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Carbon stock in agroforestry coffee plantations with different shade trees in Villa Rica, Peru

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Abstract Agroforestry has become an important land use type in Central and South America. It is important to study agroforestry systems because of their ability to sequester carbon. This study investigates plantations that are located in the foothills of the Peruvian Andes, and it evaluates the aboveground and soil carbon storage of agroforestry coffee plantations with different dominant shading trees, including *Inga* spp., *Pinus* spp. (both 15 years old) and *Eucalyptus* spp. (7 years old). These agroforestry systems were also compared to a coffee plantation without shading trees. Biomass and carbon were estimated for trees and coffee shrubs using allometric equations. Soil (within depth of 30 cm) and litter carbon were estimated using field sampling and laboratory analyses. The total carbon stock for the site dominated by *Inga* spp. was 119.9 ± 19.5 Mg ha^{-1}, while for the sites dominated by *Pinus* spp. it was 177.5 ± 14.1 Mg ha^{-1} and for the site dominated by *Eucalyptus* spp. it was 162.3 ± 18.2 Mg ha^{-1}. In the Sun coffee site the ecosystem carbon stock was 99.7 ± 17.2 Mg ha^{-1}. Most carbon was fixed in the soil compartment (57–99 %), followed by aboveground tree biomass (23–32 %), tree belowground biomass (8–9 %), coffee shrubs (0.2–2 %) and litter (1 %).

Keywords Agroforestry systems · Ecosystem carbon storage · Biomass · Soil · *Coffea arabica* · Peru

Introduction

In the last few years, the importance of research on mitigation, i.e. reducing the sources or enhancing the sinks of greenhouse gases, especially mitigation of CO_2, has been increasing due to climate change effects. Unsuitable land use activities (mainly deforestation) are the second major source of anthropogenic CO_2 emissions (IPCC 2013), and agroforestry systems seem to be an acceptable management of crop production, as well as for CO_2 mitigation through an increase in carbon stocks (Schroth et al. 2002).

In agroforestry systems, trees or shrubs are grown around or among crops or pastureland (Nair 1993), and the recognition of this system as a greenhouse gas–mitigation strategy under the Kyoto Protocol has

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earned it the right to be part of the strategy for biological carbon sequestration (Nair et al. 2009a). Research on carbon sequestration in different types of land use provide information for the Reduced Emissions from Deforestation and Forest Degradation (REDD) programs that would likely allow some countries to sell carbon credits to interested buyers or received financial support from funds (The World Bank 2011). Agroforestry systems help REDD by reducing pressure for further forest conversion to agriculture (Noponen et al. 2013) and by serving as a source of fuel-wood and construction material (Rice and Ward 2008). This system has special importance because of its applicability in agricultural lands as well as in reforestation programs (Ruark et al. 2003). Moreover, according to Smith and Scherr (2003), community-based agroforestry carbon projects have the highest potential for local livelihood benefits and pose less risk to communities than large-scale industrial plantations and strict forest protection.

Many studies have investigated the effect of agroforestry systems on carbon storage. Some of these studies have compared different types of pastures and crops and have assessed the effect of tree shading (Soto-Pinto et al. 2010; Avila et al. 2001). Schmitt-Harsh et al. (2012) examined the carbon pools of smallholders of coffee plantations in agroforestry systems and compared them with mixed dry forest systems in Guatemala. The results showed that secondary forests store more carbon (199 Mg ha^{-1}) than coffee agroforestry systems (128 Mg ha^{-1}). Similar results were found by Noordwijk et al. (2002) for secondary forests and agroforestry coffee systems in Sumatra. However, in this study, the difference in carbon storage was even larger (262 Mg ha^{-1} for secondary forests and 82 Mg ha^{-1} for agroforestry coffee systems). Hergoulaćh et al. (2012) compared the greenhouse gas balance in two coffee plantations: a monoculture and a culture shaded by *Inga densiflora,* and found that the aboveground carbon stocks in the coffee monoculture and the agroforestry system amounted to 9.8 ± 0.4 and 25.2 ± 0.6 Mg ha^{-1}, respectively. In a study by Häger (2012) from Costa Rica, carbon stock in coffee agroforestry farms was 93 ± 29 Mg ha^{-1}.

Soil plays a crucial role in carbon sequestration. Among many different types of land use focused on agronomical production, agroforestry systems can be considered as systems with high effectiveness of soil carbon storage, as well as with low vulnerability, compared with other types of intensive land management (Nair et al. 2009b). Despite continuous crop exploitation, agroforestry production conserves the soil environment due to more closed nutrients and water turnover via tree cover producing litter and shading the soil surface, as well as sustaining the less-eroded soil body. Moreover, in some studies, soil organic matter was found to have increased over 10 years by 16–42 Mg ha^{-1} in the 0–45 cm layer (Beer et al. 1998), which is about 8–21 Mg C ha^{-1}, depending on the planted shading species and commodities. On the other hand, soil organic matter dynamics are driven by many factors, in general by climate, soil type and land use management, which determine the physical, chemical and biological controls of soil carbon sequestration and turnover (Feller and Beare 1997).

Coffee (*Coffea* spp.) is very important cash crop cultivated in an area of slightly more than 100,000 km^2 (Lewin et al. 2004; Leff et al. 2004). It is traditionally grown under the shade of trees, forming typical agroforestry systems (Wintgens 2004). Shade trees provide numerous benefits; there is an added value of wood production, which can be expressed either in terms of woody biomass or carbon fixation (Batjes and Sombroek 1997; Hergoulaćh et al. 2012; Häger 2012), and these plantations may also act as a critical refuge for forest biota, including birds, insects, mammals and reptiles (Perfecto et al. 1996; Moguel and Toledo 1999).

In Peru, the conversion of forests and grasslands to agricultural purposes is the main source of GHG emissions (MINAM 2010). According to Stephen (2005), 1879 km^2 of forests were lost annually between 1985 and 1990 in Peru. Oliveira et al. (2007) reported that between 1999 and 2005, disturbance and deforestation rates throughout the Peruvian Amazon were between 632 and 645 km^2 per year. According to Meza et al. (2006), about 80 % of the deforested area was left unmanaged, while the rest was used for agricultural production in Peru in 2002. This indicates a potential for agroforestry system expansion in this country.

The local leguminous species of the genus *Inga* are often used as the principal shade trees in Peru (Rice and Ward 2008). *Inga* species fix N and also produce a great deal of litter, which enriches the soil with organic material (Brack 1999; Rhoades et al. 1998). For this reason they are the ideal shade trees for coffee plantations. However, an increasing number of Peruvian coffee farmers have changed the species composition of their plantations in recent years, replacing traditional legume shade trees with native or exotic timber species. This trend has been previously observed for all of Central America (Galloway and Beer 1997). In Peru, the most common introduced tree species used for shading in coffee plantations are *Pinus* spp., *Eucalyptus* spp. and *Acrocarpus fraxinifolius*. Until now, only a few studies have investigated the impact of the aforementioned introduced tree species on coffee plantations. Shaller et al. (2003), in his study from Costa Rica, found that *Eucalypthus deglupta* is a suitable shade tree for coffee on sites with high precipitation. With regard to studies dealing with *Pinus* spp. as agroforestry system species, there are only papers about outplantings of pines on pasturelands (Yeates et al. 2000; Sequeira and Gholz 1991).

On optimal sites, coffee can also be grown without shade (Campanha et al. 2004) but using high agrochemical inputs (Beer et al. 1998). It is estimated that in Mexico, Colombia, Central America and the Caribbean, approximately 40 % of agroforestry coffee plantations were converted to sun coffee in the 1990s (Rice and Ward 1996). Monoculture coffee plantations could be a threat to tropical rainforests because of land degradation and poor land management (Fernandez 2001). The quantity of shade influences the coffee yield: according to Soto-Pinto et al. (2000) shade tree cover had a positive effect in a range between 23 and 38 % shade cover while Muschler (1997) found the best yields at 40 % shade cover. Between 38 and 48 % shade, yield is maintained and it decreases with a shade cover greater than 50 % (Soto-Pinto et al. 2000).

It is important to assess carbon stocks provided by agroforestry ecosystems under different shade trees as an additional ecosystem service. The goal of this study was to compare the ecosystem carbon storage ability of agroforestry coffee plantations with different shade trees and without shading, in both aboveground and belowground carbon pools. The results of this study may contribute to the preservation and planting of shade trees for the benefit of carbon sequestration. Evaluating the carbon storage capacity of coffee agroforestry systems with different shade tree species will contribute to a better understanding of the role that these ecosystems can play in REDD + programs because, as mentioned by Schmitt-Harsh et al. (2012), quantifying and understanding carbon budgets of shade-grown coffee systems is needed for the development of sound climate change mitigation strategies.

Materials and methods

Study area description

This study was conducted in the Villa Rica district, in the Pasco region of Peru (Fig. 1). The average annual rainfall in this tropical humid mountain forest zone is 1,590 mm, and the average annual temperature is 17.8 °C (Ponce et al. 2008). The rainy season lasts from November to May, while a dry season occurs during July and August (Hamling and Salick 2003). According to the FAO (Food and Agriculture Organization), soils in this region are classified as dystric Cambisols (Egg 2012; Michéli et al. 2006) of low structural stability. The main economic activity in the district is agriculture, mostly from coffee production. Villa Rica is one of the most important districts for coffee production and export in Peru; its landscape is characterised by shaded coffee plantations with some cattle farming.

The following agroforestry coffee plantations were selected for study: Ave Fénix, which was divided into two parts: a first part shaded by *Inga* spp. (further termed as *Inga* site) and a non-shaded part (Sun coffee site); Santa Rosa shaded by *Pinus* spp. (*Pinus* site) and Gabriela shaded by *Eucalyptus* spp. (*Eucalyptus* site). In the past, these sites were used as pastureland. Currently, they are maintained as typical agroforestry systems (except the Sun coffee site) with *Coffea arabica* as the principal crop, with sparse stands of shading trees.

The coffee plantation Ave Fénix is located in Alto Palomar, near the town of Villa Rica (Table 1; Fig. 1). The *Inga* site forms one part of this plantation shaded predominantly by *Inga* spp. It represents a typical shaded coffee plantation in this region as regards management and tree species composition. The other part of the Ave Fénix plantation, where shade trees were absent, is the Sun coffee site serving as a reference coffee plantation without shading. The field has rough-broken topography with an average slope angle of 18.2°. The upper 30 cm of soil at the *Inga* and Sun coffee sites has its texture classified as loam (*Inga* site: clay 25.4 %, silt 33.6 %; Sun coffee site: clay

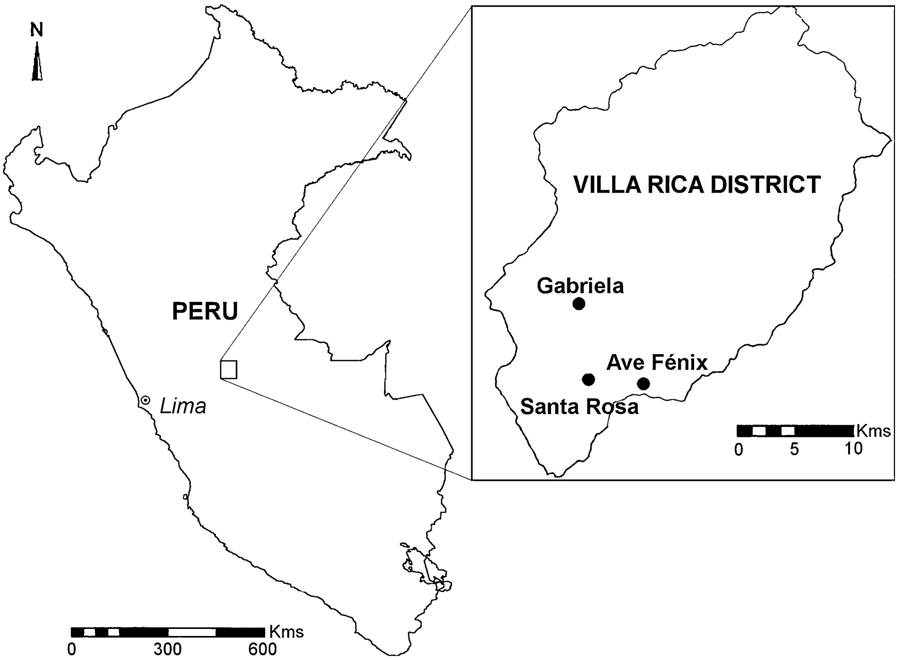

Fig. 1 Location of studied plantations

Table 1 Selected plantations, their location, area, mean altitude, dominant tree species and age

Plantation	Site	X (UTM)	Y (UTM)	Area (ha)	Altitude (m.a.s.l.)	Dominant tree species	Stand age (years)
Ave Fénix 1	*Inga*	475784	8808864	7.37	1550	*Inga* spp.	15
Ave Fénix 2	Sun coffee	475784	8808864	0.98	1550	(n.a.)	(n.a.)
Santa Rosa	*Pinus*	471531	8809929	3.98	1540	*Pinus* spp.	15
Gabriela	*Eucalyptus*	471882	8816212	0.96	1660	*Eucalyptus* spp.	7

UTM Universal transverse mercator, *m.a.s.l.* meters above sea level, dominant tree species and age, *n.a.* not applicable

24.4 %, silt 31.3 %, respectively), with extremely acidic soil reaction (pH/KCl 4.0 and 3.7, respectively), and a high amount of organic carbon (Table 5). In the Ave Fénix plantation, we identified the following coffee varieties: Typica, Catimor, Caturra and Catuai.

The Santa Rosa plantation (*Pinus* site) is located in Oconal, 4 km south of the town of Villa Rica (Table 1; Fig. 1). The average slope angle is 16.4°. In the first 30 cm, soil texture is classified as loam (clay 15.0 %; silt 37.0 %), soil reaction is extremely acidic (pH/KCl 4.1), and the amount of organic carbon is very high (Table 5). The Santa Rosa plantation was chosen because of the *Pinus* spp. dominance. It is the first generation of coffee shaded by *Pinus* spp. after a change from pastureland and is also one of the first coffee agroforestry plantations shaded by *Pinus* spp. in the region. The following coffee varieties were found: Typica, Catimor and Caturra.

The plantation Gabriela (*Eucalyptus* site) is located 4 km north of the town of Villa Rica (Table 1; Fig. 1). The Gabriela plantation is the smallest, and *Eucalyptus* spp. are the dominant shade tree species there. This is the first generation of coffee shaded by *Eucalyptus* spp. after conversion from pastureland, and it is also one of the first coffee plantations shaded by *Eucalyptus* spp. in the region. The site is more homogenous with an average slope angle of 18.5°. The soil by its texture is classified as loam (clay 19.0 %; silt 33.3 %), with strongly acidic soil reaction (pH/KCl 4.4), and a high amount of organic carbon (Table 5). The following coffee varieties were present: Typica, Catimor and Caturra.

Table 2 Allometric models used for aboveground biomass calculation for individual tree species

Species group	Allometric model	References
Inga spp.	$\log_{10} y = -0.889 + 2.317 \times \log_{10} DBH$	Segura et al. (2006)
Pinus spp.	$y = 0.1229 \times (DBH)^{2.3964}$	Návar (2009)
Eucalyptus spp.	$y = 2.08 + (150.9 + 0.28AGE)(DBH^2H)^{(0.87+0.0012AGE)}$	Saint-André et al. (2005)
Other trees	$y = 0.0776 \times (\rho DBH^2H)^{0.94}$	Chave et al. (2005)

Segura et al. (2006) model for *Inga punctata* and *I. tonduzzi* tree species

y Aboveground biomass (kg/tree), *DBH* diameter at breast height (cm), *H* tree height (m), *ρ* wood density (g/cm^3), *AGE* tree/plantation age (years)

All plantations are certified as organic with similar management and inputs. In the past, the selective thinning of shade trees and coffee shrubs has been used on all plantations. Currently, the shade trees are planted at the same time as coffee shrubs, and after 15–20 years, they are removed and replaced by new ones. Coffee is pruned regularly in systematic way (one line of coffee shrubs is pruned every year) at a height of 0.3–0.5 m, and all farmers left the organic material from pruning on their farm to decompose. Management is relatively simple and applied identically across all coffee plantations at each location.

The actual climate at the studied sites is documented by the vapour pressure deficit (VPD) measured at the *Inga* and Sun coffee sites during 2011 and 2012. The mean monthly values reach approximately 500 Pa during the dry season, while the VPD is markedly lower during the rainy season. This trend is identical for shaded and open locations, but the VPD in tree shading locations (in this case, in an area dominated by *Inga* spp.) is generally lower compared to open space coffee plantations.

Tree measurement, biomass and carbon stock estimation

Field measurements were conducted in 2011 and 2012. Diameters at breast height (DBH; measured at 1.3 m) of all tree species ≥10 cm were measured at each study site. In total 1368 trees were measured in the *Inga* site, 492 in the *Pinus* site and 511 in the *Eucalyptus* site. Tree heights were measured by Impulse Forest Pro for almost all trees in the study plots. The missing tree heights for the remaining trees, representing 3.7 % of the entire dataset, were estimated based on the approximated height model according to Eq. 1,

$$H = 1.3 + \mathrm{p}_1 * \exp(-\mathrm{p}_2/DBH) \tag{1}$$

where *DBH* is the diameter at breast height and p_1 and p_2 are the parameters that were fitted. This exponential model (Ratkowsky 1990) was parameterised for each tree species individually.

The dry aboveground biomass of shade trees was estimated using available allometric models applicable for the species present at the studied plantations. In the case of *Inga* spp., *Pinus* spp. and *Eucalyptus* spp., the corresponding specific allometric models were used. For all other trees, the generic allometric model developed by Chave et al. (2005) for moist forest stands was used (Table 2), as it was found to be best suited for our study. For this model, the values of tree density from different sources were employed (Nogueira et al. 2005; Barker et al. 2004; Brown 1997; Silva et al. 1994). If a species was included in different databases, then the lowest published wood density was applied. Adjusted values for tree aboveground biomass means and confidence intervals for each plot were obtained by a bootstrapping procedure, using SYSTAT 13.1 statistical software (SYSTAT Software. Inc. USA). The belowground tree biomass component was estimated using the regression equations for predicting root biomass density used by Cairns et al. (1997) (Eq. 2),

$$\mathrm{Y}\left(\mathrm{Mg\,ha^{-1}}\right) = \exp[-1.0850 + 0.9256 * (\ln \mathrm{ABD})] \tag{2}$$

where *ABD* is the aboveground biomass density.

For calculations with errors the method of standard deviation was used (Eq. 3),

$$z = x + y \rightarrow \Delta z = \sqrt{(\Delta x)^2 + (\Delta y)^2} \quad (3)$$

where x and y are measured quantities and Δx and Δy their uncertainties.

The quantity of carbon was measured as 50 % of the estimated biomass (IPCC 2003; Roy et al. 2001).

Coffee plant measurement and biomass and carbon stock estimation

Field measurements of coffee shrubs were conducted in 2011. In total, 64 rectangular sample plots of 100 m^2 were established to monitor coffee plants. Plots were located randomly in the systematic grid of squares, and the heights of all coffee shrubs were measured. The dry aboveground biomass of coffee plants (B_C) was estimated based on the model developed in Segura et al. (2006). We used this equation (Eq. 4) because it was applicable for coffee plants using plant height as the sole independent variable in the logarithmic form

$$\mathrm{Log}_{10}(\mathrm{B_C}) = -0.779 + 2.338 * \mathrm{Log}_{10}(\mathrm{H}) \quad (4)$$

where *H* is the height of coffee shrubs.

The carbon quantity was measured using the same formula used for trees, which was 50 % of the estimated biomass of coffee shrubs (IPCC 2003; Roy et al. 2001).

Soil properties

Soil samples were collected from six rectangular plots in each site (24 in total) with similar slopes (approximately 15°) which were selected from 64 coffee survey plots. In each square plot, soil samples were collected from three randomly selected sample locations. At each sample location, the soil samples were collected as (1) undisturbed soil samples (physical ring with volume 100 cm^3), which were collected from three soil pits in four sampling depths (0–3.5; 3.5–12.5; 12.5–21.5; and 21.5–30 cm), and (2) litter from a circle with a diameter of 0.336 m. Samples were weighed as fresh, as well as oven-dried at 105 °C. The bulk density was calculated using the following formula (Eq. 5),

$$\mathrm{r_d} = \mathrm{m_{od}}/\mathrm{V}\left(\mathrm{g/cm^3}\right) \quad (5)$$

where r_d is the bulk density, m_{od} is the weight of the oven-dried soil sample in g, and *V* is the volume of the soil sample (100 cm^3).

Because the presumed prevailing form of carbon in the investigated soils was the carbon present in soil organic matter (SOM), the carbon content was assessed as the oxidative carbon (C_{ox}) percentage (%), according to Walkley and Black (1934). Soil carbon in Mg ha^{-1} (SC) was calculated using Eq. 6,

$$\mathrm{SC} = \mathrm{r_d} * \mathrm{s_t} * \mathrm{C_{ox}}\left(\mathrm{Mg\,ha^{-1}}\right) \quad (6)$$

where r_d is bulk density in g × cm^3, s_t is the depth of the sampling zone in cm and C_{ox} is oxidative carbon content in %.

SC was expressed (1) as the cumulative SC content (CSC) within the 30 cm depth to obtain the total SC storage and (2) as the relative value of soil carbon content in 1 cm of each sampling depth (relative soil carbon—RSC). To quantify litter amount, litter samples were oven dried at 105 °C and weighed. The results were recalculated to Mg ha^{-1}. Soil reaction was measured as pH/H_2O and pH/1 M KCl, both in a suspension soil sample: extractant 1:1 (w:v), soil texture was assessed using a sedimentary method.

Results

Dendrological and mensurational data

Some of the dominant species in the *Inga* site based on basal area (BA) were as follows: *Inga* spp. (*Inga adenophylla* Pittier, *I. densiflora* Bentham, *I. edulis* C. Marius, *I. feuillei* DC., *I. velutina* Willdenow), *Pinus* spp (*Pinus oocarpa* D. Don., *P. tecunumanii* (Schwd) Equiluz & Perry), *Retrophyllum rospigliosii* (Pilger) C. Page (Table 3) and other trees that were less represented, including *Euphorbia heterophylla* L. and *Ficus* spp. The *Pinus* site was dominated by *Pinus* spp. (*Pinus oocarpa, P. tecunumanii*) and the most represented tree species were *Acrocarpus fraxinifolius* Wt. & Arn., *Eucalyptus* spp., *Inga* spp., *Pinus* spp. and *Retrophyllum rospigliosii* (Table 3). *Eucalyptus* spp. was the dominant tree species at the *Eucalyptus* site; other tree species included *Acrocarpus fraxinifolius*, *Inga* spp., *Pinus* spp. and *Retrophyllum rospigliosii* (Table 3). The hectare indices of counts and the stand basal area of trees and coffee shrubs in the plantations are documented in Table 4. As for tree density, it was highest at the *Eucalyptus* site and lowest at the *Pinus* site. The *Eucalyptus* site also had the largest stand

Table 3 Tree species composition based on count and stand basal area (BA) representation

Species	*Inga* site		*Pinus* site		*Eucalyptus* site	
	Count (%)	BA (%)	Count (%)	BA (%)	Count (%)	BA (%)
Inga spp.	63.8	45.9	2.6	1	5.1	2.4
Pinus spp.	7.2	7.8	67.5	61.9	2.4	0.5
Eucalyptus spp.	3.8	3.1	23.8	32.7	72.4	87.7
Retrophyllum rospigliosii	4.1	5.7	4.7	3.9	0.2	0
Acrocarpus fraxinifolius	9.8	2.8	0.6	0	18.8	8.4
Other	11.3	34.7	68.3	0.5	1.1	1

Table 4 Tree and coffee plant counts per hectare stand basal area and mean tree height

	Inga site	*Pinus* site	*Eucalyptus* site
Trees per 1 ha—live (pcs)	176	124	472
Stand basal area—live (m^2 ha^{-1})	12.9	16.6	18.5
Tree H (m)	13.7 ± 2.4	22.2 ± 4	20.8 ± 3.8
Number of coffee shrubs per ha	6830	4840	2950

basal area. Inversely to above, the highest density of coffee shrubs was present at the *Inga* site.

Biomass and carbon stock

The aboveground dry biomass of shade trees varied between 9.9 kg (*Erythrina edulis* Triana ex Micheli) and 18,400 kg (*Cariniana decandra* Ducke) per tree (DBH $\geq$ 10 cm). The biomass of coffee plants was approximately two orders of magnitude smaller, with a mean of 0.5 ± 0.2 kg per coffee plant. The estimated total aboveground biomass was 60.6 ± 6.4 Mg ha^{-1} for the *Inga* site, 124 ± 9.4 Mg ha^{-1} for the *Pinus* site, 107 ± 6.2 Mg ha^{-1} for the *Eucalyptus* site and approximately 1.9 ± 0.2 Mg ha^{-1} for the Sun coffee site.

A comparison of the tree carbon stock in dominant tree species on the plantations studied yielded approximately 115 ± 51 kg/tree for *Inga* spp., 387 ± 152 kg/tree for *Pinus* spp. and 270 ± 197 kg/tree for *Eucalyptus* spp. The distribution of carbon stocks for dominant tree species by 10-cm diameter classes is shown in Fig. 2.

As expected, the relative soil carbon (RSC) values are the highest in all cases in the upper layers of soil and decrease with depth (see Table 5; Fig. 3). Variability is relatively large at the surface layers of soil at the *Inga*, *Pinus* and *Eucalyptus* sites, where higher heterogeneity due to more intensive interaction with external carbon sources can be expected, which corresponds to variation in litter content (Table 7). The values of RSC, as well as C_{ox} and cumulative SC (Table 7), are highest at the *Pinus* site, which is mainly due to a slower decrease in carbon content as depth increased. However, at the Sun coffee site, the carbon storage characteristics are not as low as expected due to the absence of trees, but they are higher than at the *Inga* site. This may be caused by the young age of the plantations (Hergoulaćh et al. 2012) because the effect of shading trees in the agroforestry system is not yet evident on the level of the soil environment. For the cumulative SC values (Fig. 4), polynomial equations were used (Table 6) to compare our values with the results of other studies.

A comparison of the total carbon stock in the different types of coffee plantations is shown in Table 7 and in Fig. 5. The highest amount of carbon in tree biomass was fixed at the *Pinus* site. The amount of carbon held in the coffee shrubs was also highest at the same site. The amount of carbon held in tree biomass was smaller at the *Eucalyptus* site and smallest in the *Inga* site. Although *Inga* spp. trees have large crowns, their stem diameter and planting densities are low, which explains the lower values of carbon held in tree biomass compared to other plantations with different tree species used for shading. The carbon stock in coffee shrubs was about the same at the *Inga* and *Eucalyptus* sites. The smallest amount of carbon held in coffee shrubs was observed in the Sun coffee site.

Fig. 2 Distribution of carbon stocks in 10-cm diameter classes for *Inga* spp., *Pinus* spp., *Eucalyptus* spp. and other tree species

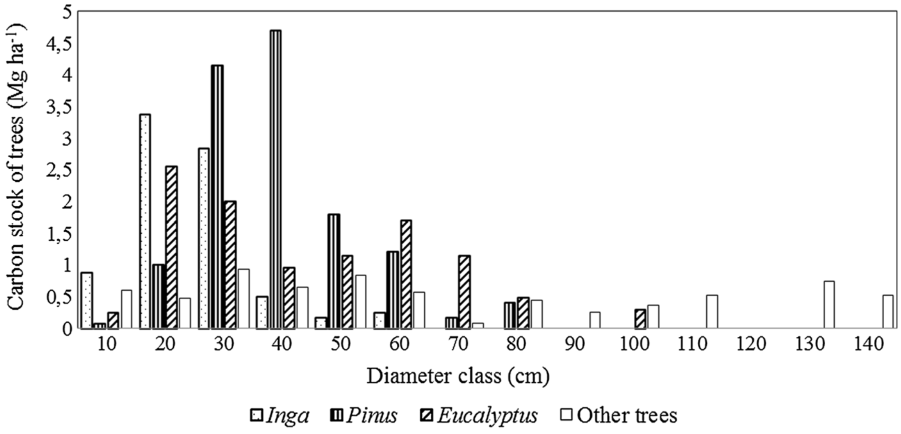

Table 5 Soil carbon stock at the investigated sites at different sampling depths

Site	Sampling depth (cm)	C_{ox} (%) ± 1/2 SD	CSC (Mg ha^{-1}) ± 1/2 SD	RSC (Mg ha^{-1}) ± 1/2 SD
Inga	3.5	4.44 ± 0.87	19 ± 7.3	5.43 ± 1.04
	12.5	2.55 ± 0.73	50 ± 23.2	3.45 ± 0.96
	21.5	1.69 ± 0.65	71.5 ± 35.4	2.38 ± 0.82
	30	0.89 ± 0.25	82.6 ± 38.4	1.31 ± 0.35
Sun coffee	3.5	4.65 ± 0.64	19.2 ± 5.3	5.49 ± 0.76
	12.5	3.11 ± 0.80	51.5 ± 15.3	3.58 ± 0.78
	21.5	2.44 ± 0.74	81.2 ± 25.3	3.31 ± 1.04
	30	1.45 ± 0.48	98.7 ± 34.3	2.06 ± 0.72
Pinus	3.5	4.55 ± 0.77	19.8 ± 6.9	5.66 ± 0.99
	12.5	4.05 ± 0.73	62.7 ± 17.7	4.76 ± 0.82
	21.5	2.31 ± 0.43	89.8 ± 24.2	3.01 ± 0.56
	30	1.02 ± 0.21	101.8 ± 26.7	1.42 ± 0.31
Eucalyptus	3.5	4.56 ± 0.84	18 ± 6.4	5.16 ± 0.91
	12.5	3.18 ± 0.60	55.6 ± 18.3	4.17 ± 0.80
	21.5	1.99 ± 0.53	81.9 ± 30.5	2.93 ± 0.80
	30	1.14 ± 0.31	96.6 ± 35.8	1.72 ± 0.46

C_{ox} Oxidative carbon, *CSC* cumulative soil carbon, *RSC* relative soil carbon in 1 cm of sampling depth, *SD* standard deviation

The total carbon stock at the *Inga* site was 119.9 ± 19.5 Mg ha^{-1}, of which 69 % was located in the soil and 29 % was located in the trees. The Sun coffee site contained 99.7 ± 17.2 Mg ha^{-1}, which was mainly located in the soil (99 %), while litter and coffee shrubs represented the remaining fraction, estimated at 1 and 0.2 %, respectively. The total carbon stock at the *Pinus* site was 177.5 ± 14.1 Mg ha^{-1}, where the majority of carbon was fixed in the soil (57 %) and trees (40 %). The total carbon stock at the *Eucalyptus* site was 162.3 ± 18.2 Mg ha^{-1}, which was mainly located in the soil (59 %) and trees (39.5 %).

The *Eucalyptus* site fixed the most carbon per year into tree biomass (7.3 Mg ha^{-1} per year), while slightly less was fixed at the *Pinus* site (3.8 Mg ha^{-1} per year); the lowest amount of carbon was fixed at the *Inga* site (1.8 Mg ha^{-1} per year).

Discussion

The disappearance of a large proportion of tropical forests at all latitudes could lead to an increase in GHG emissions if sustainable management and conservation

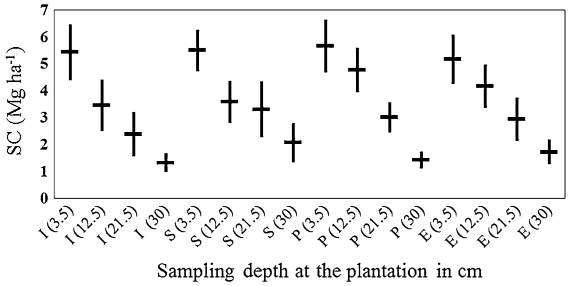

Fig. 3 Relative soil carbon content (RSC) at different sampling depths at the study sites. The values are organised as the mean ± ½ of the standard deviation (SD). The abbreviations used are as follows: I—*Inga* site; S—Sun coffee site; P—*Pinus* site; E—*Eucalyptus* site

Table 6 Polynomial equations for carbon content in the soil

Inga site	$y = -0.0699x^2 + 4.7967x + 1.2791$
Sun coffee site	$y = -0.0507x^2 + 4.7799x + 1.1166$
Pinus site	$y = -0.0923x^2 + 6.1722x - 0.2625$
Eucalyptus site	$y = -0.07x^2 + 5.3129x + 0.1355$

policies are not employed (Dixon 1995). In Peru, this problem is evident due to the fast rate of deforestation (Stephen 2005, Oliveira et al. 2007), and it is obvious that agroforestry systems are one of the possibilities that can mitigate GHG emissions from crop production. Our study from the Peruvian Amazon finds that agroforestry systems are important for carbon mitigation. As with other authors (Avila et al. 2001; Hergoulaćh et al. 2012; Soto-Pinto et al. 2010; Dossa et al. 2008), our results demonstrate that carbon stocks are greater in agroforestry coffee plantations than in the coffee plantations without shade. The difference in carbon stocks between agroforestry and sun plantations range from 20.4 Mg ha^{-1} (the Sun coffee site compared with the *Inga* site) to 77.8 Mg ha^{-1} (the Sun coffee site compared with the *Pinus* site). Other authors reported the following differences between carbon stocks in agroforestry plantations and sun coffee plantations: Hergoulaćh et al. (2012) found a difference of 15.4 Mg ha^{-1} (for coffee–*Inga* association) and Dossa et al. (2008) 123.6 Mg ha^{-1} (for coffee–*Albizia* association).

It is clear that agroforestry systems store more carbon than open space plantations, but it is also important to identify the distribution of carbon in the ecosystem. In our study, the amount of carbon in tree biomass (which ranges from 27.5 ± 3.2 to 57.5 ± 4.5 Mg ha^{-1}) is greater than the amount published in other studies. In Häger's study (2012), shade tree carbon storage in an organic agroforestry coffee plantation was 23.2 Mg ha^{-1} (shaded by *Dracaena fragrans* and *Yucca guatemalensis*) and in the study of Häger (2012) for an *Inga* shaded agroforestry system, it was only 13.9 Mg ha^{-1}. It should be noted

Fig. 4 Curves of cumulative carbon storage (CSC) at the study sites used for expressing soil carbon content within 30 cm of soil depth. The abbreviations used are as follows: I—*Inga* site; S—Sun coffee site; P—*Pinus* site; E—*Eucalyptus* site

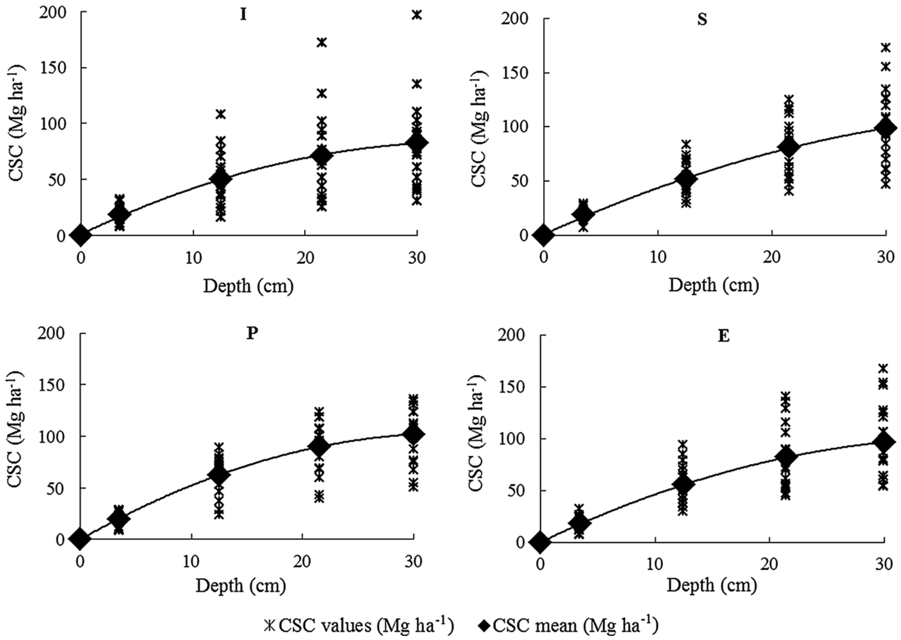

Table 7 Total carbon stocks in studied coffee sites (Mg ha^{-1})

	Inga site	Sun coffee site	*Pinus* site	*Eucalyptus* site
Coffee shrubs	1.6 ± 0.3	0.2 ± 0.03	2.8 ± 0.6	1.5 ± 0.4
Trees (≥10 cm DBH)	27.5 ± 3.2		57.5 ± 4.5	51.2 ± 3.1
Litter	1.2 ± 0.2	0.7 ± 0.1	1.7 ± 1.1	0.7 ± 0.1
Aboveground pools	30.3 ± 3.2	1 ± 0.1	62 ± 4.7	53.5 ± 3.1
Roots of trees	7 ± 0.8	–	13.7 ± 1.1	12.3 ± 0.4
Soil (in depth 30 cm)	82.6 ± 19.2	98.7 ± 17.2	101.8 ± 13.3	96.7 ± 17.9
Belowground pools	89.6 ± 19.2	98.7 ± 17.2	115.4 ± 13.3	108.8 ± 17.9
Total	**119.9 ± 19.5**	**99.7 ± 17.2**	**177.5 ± 14.1**	**162.3 ± 18.2**

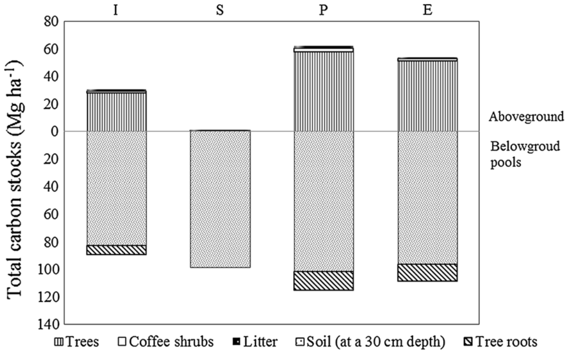

Fig. 5 Total carbon stocks (Mg ha^{-1}) of coffee agroforestry plantations with different shade trees. The abbreviations used are as follows: I—*Inga*; S—Sun coffee site; P—*Pinus* site; E—*Eucalyptus* site

that the biomass estimates do not include error components. For example, only the standard error associated with the allometric model of Chave et al. (2005) is 12.5 % and adding sampling and measurement errors would further increase the total uncertainty bounds. But this is inherent in all similar studies.

The carbon stock in coffee biomass by the same authors is 2.3 Mg ha^{-1} (Häger 2012) and 9.1 Mg ha^{-1} (Hergoulaćh et al. 2012) with a coffee density of 6045 plants ha^{-1} and 4722 plants ha^{-1}, respectively. If we compare these data with our results, we see that only the *Pinus* site has carbon stocks (2.8 Mg ha^{-1}) comparable to the Häger (2012) study, and in the rest of sites, our values are smaller. The coffee density in the Häger (2012) study is comparable with the *Inga* site (6830 plants ha^{-1}) and that of the Hergoulaćh et al. (2012) study with the *Pinus* site (4840 plants ha^{-1}), as seen in Table 4. The carbon stock in the litter in studied sites (0.7–1.7 Mg ha^{-1}, Table 7) is smaller than in the studies of Häger (2012) (4.8 Mg ha^{-1}) and Hergoulaćh et al. (2012) (2.2 Mg ha^{-1}). Avila et al. (2001) studied the carbon stock in agroforestry systems in Costa Rica and found that the carbon stock in aboveground pools of 8-year-old *Coffea-Eucalyptus* plantations was 12.3 Mg ha^{-1} which is less than in the *Eucalyptus* site.

Comparing our results from the Sun coffee site with other studies, we conclude that the carbon stock in coffee shrubs and litter is less in our studied site. Hergoulaćh et al. (2012) published the value 8.5 and 1.3 Mg ha^{-1} for the amount of carbon in aboveground coffee biomass and litter.

Our results of carbon fixed in the deepest 10 cm of soil using equations from Table 6 indicate that the average carbon contents were as follows: 42.3 Mg ha^{-1} at the *Inga* site; 43.9 Mg ha^{-1} at the Sun coffee site; 52.2 Mg ha^{-1} at the *Pinus* site, and 46.3 Mg ha^{-1} at the *Eucalyptus* site. Schmitt-Harsh et al. (2012) found that the soil in a coffee agroforestry system had a carbon content of 38.2 Mg ha^{-1}, while the value in the secondary forest was 45.1 Mg ha^{-1}. Using equations from studies on carbon stocks in the topsoil (0–25 cm, Table 6), we see the following values: *Inga* site: 77.5 Mg ha^{-1}, Sun coffee site: 88.9 Mg ha^{-1}, *Pinus* site: 96.4 Mg ha^{-1}, and *Eucalyptus* site: 89.2 Mg ha^{-1}, which are comparable with the results of Avila et al. (2001) (108.6 Mg ha^{-1}) and Häger (2012) (73 Mg ha^{-1}). Soto-Pinto et al. (2010) studied the soil to a depth of 30 cm and obtained the value 151.0 Mg ha^{-1}, which is greater than our results for all studied plantations. Another study from Indonesia (Noordwijk et al. 2002) found that the total carbon stock (above 30 cm in the soil) for shade coffee was 82 Mg ha^{-1}, which is comparable with the value from the *Inga* site.

The published values of total carbon stocks for coffee agroforestry plantations range from 82 to

198 Mg ha^{-1}, while soil carbon might reach over 89 % the total (Avila et al. 2001; Schmitt-Harsh et al. 2012; Noordwijk et al. 2002; Häger 2012; Soto-Pinto et al. 2010; Vásquez et al. 2007; Roncal-García et al. 2008; Dossa et al. 2008). Our results for all studied types of agroforestry plantations are inside this range. However, in our study, the percentage of the entire carbon stock comprised by SC (soil carbon) was 75 % for the *Inga* site, 65 % for the *Pinus* site and 67 % for the *Eucalyptus* site. With no trees present at coffee plantations, the ecosystem carbon stock is basically determined by soil compartment, whereas the carbon held in aboveground pools is not significant: it represented only 1 % of the total in the Sun coffee site.

However, comparing soil carbon stock from the available literature is not easy. This is due to inconsistencies in methodological approaches for soil carbon assessment (Nair 1993) and several factors conditioning carbon sequestration potential. Factors in soil carbon sequestration potential and carbon turnover include soil properties like biological activity, microbial community composition, the molecular recalcitrance of organic matter, soil mineralogy, structure and texture, continuous temperature and humidity. In the case of loam texture with clay content <20 % in soils containing low activity clay (Feller and Beare 1997), the stability of organo-mineral complexes is not obvious, just like resistance to soil erosion. Hence soil carbon needs to be enhanced by suitable management, which might be based on suitable soil cover care, coarser and more stable soil structure and organic matter supply.

Besides natural conditions (climate, topography, soil-forming substrate etc.) the type of agroforestry management also significantly affects the soil carbon sequestration process (von Lützow et al. 2006; Six et al. 2000; Schimel 1994; Parton et al. 1987; Feller and Beare 1997). It includes the type, density and distribution of shading trees providing differently decomposing litter, as well as litter utilization either as mulch retained on the plantation or as a base material for compost production, compost management etc. In addition, management is often changed over time. Hence, time-sequence studies on soil carbon are rare in agroforestry systems (Nair et al. 2009b). Therefore, the data on carbon stock might be estimated as surrogates or indicators of carbon sequestration potential.

The benefit of agroforestry systems for reducing the CO_2 in the atmosphere is not only the direct near-term C storage in trees and soils but also the potential to offset immediate GHG emissions associated with deforestation and subsequent shifting agriculture (Dixon 1995). For growers, it is important to know how much wood they could produce in an agroforestry system and what they will do with it. In our study, we studied plantations shaded by introduced and local tree species. The wood of *Inga* trees is usually used as firewood by the plantation owners, and the wood of *Eucalyptus* spp. and *Pinus* spp. is sold as construction material. Both uses are very important because they reduce pressure on the rainforests from the local community.

The Peruvian state should improve the monitoring of agroforestry plantations, assessing their area and quality. This information would help to better understand the role of agroforestry in the landscape and make the related policy decisions more effective. It is important to continue to study introduced species in agroforestry plantations in South America and evaluate more precise equations for local plantations. It is also essential to study the behaviour of *Eucalyptus* and *Pinus* tree species, especially in agroforestry systems in South America, because it is a new trend and information on the effects on plantations shaded by these species is insufficient.

Conclusions

Agroforestry systems play an important role in fixing carbon in agricultural landscapes that have lost their original forest cover. They are especially important in tropical areas that have been suffering over the past century from exceptional rates of change as they are degraded by human activities. The amount of sequestered carbon depends on the tree species used for shading. Our study, conducted in Peru, suggests that the coffee agroforestry plantations shaded by introduced tree species (*Pinus* spp., *Ecualyptus* spp.) perform better with regard to carbon storage than those shaded by the local tree genus *Inga*.

The results should be generally applicable to agroforestry coffee plantations with organic certification, where the coffee is grown at a comparable altitude, in a similar climate and with comparable soil conditions. The carbon sequestration potential can also be considered in REDD + programs in which Peru could participate. However, it is also important to consider and evaluate the impact of introduced tree species on biodiversity, soil fertility, hydric function and appearance of coffee diseases in order to make sound management decisions on the tree species used for shading.

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