee – El Dorado	*Cedrela odorata*	Meliaceae	36.7	256.9
	Theobroma cacao	Malvaceae	16.7	116.9
	Vitex cimosa	Lamiaceae	6.7	46.9
	Mangifera indica	Anacardiaceae	6.7	46.9
	Aniba amazonica	Lauraceae	6.7	46.9
	Ceiba petandra	Malvaceae	3.3	23.1
	Inga edulis	Fabaceae	3.3	23.1
	Guarea guidonia	Meliaceae	3.3	23.1
	Ficus insipida	Moraceae	3.3	23.1
	Terminalia oblonga	Combretaceae	13.3	93.1
Polyculture-shaded coffee – Lamas	*Vitex cimosa*	Lamiaceae	16.7	100.2
	Swietenia macrophylla	Meliaceae	12.5	75
	Aniba amazonica	Lauraceae	8.3	49.8
	Syzygium jambos	Myrtaceae	8.3	49.8
	Cedrela odorata	Meliaceae	8.3	49.8
	Brosimum alicastrum	Moraceae	4.2	25.2
	Ficus insipida	Moraceae	4.2	25.2
	Persea americana	Lauraceae	4.2	25.2
	Apuleia leiocarpa	Fabaceae	4.2	25.2
	Sickingia williamsii	Rubiaceae	12.5	75
	Schizolobium amazonicum	Fabaceae	8.3	49.8
	Morphospecies 1	Combretaceae	8.3	49.8
Polyculture-shaded coffee – Moyobamba	*Acrocarpus fraxinifolius*	Fabaceae	40.5	283.5
	Colubrina glandulosa	Rhamnaceae	19.1	133
	Inga edulis	Fabaceae	11.9	83.3
	Schizolobium amazonicum	Fabaceae	14.3	100.1
	Syzygium jambos	Myrtaceae	2.4	16.8
	Hura crepitans	Euphorbiaceae	2.4	16.8
	Erythrina spp.	Fabaceae	2.4	16.8
	Inga ruiziana	Fabaceae	2.4	16.8
	Morphospecies 2	Combretaceae	4.7	32.9

DBH (r: 0.6084; R^2: 0.3701), aboveground C stocks and basal area (r: 0.4565; R^2: 0.2084), and aboveground C stocks and the Shannon–Weiner diversity index H' (r: 0.7834; R^2: 0.6137) (Fig. 2). The variations in the variables evaluated of the different agroforestry systems were due to factors such as system management, edaphoclimatic conditions and farm history.

Coffee yield increased as the percentage of shade cover decreased. The shade covers of the polyculture-shaded and *Inga*-shaded coffee systems were about 50 and 35%, with mean annual yields, based on the past 3 years, of 1.7 and 1.9 t/ha, respectively. The yield in the unshaded coffee system was 2.1 t/ha (Table 1). The interviewed farmers identified a total of 18 species as economically important. This represents 75% of the total number of tree species recorded in the coffee-growing systems. The uses of the shade trees were classified into five groups: fodder, food, wood, firewood and medicine (Table 4). All the useful species are used as firewood and the shade trees are additionally used as wood (55.6%), food (33.3%), medicine (16.7%) and fodder (5.6%). According to the interviews, farmers' decisions to conserve or plant trees in agroforestry systems are influenced by their own view of perceived increased value and environmental benefits.

Carbon stocks

Total C stocks and their distribution in the different compartments in the three coffee growing systems are presented in Table 5 ($P < 0.05$). Total C stocks were significantly higher in the shaded coffee growing systems than in the unshaded system and at the same time, the polyculture-shaded coffee system stored

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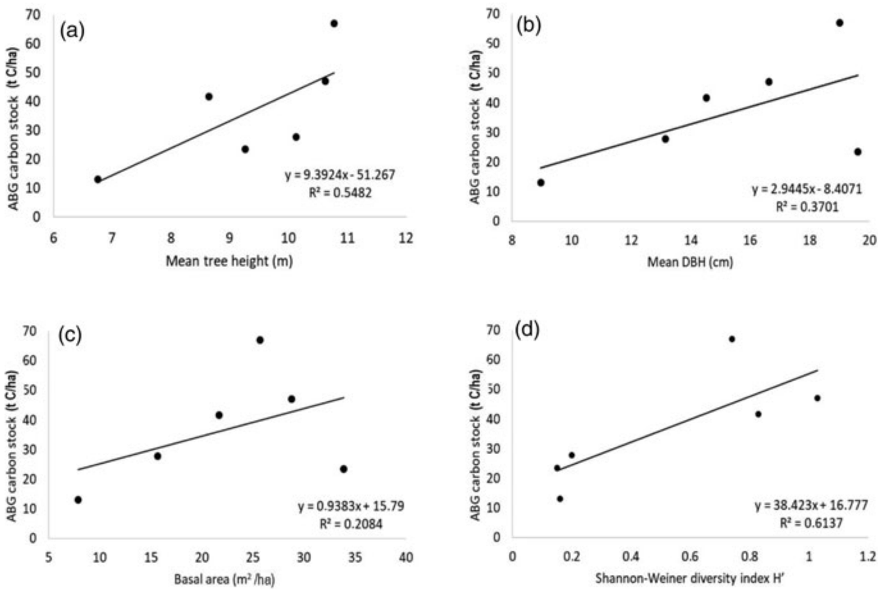

Fig. 2. Significant linear relationships between the aboveground (ABG) carbon stock with (*a*) the tree height, (*b*) the diameter at breast height (DBH), (*c*) the basal area and (*d*) the Shannon–Weiner diversity index H'.

Table 4. Use of shade tree species identified in shaded coffee plantations.

Species	Local name	Uses
Acrocarpus fraxinifolius	Cedro rosado	The wood is used for manufacturing furniture and building fences. The branches and the stems are used as firewood.
Aniba amazonica	Moena	The wood is used for manufacturing furniture and in construction. The branches are used as firewood.
Cedrela odorata	Cedro	The branches are used as firewood and the wood obtained from the stems is used for manufacturing furniture and in construction.
Ceiba petandra	Lupuna	The stem bark is used for the treatment of wounds and rheumatism. The wood is used in construction and as firewood.
Colubrina glandulosa	Shaina	The wood is used in rural constructions and the stems are used as firewood.
Erythrina spp.	Eritrina	The leaves are used as fodder for guinea pigs.
Ficus insipida	Ojé	Latex is used as purgative and against snakebites.
Inga edulis	Guaba	The fruits are edible and the stems are used as firewood.
Inga ruiziana	Shimbillo	The fruits are edible and the stems are used as firewood.
Mangifera indica	Mango	The fruits are edible and the stems are used as firewood.
Persea americana	Palta	The fruits are edible and the seeds are used for the treatment of diarrhoea.
Schizolobium amazonicum	Pinochuncho	The wood is used in construction and as firewood.
Sickingia williamsii	Pucaquiro	The wood is used for in the construction of houses and fences. The branches are used as firewood.
Swietenia macrophylla	Caoba	The wood is used for manufacturing furniture.
Syzygium jambos	Pomarrosa	The fruits are edible.
Terminalia oblonga	Rifari	The wood is used in construction and as firewood.
Theobroma cacao	Cacao	The seeds are used to produce chocolate and local drinks.
Vitex cimosa	Paliperro	The wood is used in the construction of houses and fences.

significantly more C than the *Inga*-shaded system. The total C stocks of the polyculture-shaded system ranged from 178 to 206 t C/ha with a mean of 189 t C/ha (Table 5). Moreover, 67.2% of the total C stored in the polyculture-shaded system was found in the soil, 24.4% in aboveground biomass of trees, 5.3% in roots of trees, 1.7% in litter, 1.3% in coffee plants and less than 1% of the total C stock was stored in dead wood. The species that contributed most to the aboveground C stock in the polyculture-shaded coffee system were: *Acrocarpus fraxinifolius* (7 t C/ha), *Cedrela odorata* (6.6 t C/ha), *Ficus insipida* (5 t C/ha) and *Schizolobium amazonicum* (5 t C/ha) (Fig. 3). The total C stored in *Inga*-shaded coffee system ranged from 137 to 155 t

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Table 5. Summary of carbon stocks in the different compartments in three coffee-growing systems.

	Polyculture-shaded coffee ($Mg\ C\ ha^{-1}$) ± SD	*Inga*-shaded coffee ($Mg\ C\ ha^{-1}$) ± SD	Unshaded coffee ($Mg\ C\ ha^{-1}$) ± SD
Coffee plants	2.4 ± 1.2[a]	1.6 ± 0.9[a]	2 ± 1.1[a]
Trees	46.1 ± 13.3[a]	15.8 ± 8.3[b]	–
Litter	3.3 ± 0.9[a]	4.2 ± 1.4[a]	2 ± 0.8[a]
Dead wood	0.2 ± 0.1[a]	0.2 ± 0.08[a]	–
Roots of trees	10 ± 2[a]	4.2 ± 1.9[b]	–
Soil (0–60 cm)	127 ± 6[a]	120 ± 2.9[ab]	109 ± 10[b]
Total	189 ± 14.9[a]	146 ± 8.8[b]	113 ± 9.8[c]

[(*)] Means followed by equal letters in the rows do not differ according to the Tukey test (*P < 0.05*).
SD, standard deviation.

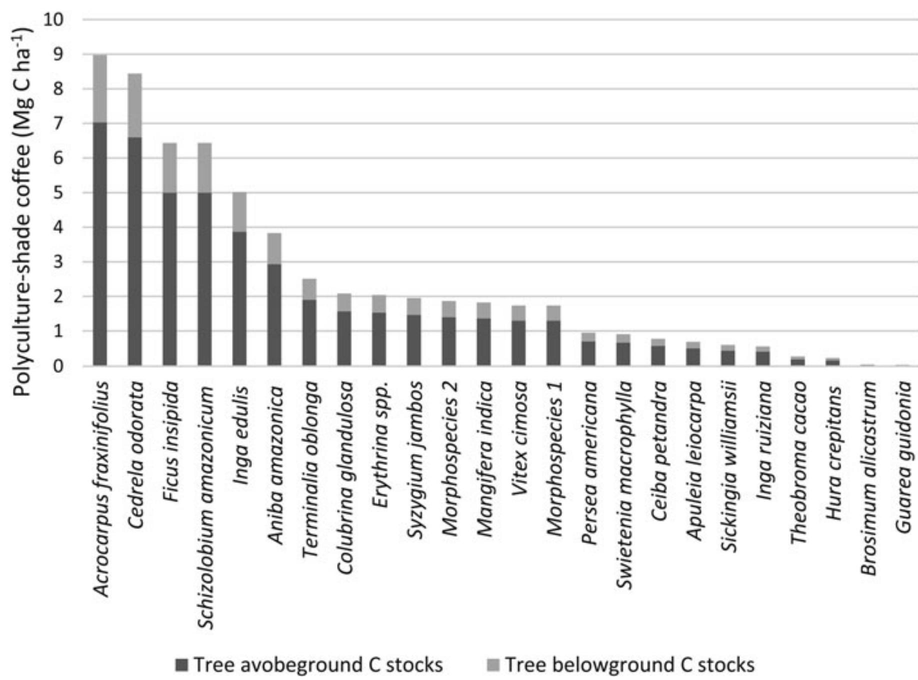

Fig. 3. Above- and belowground carbon stocks of trees at the species level in polyculture-shaded coffee.

C/ha with a mean of 146 t C/ha (Table 5). The distribution of C followed a similar trend than the polyculture-shaded coffee system, with the highest amount of C found in the soil (82.2%), followed by aboveground biomass of *Inga* trees (10.8%), roots of trees (2.9%), litter (2.9%), coffee plants (1.1%) and less than 1% of the total C stock was stored in dead wood. The total C stored in the unshaded coffee system ranged from 102 to 119 t C/ha, with a mean of 113 t C/ha. The highest amount of C was found in the soil (96.4%), while coffee plants (1.8%) and litter (1.8%) represented the remaining fraction (Table 5).

As expected, the largest C stock of all coffee systems was found in the soil. The SOC stock in the upper 60 cm was significantly higher in the polyculture-shaded coffee system (Table 5), which also had a significantly higher SOC stock in the layers 0–10 and 10–30 cm in comparison with the other systems. Regarding the 30–60 cm soil layer, there were no significant differences in the SOC stocks between any of the three coffee growing systems (Fig. 4, $P < 0.05$).

Discussion

Metrics and use of shade trees

The floristic composition of the studied agroforestry systems showed that polyculture-shaded coffee farms contained between 9 and 12 different species, approximately the same floristic richness found in Colombia, with agroforestry systems containing between 9 and 14 different species (Arango-Arroyave *et al.*, 2009). Another study from the Ucayali region (Peru) registered a much higher floristic richness in cacao agroforests, with 105 tree species identified (Vebrova *et al.*, 2014). The variations in the floristic composition of different agroforestry systems are brought about by factors such as location, management, cultural differences and farm history (Schroth and Harvey, 2007). The floristic composition of shade trees in coffee plantations, to a large extent, determines the conservation value of the plantation and their potential for the provision of goods and services, hence it is important to enhance the diversity of trees.

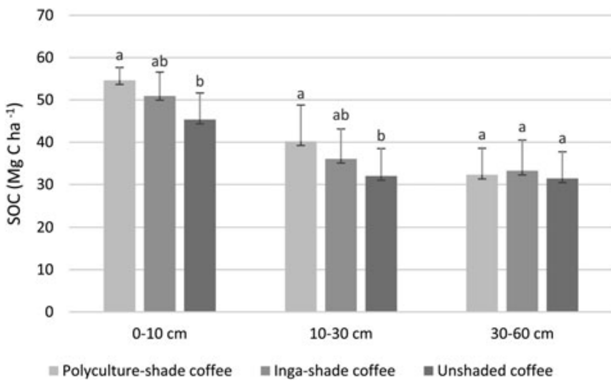

Fig. 4. Soil organic carbon (SOC) content in relation to depth in different coffee growing systems. Bars with equal letters in each soil depth do not differ according to the Tukey test.

The polyculture-shaded coffee system included tree species known to be severely negatively affected by selective logging, such as *Cedrela odorata* and *Swietenia macrophylla* (MINAM, 2015), showing that the inclusion of trees in coffee systems in agricultural landscapes enhances biodiversity and provides useful trees. Moreover, the main importance of shaded agricultural systems as a refuge for biodiversity is in areas that have been particularly affected by deforestation (Perfecto *et al.*, 1996). In West African landscapes, Dawoe *et al.* (2016) evaluated trees with DBH ⩾ 15 cm and found that the Shannon–Weiner diversity index H' ranged from 0.99 to 1.54 in 10 sites of shaded-cacao systems in West African landscapes. In the same line, Sambuichi *et al.* (2012) evaluated trees with DBH ⩾ 10 cm and found that the Shannon–Weiner diversity index H' ranged from 3.31 to 4.22 in shaded-cacao farms in Southern Bahia, Brazil. The present study evaluated trees with DBH ⩾ 3 cm and obtained lower values for the Shannon–Weiner diversity index H' (0.30–0.58), indicating that the evaluated coffee growing systems are less diverse.

The use of shade trees is of great importance to reduce pressure on forested lands and may contribute to diet diversification and income stability. Rice (2011) found that in Peru and Guatemala the overall importance of fruits from coffee systems accounts for a relatively small portion of the total value coming from the coffee area (about 10%); however, the consumption and sales of the various products generate needed income or sustenance for most farmers. In the current study, 33% of the species identified as economically important in the shaded coffee systems had edible fruits. Furthermore, 56 and 17% of the useful trees were reported as providers of wood and medicine, respectively. Guinea pigs are an important source of food in the rural communities of the region and the leaves of *Erythrina* spp. are used to feed these animals. Therefore, agroforestry systems allow the production of food, fodder, medicinal and timber plants without displacing traditional crops (Rice, 2008, 2011), thereby providing farmers with an extra source of income (Jezeer *et al.*, 2018).

Carbon stocks

The present study found large differences in total C stocks between shaded and unshaded coffee plantations, ranging from 33 (*Inga*-shaded coffee compared with unshaded coffee) to 76 t C/ha (polyculture-shaded coffee compared with unshaded coffee). These results are in agreement with findings of Ehrenbergerová *et al.* (2016), who found differences ranging from 20.2 to 77.8 t C/ha when comparing coffee agroforestry systems and unshaded coffee. The differences were mainly due to variations of C stocks in trees and soils in the different coffee growing systems, which in turn were caused by differences in edaphoclimatic conditions and local agricultural practices (Soto-Pinto *et al.*, 2010; Häger, 2012). Although the total C stock of the polyculture-shaded coffee plantation was 47.5% of the total C stock of primary forests in the same region (Díaz *et al.*, 2016), the C stocks found in the agroforestry systems in question (189 t C/ha) fell above the range of C storage potential reported for agroforestry systems in humid tropics of South America (39–102 t C/ha) (Albrecht and Kandji, 2003). This highlights the importance of locally adapted agroforestry practices for reducing CO_2 concentrations in the atmosphere by fixing C in agricultural landscapes. This is especially important in the Peruvian Amazon, as it is a hotspot of deforestation (Finer and Mamani, 2018).

The tree size rather than the number of trees contributed most to C stocks in the aboveground biomass, showing that the incorporation of long-lived trees in agroforestry systems provide opportunities to increase C storage in agricultural fields (Albrecht and Kandji, 2003). In our study area, *Acrocarpus fraxinifolius*, *Cedrela odorata*, *Ficus insipida* and *Schizolobium amazonicum* were the four species that most contributed to the aboveground C stock in the polyculture-shaded coffee system (51.2%); however, these species are little used in the implementation of agroforestry systems. The shading in the conventional coffee plantations of San Martin derives mainly from trees of *Inga* spp. (Jezeer and Verweij, 2015) but considering the contribution to the C stock of the four species previously mentioned, it is advisable to diversify the tree species used in the implementation of agroforestry systems. Aligned with our results, other studies performed across the tropics suggest that management practices in agroforestry systems increase C stocks and enhance tree diversity (Henry *et al.*, 2009; Jacobi *et al.*, 2014; Sari *et al.*, 2020).

The aboveground C stock in the unshaded system was 4 t C/ha, while Hergoualc'h *et al.* (2012) reported aboveground C stocks of a monoculture coffee plantation in Costa Rica to be 9.8 t C/ha. The literature reports that coffee plants contain higher biomass when they grow without shade, which is probably a consequence of greater light absorption (Dossa *et al.*, 2008). The present study did not find differences in C stocks of coffee plants among the evaluated systems, probably because the coffee plants had already reached the maximum vegetative development and, moreover, farmers control vegetative development of coffee branches through pruning. The C stored in litter of the investigated coffee systems ranged from 2 to 4.2 t C/ha and was higher in *Inga*-shaded coffee. These values are similar to those reported by Häger (2012) ranging from 3.3 to 4.8 t C/ha. *Inga edulis* is a species widely used in agroforestry systems of the San Martin region (Jezeer and Verweij, 2015) because it is tolerant to pruning and produces abundant branches, which provide enough foliage for a permanent cover of litter. Accordingly, the *Inga*-shaded coffee-growing system showed the highest C content in litter, although not significantly different from the contents of the other systems analyzed.

The land-use history of the coffee plantations included in our study is likely to have affected the current SOC stocks. The previous land-use of the sites under polyculture-shaded coffee plantations were secondary forests while the sites under the other coffee-growing systems were mainly used for cultivation of maize and banana. As SOC stocks of the secondary forests were most likely higher than stocks under maize and banana – and

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as the SOC pool responds slowly to changes in land-use – the high SOC stocks under polyculture-shaded coffee plantations are likely to be partially caused by this difference in land-use history (Laganière *et al.*, 2010; Bruun *et al.*, 2013). However, as transitions from secondary forest to polyculture-shaded coffee and transitions from extensive agriculture to the other types of coffee growing systems represent the common transition pathways in the region, we consider this potential effect of the previous land-use as an inherent part of the systems.

The effects of forest clearing and continuous cropping systems on SOC stocks are most pronounced in surface layers (Sommer *et al.*, 2000; Bruun *et al.*, 2018) and in line with this, the polyculture-shaded coffee system had higher SOC stock than the other coffee-growing systems in the 0–10 and 10–30 cm soil layers. The SOC stocks in the upper 30 cm of the soil were 95, 87 and 77 t C/ha for the polyculture-shaded, *Inga*-shaded, and unshaded coffee systems, respectively. In the same line, the polyculture-shaded coffee had 127 t C/ha in the 0–60 cm soil depth interval, 16.5 and 5.8% more than in *Inga*-shaded and unshaded coffee systems, respectively. The present findings are comparable to the SOC stocks found in the Pasco region of Peru in the 0–30 cm soil layer of different coffee growing systems, which ranged from 82.6 to 101.8 t C/ha (Ehrenbergerová *et al.*, 2016). The high SOC stocks in shaded systems are related to the previous land-uses and to the high input of organic matter from trees that also maintain sufficient litter layers to protect the soil surface (Bruun *et al.*, 2009; Hairiah *et al.*, 2020). Moreover, no significant effects were observed in the 30–60 cm soil layer in any of the evaluated coffee systems.

Agroforestry systems that use native trees can contribute to conservation by providing habitat and resources to a wide range of plant and animal species, enhancing landscape connectivity, reducing edge effect and improving local climate (Asase and Tetteth, 2010; Jacobi *et al.*, 2014). In addition, they can store large amounts of C over the long run (Jose and Bardhan, 2012). However, agroforestry systems require the conservation of forest patches in agricultural landscapes (Schroth and Harvey, 2007) for creating biological corridors that connect forests with the implemented agroforestry systems. The relationship between forests, agroforestry and biodiversity can be made most productive through applying adaptive management approaches that incorporate ongoing research and monitoring in order to feed information back into the management system (McNeely, 2004). This information will assist in determining more pragmatic approaches to managing coffee production landscapes in order to protect remnant forests.

Conclusions

The inclusion of trees in coffee farming systems not only has environmental value, but that same shade component contributes to the diversification of the diet and to the generation of income. The tree species richness had a positive impact on both above- and belowground carbon stocks, which influenced for that the total carbon stock in the polyculture-shaded coffee system to be higher than the *Inga*-shaded and unshaded systems. Moreover, as expected, the largest C stock of all investigated coffee systems was found in the soil. Therefore, agroforestry systems in the area play a significant role in carbon storage by promoting conservation of useful trees in agricultural landscapes, thereby potentially reducing human pressure on forested lands.

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