Carbon stocks in coffee farms and secondary forest systems in the Peruvian Amazon rainforest

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Abstract

Secondary forests and coffee cultivation systems with shade trees might have great potential for carbon sequestration as a means of climate change adaptation and mitigation. This study aimed to measure carbon stocks in coffee plantations under different managements and secondary forest systems in the Peruvian Amazon rainforest (San Martín Region). The carbon stock in secondary forest trees was estimated using allometric equations, while carbon stocks in soil, herbaceous biomass, and leaf litter were determined through sampling and laboratory analysis. The biomass carbon stock in secondary forests was 132.2 t/ha, while in coffee plantations with Inga sp. shade trees it was 118.2 t/ha. Carbon stocks were 76.5 t/ha in coffee with polyculture farming, and the lowest amount of carbon was found in coffee without shade trees (31.1 t/ha). The carbon sequestered by coffee plants in all agroforestry systems examined had an average of 2.65 t/ha, corresponding to 4.63 % of the total carbon sequestered, being the highest stored in the coffee system with Inga sp. shade trees. A higher content of glomalin-related soil proteins (GRSP) was found in coffee without shade trees, with 18.5 mg/g. This is evidence that Inga sp. is the most compatible model of shade system for coffee farms. We recommend the conservation of secondary forests due to the greater biomass and carbon storage, and establishing coffee plantations with Inga sp. shade trees for its integral benefits, such as climate change mitigation.

INTRODUCTION

Despite multiple efforts and studies, there is still no balanced consensus on the impact of agronomic intensification on shade trees (Haggar et al. 2021). This agroforestry tool could be highly limited due to global climate change, challenging farmers to maintain agricultural production levels in the future (Gomes et al. 2020). Nevertheless, agroforestry has great climate change mitigation potential. In particular, the importance of coffee agroforestry systems to preserve biodiversity and ecosystem services has been recognized in different parts of the world (Hundera et al. 2013; Anil et al. 2018; Solis et al. 2020). Since coffee shrubs are perennial crops, coffee-based agroforestry practices are believed to have higher biomass carbon sequestration, biodiversity, and ecosystem functioning than other agroforestry practices (Hylander et al. 2013; Buechley et al. 2015; Tesfay et al. 2022).

There is limited knowledge of the effects of arbuscular mycorrhizal fungi (AMF) on carbon sequestration in agroforestry systems across different agroecological settings (Tschora and Cherubini 2020). Such a role of AMF can be mediated or explained by its production of glomalin. Nautiyal et al. (2019) highlighted the importance of glomalin in maintaining soil aggregation and its positive correlation with soil organic carbon (SOC) that not only increases total carbon stock, but also binds to soil organic matter (SOM), preventing soil erosion, and further improving its aggregation. Coffee agroforestry systems are considered to benefit the environment by fulfilling an important role in carbon storage, at the same time AMF contributes to a greater extent to regulating glomalin and glomalin-related soil proteins (GRSP) content, which are an important indicator of SOC stock (Li et al. 2020; Santos et al. 2022), varying according to the type of agroforestry system (Santos et al. 2022).

Likewise, secondary forests are important carbon sinks, absorbing CO_2 from the atmosphere through photosynthesis and photosynthate storage in their aboveground living biomass (Cassol et al. 2018). Therefore, healthy secondary forests are well-adapted and constitute efficient carbon sinks whose conservation is vital to mitigate and adapt to climate change and to support biodiversity (Aragon et al. 2021). Secondary forests have been reported to sequester carbon at higher rates through accelerated plant growth, making them attractive for climate change mitigation activities (Griscom et al. 2020). They also have higher CO_2 sequestration rates than costly and poorly adapted afforestation and reforestation initiatives (Chazdon and Guariguata 2016).

Despite the potential of secondary forests for carbon sequestration, they are almost completely ignored on land use management in Latin America. In Peru, these amazonian ecosystems could help to reach the country's compromises on climate change adaptation and mitigation. Peru committed to restoring 3.2 million hectares of forests by 2030, of which 2 million hectares will be restored through commercial plantations – including naturalized and non-native species. However, in these commitments, secondary forests were not explicitly included (UNFCCC 2016). These commitments were made aiming at reducing emissions by 30% (Aragon *et al.* 2021). Knowing the potential of Peruvian Amazonian ecosystems, agroforestry systems and secondary forests are of great importance for climate change adaptation and mitigation, and carbon sequestration. In the Peruvian Amazon, there is little research on above- and belowground carbon variations in agroforestry systems with coffee and shade trees. Therefore, the impact of coffee-based agroforestry systems on carbon stocks remains unexplored.

MATERIAL AND METHODS

Study area

The study was carried out in the annexes of the Tabalosos district in the province of Lamas, San Martín region in the Peruvian Amazon between the months of September 2022 to January 2023 (Fig. 1). The province is located at an altitude range between 310 and 814 m.a.s.l. The average annual rainfall and temperature in this district is 1013 mm and 32°C, respectively, with August and December being the summer months and March to April being the winter months, very similar to the majority of districts in the region.

Sampling design

Four vegetation cover types were identified in three zones with coffee and one zone of secondary forest (Table 1). These were: (1) Coffee without shade trees (monoculture), that is, coffee plantations with a higher planting density than the other systems (2000 coffee plants per hectare), made up of the Caturra, Pache, and Catimore varieties (all growing together). (2) Coffee with *Inga* sp. shade trees, with a density of 1500 plants per hectare of the Caturra, Catimore, and Pache varieties (all growing together). (3) Coffee with polyculture farming, with a density of 1450 plants per hectare of the Caturra and Pache varieties, conformed by a diversity of agroforestry crops (specified in Table 1). (4) A secondary forest with a diversity of trees more than 15 years old (Table 1). Organic coffee farms between 9 and 13 years old (age of coffee trees) were considered, with similar agronomic management between them.

The biomass and carbon of the trees were evaluated in four plots (one plot per cover type) with an area of 30 m × 30 m with slopes between 0° and 40°. Four subplots of 4 m × 25 m were established in each plot to facilitate the evaluation of trees and coffee shrubs, for a total of 16 subplots. The height and diameter of the woody components were measured with Suunto Clinometer and tape measure, respectively. The diameter of coffee plants was measured at 15 cm above the ground (d15) and for trees at 1.3 m above the ground (DBH: diameter at breast height). In the same subplots, herbaceous material and litter were measured in a 0.5 x 0.5 m grid according to Siarudin et al. (2021). After removing litter and organic debris, soil was sampled between 0 to 15 cm of soil depth, making soil pits in each management system and considering four subplots per system (for a total of 16 soil samples).

Estimation of aboveground carbon

Allometric equations were used to estimate aboveground biomass based on DBH and d15 (Table 2). The wood density value for each identified species was obtained from the 'Global Wood Density Database' (Zanne et al. 2009). Root biomass was estimated using the regression equations developed by Cairns et al. (1997) (Table 2). The aboveground and root biomass values obtained for each tree within the same plot were summed to calculate the total tree biomass of the plot and the resultant was extrapolated to obtain the biomass stock of 1 ha. Herbaceous biomass was obtained by determining the wet weight of a sample of approximately 500 g; the samples were then taken to the laboratory and dried at 70°C for 48 h to determine the dry weight. With this information, the moisture content and dead biomass were determined using the following equations:

$$Moisturecontent = \frac{Wetweightofthesample - Dryweightofthesample}{Wetweightofthesample}$$

$$Deadbiomass = \sum_{i=1}^{n} \left(Totalwetweight - (TotalwetweightxMoisturecontent)\right)$$

Leaf litter biomass was determined in the same way as dead wood biomass. It was assumed that the carbon present in the biomass could be 50% (IPCC 2003). The C content obtained in each sampled component was extrapolated to estimate C stocks per hectare.

Estimation of soil organic carbon

The cylinder method of 5.5 cm diameter and 5 cm height proposed by Blake and Hartge (1986) was used to calculate the bulk/apparent density (AD) of the soil in g cm^3, determined by the following formula:

DA: Wd/V…… (1)

where AD is the apparent density (g/cm^3), Wd is the weight of the oven-dried soil sample (g), and V is the volume of the sampled soil (cm^3). Therefore, SOC was determined using the method developed by Walkley and Black (1934) in the laboratory, using the formula:

SOC (tC/ha) = OC × Pf × DA……. (2)

where OC is soil organic carbon content (%), Pf is soil sampling depth (cm), and AD is the apparent density (g/cm3).

Thus, we determined the weight of sequestered carbon dioxide in the tree by multiplying the tree's carbon weight by 3.67 (Paniagua-Ramirez et al. 2021).

Estimation of arbuscular mycorrhizae and glomalin content in soils

The quantification of AMF spores was performed by wet sieving and decanting, as proposed by Gerdemann and Nicholson (1963), with some modifications. Likewise, in order to determine GRSP content, soil samples were taken following the methodology of Solis et al. (2022). The total GRSP fraction was extracted according to Wright & Upadhyaya (1998) and quantified by the method of Bradford (1976).

Statistical analyses

The statistical analyses were performed through R Studio (R Core Team 2023). To analyze the effect of the vegetation cover factor on carbon content, AMF spores, and GRSP content analysis of variance (ANOVA) was performed with Tukey's test for comparison of means at a 5% probability of error. A Principal Component Analysis (PCA) biplot was performed to evaluate the correlations between variables. The variables were standardized and the *fviz_pca_biplot* function of the Factoextra package of R (Kassambara and Mundt 2022) A correlogram was also performed to test these correlations, using the pearson correlation coefficient ($p < 0.05$), using the *ggpairs* function of the GGally package of R (Schloerke et al. 2022).

RESULTS

Carbon storage capacity in coffee and secondary forest

Carbon stocks varied according to the type of vegetation cover (Table 3). The total carbon stock in the different vegetation cover types ranged from 31.1 t C/ha in coffee without shade trees to 132.2 t C/ha in the secondary forest (Table 3). The overall mean of carbon stocks in the different types of vegetation cover was 89.5 t C/ha. The highest carbon content was found in the secondary forest and coffee with *Inga* sp. shade trees with a total of 132.2 and 118.2 t/ha ($p < 0.05$), respectively.

Aboveground carbon stocks varied from 1.6 t C/ha in coffee without shade trees to 75.8 t/ha in the secondary forest (Table 3). The total carbon storage capacity (t C/ha) in the different cover types decreased in the following order: aboveground carbon (AGC) > soil organic carbon (SOC) > belowground carbon (BGC) > litter carbon (LC) > herbaceous carbon (HC). Vegetation cover influenced carbon stocks in the different components with the exception of SOC ($p < 0.05$). The AGC compartment had the highest C content in all the sampled cover types. The secondary forest and the coffee system with *Inga* sp. shade trees had the highest AGC (75.8 and 55.8 t C/ha) and BGC (10.7 t C/ha) carbon stocks (Table 3). Likewise, coffee without shade trees had the lowest LC and SOC carbon stocks, with 0.2 and 0.6 t C/ha, respectively. With respect to SOC, we found values ranging from 28 t C/ha in coffee without shade trees to 45.7 t C/ha in the coffee with *Inga* sp. shade trees (Table 3). Likewise, SOC showed a higher coefficient of variation (CV = 43.9%), followed by LC (CV = 26.3%), AGC (24.6%), BGC (23.8%), and HC (19.1%), indicating a greater spatial variability of carbon stocks in soils than in vegetation.

The proportions of carbon stored in the different vegetation and soil compartments were affected by the different vegetation cover types ($p < 0.05$). The secondary forest sequestered 57.4% of carbon as AGC, 8.1% as BGC, 27.0% as SOC, and the rest as LC and HC (Fig. 1). The coffee with *Inga* sp. shade trees sequestered 46.7% of carbon as AGC, 39.2% as SOC, and 14.1% as LC, HC, and BGC. Coffee with polyculture farming sequestered 54.2% of carbon as SOC, 27.7% as AGC, 8.3% as LC, and 9.8% as HC and BGC; whereas the coffee without shade trees sequestered 89.4% of carbon as SOC, followed by AGC, HC, BGC, and LC with 5.5%, 2.5%, 2.0%, and 0.6%, respectively (Fig. 2).

Glomalin and spore content of arbuscular mycorrhizal fungi (AMF)

The lowest number of AMF spores was found in the secondary forest with 102 spores on average, showing significant differences (Fig. 2). The highest GRSP content was found in coffee without shade trees with an average of 18.5 mg/g, and the lowest content

was found in the secondary forest with 7.1 mg/g on average, showing significant differences for both covers ($p < 0.05$). Whereas coffee cover with *Inga* sp. shade trees and coffee with polyculture farming did not show significant differences for GRSP content among them (Fig. 3).

Carbon sequestration

Coffee plants also contributed to the total carbon stock in the different types of vegetation cover. The carbon sequestered by coffee plants was 2.97, 2.82, and 2.17 t C/ ha in coffee with *Inga* sp. shade trees, coffee with polyculture farming, and coffee without shade trees, respectively (Table 4). Coffee plants contributed about 7.46%, 3.89%, and 2.54% of the carbon sequestered in coffee without shade trees, coffee with polyculture farming, and coffee with *Inga* sp. shade trees, respectively (Table 4). The overall average carbon sequestered by coffee plants in the different types of vegetation cover was 2.65 t C/ha (average of 4.63% of total sequestered carbon). The mean values of carbon sequestered by coffee plants with *Inga* sp. shade trees and polycultures were significantly different from those of coffee without shade trees, but did not differ significantly from each other; while the secondary forest was not taken into account due to the absence of coffee plants (Table 4).

In the study area, coffee agroforestry systems sequestered a large amount of carbon in vegetation, including coffee plants and soils proportional to the area of each stratum, approximately 118.20, 76.48, and 2.17 t C/ha were stored in coffee cover with *Inga* trees, polyculture, and coffee without shade trees, respectively (Table 5). This shows that a total of 196.85 t C/ha was stored in all coffee agroforestry systems in the study area. Particularly, coffee plants added a total of 7.96 t C/ha in the coffee agroforestry systems (Table 5). All coffee agroforestry systems in the current study area trapped 722.44 t of CO_2 from the atmosphere, while coffee plants captured 29.23 t of CO_2 from the atmosphere and stored it as carbon in the agroforestry systems.

GRSP and mycorrhizae-mediated carbon

The variation of carbon stocks, number of AMF spores, and GRSP content in the different vegetation covers was explained by 75.9% in the first two principal components of a PCA (Fig. 4). Coffee without shade trees was characterized by the highest values of GRSP and number of AMF spores, variables that were positively associated (Fig. 3). Likewise, the secondary forest was characterized by the highest values for AGC, BGC, and LC, variables that showed positive associations. That is, carbon in aboveground biomass increases as underground biomass and litter biomass increase in the secondary forest cover.

The variable GRSP ranged between 6.22 and 24.36 (mg/g) and the number of AMF spores between 99 and 145 units for 25 g of soils (Fig. 5), variables that presented significant and positive correlation with a value of 0.766. GRSP presented significant and negative correlation with AGC, LC, and BGC with values of -0.657, -0.703, and -0.591, respectively. AMF spore number only presented significant and negative correlation with litter carbon with a value of -0.788.

DISCUSSION

Carbon stocks in coffee and secondary forest

The higher carbon content present in the secondary forest was due to a higher aboveground biomass and population density of the tree species present, as also found by Birhane et al. (2020) who observed that the least disturbed plant community, which had a higher density of trees and shrubs, had the highest SOC stocks compared to more disturbed communities. Secondary forests are of great importance due to the conservation and greater diversity of timber and non-timber trees present, storing more carbon than coffee crops. Soils that form under forests tend to accumulate high levels of organic carbon near the surface and have lower levels of carbon in the subsoil (Yohannes and Webb 1999; Girmay et al. 2008). Cover types affected the proportion of carbon stocks stored at different compartments. The results indicate that the highest carbon content was stored as AGC followed by SOC (Niguse et al. 2022).

GRSP and spore contents of arbuscular mycorrhizal fungi

The highest number of AMF spores was found in coffee without shade systems, where the soils presented the lowest values of pH, total N, and available P with averages of 5.42, 0.13%, and 1.32 mg kg^{-1}, respectively (Table 1). The larger population of coffee plants present in the coffee system without shade trees probably favors a symbiotic association between coffee plants and AMF, promoting favorable living habitats for the survival and massive multiplication of AMF spores (Vallejos-Torres et al. 2022). As response to

mycorrhization, coffee plants show a clear reorganization of the main metabolic pathways, which involve nutrient acquisition, carbon fixation, and primary and secondary metabolism, particularly under low phosphorus conditions (Chialva et al. 2023). This makes coffee a highly mycotrophic plant (Hernández-Acosta et al. 2021).

Our results on higher number of AMF spores on coffee without shade are analogous to those by Polo-Marcial et al. (2023), who found that the abundance and richness of AMF, especially glomerospores, was higher in agroforestry systems than in secondary forest. The presence of AMF plays an important role in the accumulation of GRSP, a critical component of the hyphal cell wall (Hossain 2021). Therefore, mycorrhizal hyphae prominently promote enhanced accumulation and preservation of organic carbon in aggregates and soil C pool (Wang et al. 2022). This may have contributed to soil carbon accumulation in coffee without shade trees with 28.0 t/ha.

Amazonian carbon sequestration and its implication for climate change mitigation

Carbon stocks varied according to the type of vegetation cover, with the secondary forest cover storing the highest carbon content, followed by the coffee system with *Inga* sp. shade trees, coffee with polyculture farming and, to a lesser extent, the coffee system without shade trees. Secondary forests growing on previously cleared land could be a low-cost climate change mitigation strategy due to their potential to sequester CO_2 (Elias et al. 2022).

The carbon stock found in coffee with *Inga* sp. shade trees (125.3 t/ha) was lower than the average carbon stocks reported for agroforestry systems with coffee by Niguse et al. (2022) in Ethiopia (287.1 t C/ha), by Schmitt-Harsh et al. (2020) in Guatemala (259 t C/ha), and by Soto-Pinto et al. (2010) in Mexico (213.80 t C/ha). Similarly, the average SOC content found in this study for the coffee system with *Inga* sp. shade trees (52.8 t/ha) was lower than that reported by Niguse et al. (2022) (91.5 t C/ha) and lower than that reported by Solis et al. (2020) (123.5 t C/ha), both with different shade trees than in our study. Differences in carbon stocks observed in different parts of the world could be attributed to a variety of factors, including coffee variety, management practices, plantation ages, and site factors such as climate and soil conditions (Anguiano et al. 2013), among others. Overall, our findings show that coffee agroforestry systems can sequester a substantial amount of carbon by trapping CO_2 from the atmosphere, which helps mitigate the effects of climate change (Niguse et al. 2022). Glomalin helps maintain soil carbon stock and organic matter retention (Plaza et al. 2013; Six and Paustian, 2014). GRSP produced in hyphal cell walls is a carbon storage compartment that influences aggregate formation and stability, and contributes to soil carbon sequestration (Nautiyal et al. 2019).

CONCLUSIONS

Coffee plants associated with agroforestry systems sequester substantial amounts of carbon and have AMF that generate glomalin-related soil protein, since coffee is a highly mycotrophic plant. That is, coffee benefits from the mycorrhizal association, contributing greatly to the accumulation of carbon in the soil. The carbon sequestration potential of coffee plants with *Inga* sp. shade trees is influenced by the compatibility of the trees present in the management system. Coffee plants and agroforestry can be considered potential systems for sustainability in forest management. Similarly, secondary forest plantation had very high carbon sequestration potential. Therefore, we suggest the expansion of coffee agroforestry farming and the initiation of coffee carbon credits as strategies to encourage farmers to grow more organic coffee plants, to conserve trees, and to contribute to climate change mitigation (Tedersoo et al., 2023).

Declarations

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References

1. Anguiano JM, Aguirre J, Palma JM (2013) Secuestro de carbono en la biomasa aérea de un sistema agrosilvopastoril de *Cocos nucifera*, *Leucaena leucocephala* Var. *Cunningham y Pennisetum* pur-pureum. Avances en Investigación Agropecuaria, 17(1):149-160. https://www.redalyc.org/pdf/837/83725698009.pdf
2. Anil NP, Saleem AIK, Balakrishnan V (2018) Coffee, climate and biodiversity: understanding the carbon stocks of the shade coffee production system of India, in: Handbook of Climate Change and Biodiversity, eds W. Leal Filho, J. Barbir, R. Preziosi (Berlin: Springer), 113–134. https://doi.org/10.1007/978-3-319-98681-4_7
3. Aragón FM, Oteiza F, Rud JP (2021) Climate change and agriculture: Subsistence farmers' response to extreme heat Am. Econ. J.: Econ. Policy, 13 (1):1-35. https://www.aeaweb.org/doi/10.1257/pol.20190316
4. Birhane E, Ahmed S, Hailemariam M, Negash M, Rannestad M, Norgrove L (2020) Carbon stock and woody species diversity in homegarden agroforestry along an elevation gradient in southern Ethiopia. Agroforest Syst 94, 1099–1110. https://doi.org/10.1007/s10457-019-00475-4
5. Blake GR, Hartge K (1986) Bulk density. Methods Soil Analysis 5:363–375. https://doi.org/10.2136/sssabookser5.1.2ed.c13
6. Bradford MMA (1976) Rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. Analytical Biochemistry, 72:1-2, 248-254. https://doi.org/10.1016/0003-2697(76)90527-3
7. Buechley ER, Şekercioğlu ÇH, Atickem A, Gebremichael G, Ndungu JK, Mahamued BA, Beyene T, Mekonnen T, Lens L (2015) Importance of Ethiopian shade coffee farms for forest bird conservation. Biological Conservation, 188(1):50–60. https://doi.org/10.1016/j.biocon.2015.01.011
8. Cairns MA, Brown S, Helmer FH, Baumgardner GA (1997) Root biomass allocation in the world's upland forests. Oecologia 111, 1–11. https://doi.org/10.1007/s004420050201
9. Cassol H, Pétré B, Degrange S, Martial C, Charland-Verville V, Lallier F, Bragard I, Guillaume M, Laureys S (2018) Qualitative thematic analysis of the phenomenology of near-death experiences. PLoS ONE 13(2):e0193001. https://doi.org/10.1371/journal.pone.0193001
10. Castellanos E, Quilo A, Mato R (2010) Metodología para la estimación del contenido de carbono en bosques y sistemas agroforestales en Guatemala. http://www.uvg.edu.gt/investigacion/ceab/cea/doc/metodologias/Metodolog%C3%ADa_Estimaci%C3%B3n%20de%20Carbono-espa%C3%B1ol_CEAB-UVG%202010.pdf
11. Chave J, Réjou-Méchain M, Búrquez A, Chidumayo E, Colgan MC, Delitti WBC, Duque A, Eid T, Fearnside PM, Goodman RC, Henry M, Martínez-Yrízar A, Mugasha WA, Muller-Landau HC, Mencuccini M, Nelson BW, Ngomanda A, Nogueira EM, Ortiz-Malavassi E, Pélissier R, Ploton P, Ryan CM, Saldarriaga JG and Vieilledent G (2014) Improved allometric models to estimate the aboveground biomass of tropical trees. Global Change Biology 20:3177–3190. https://doi.org/10.1111/gcb.12629
12. Chazdon RL, MR, Guariguata (2016) Natural regeneration as a tool for large-scale forest restoration in the tropics: prospects and challenges. Biotropica 48(6):716-730. https://doi.org/10.1111/btp.12381
13. Chialva M, Patono DL, de Souza LP, Novero M, Vercellino S, Maghrebi M et al (2023) The mycorrhizal root-shoot axis elicits *Coffea arabica* growth under low phosphate conditions. New Phytologist. https://doi.org/10.1111/nph.18946
14. Gerdemann JW, TH, Nicolson (1963) Spores of mycorrhizal Endogone species extracted from soil by wet sieving and decanting. Trans. Br. Mycol. Soc. 46:235-244. https://doi.org/10.1016/S0007-1536(63)80079-0
15. Girmay G, Singh BR, Mitiku H, Borresen T, Lal R (2008) Carbon stocks in Ethiopian soils in relation to land use and soil management. Land Degrad Dev 19(4):351–367, https://doi.org/10.1002/ldr.844
16. Gomes LC, Bianchi FJJA, Cardoso IM, Fernandes RBA, Fernandes POR (2020) Schulte, agroforestry systems can mitigate the impacts of climate change on coffee production: A spatially explicit assessment in Brazil, Agriculture, Ecosystems & Environment, 294:1-11, https://doi.org/10.1016/j.agee.2020.106858.
17. Griscom BW, Busch J, Cook-Patton SC, Ellis PW, Funk J, Leavitt SM, Lomax G, Turner WR, Chapman M, Engelmann J, Gurwick NP, Landis E, Lawrence D, Malhi Y, Schindler ML, Navarrete D, Roe S, Scull S, Smith P, Streck C, Walker WS, Worthington T (2020) National mitigation potential from natural climate solutions in the tropicsPhil. Trans. R. Soc. B3752019012620190126. http://doi.org/10.1098/rstb.2019.0126
18. Elias F, Ferreira J, Resende AF, Berenguer E, França F, Smith CC, Schwartz G, Nascimento RO, Guedes M, Rossi LC, Moraes de Seixas, MM, Melo da Silva C, Barlow J (2022) Comparing contemporary and lifetime rates of carbon accumulation from secondary forests in the eastern Amazon, Forest Ecology and Management, 508, https://doi.org/10.1016/j.foreco.2022.120053

19. Haggar J, Casanoves F, Cerda R, Cerretelli S, Gonzalez-Mollinedo S, Lanza G, Lopez E, Leiva B and Ospina A (2021) Shade and agronomic intensification in coffee agroforestry systems: Trade-off or synergy? Front. Sustain. Food Syst. 5:645958. https://doi.org/10.3389/fsufs.2021.645958
20. Hernández-Acosta E, Banuelos J, Trejo-Aguilar D (2021) Revisión: Distribución y efecto de los hongos micorrízicos en el agroecosistema de café. Revista de Biología Tropical, 69(2):445-461. https://dx.doi.org/10.15517/rbt.v69i2.42256
21. Hossain MB (2021) Glomalin and contribution of glomalin to carbon sequestration in soil: A Review. Turkish Journal of Agriculture - Food Science and Technology, 9(1):191–196. https://doi.org/10.24925/turjaf.v9i1.191-196.3803
22. Hundera, K., Aerts, R., Fontaine, A., Van Mechelen M, Gijbels P, Honnay O, Muys B (2013) Effects of coffee management intensity on composition, structure, and regeneration status of Ethiopian moist evergreen afromontane forests. Environmental Management 51:801–809. https://doi.org/10.1007/s00267-012-9976-5
23. Hylander K, Nemomissa S, Delrue J, Enkosa W (2013) Effects of coffee management on deforestation rates and forest integrity _ enhanced reader. Conservation Biology, 27(5):1031–1040. https://doi. org/10.1111/cobi.12079
24. IPCC (2003) Good practice guidance for land use, land chane and forestry (P LULUCF). https://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/GPG_LULUCF_FULL.pdf
25. Kassambara, A., Mundt, F (2020) Factoextra: Extract and Visualize the Results of Multivariate Data Analyses. R Package Version 1.0.7. Disponible en: https://CRAN.R-project.org/package=factoextra
26. Li, X., Han, S., Luo, X, Chen W, Huang Q (2020) Arbuscular mycorrhizal-like fungi and glomalin-related soil protein drive the distributions of carbon and nitrogen in a large scale. J Soils Sediments 20:963–972. https://doi.org/10.1007/s11368-019-02421-4
27. Nascimento HEM Laurance WF (2002) Total aboveground biomass in Central Amazonian Rainforests: a Landscape-Scale Study. Forest Ecology and Management. 311–321. https://doi.org/10.1016/S0378-1127(01)00749-6
28. Nautiyal P, Rajput R, Pandey D, Arunachalam K, Arunachalam A (2019) Role of glomalin in soil carbon storage and its variation across land uses in temperate Himalayan regime, Biocatalysis and Agricultural Biotechnology, 21. ISSN 1878-8181. https://doi.org/10.1016/j.bcab.2019.101311.
29. Niguse G, Iticha B, Kebede G, Chimdi A (2022) Contribution of coffee plants to carbon sequestration in agroforestry systems of Southwestern Ethiopia. The Journal of Agricultural Science 1–8. https://doi.org/ 10.1017/S0021859622000624
30. Paniagua-Ramirez A, Krupinska O, Jagdeo V et al (2021) Carbon storage estimation in a secondary tropical forest at CIEE Sustainability Center, Monteverde, Costa Rica. Sci Rep 11, 23464. https://doi.org/10.1038/s41598-021-03004-5
31. Plaza C, Courtier-Murias D, Fernandez JM, Polo A, Simpson AJ (2013) Physical, chemical, and biochemical mechanisms of soil organic matter stabilization under conservation tillage systems: a central role for microbes and microbial by-products in C sequestration. Soil Biol. Biochem. 57:124–134. https://doi.org/10.1016/j.soilbio.2012.07.026
32. Polo-Marcial MH, Solís-Ramos LY, Murillo-Cruz R, Ávila-Arias C, Andrade-Torres A (2023) Mycorrhizal and endophytic richness and colonization in Cedrela odorata L., in agroforestry systems and secondary forest from southeastern Costa Rica. Agroforest Syst 97:647–658. https://doi.org/10.1007/s10457-023-00816-4
33. R Core Team (2023) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.
34. Santos M, Cajaiba RL, Bastos R, Gonzalez D, Petrescu Bakış AL, Ferreira D, Leote P, Barreto da Silva W, Cabral JA, Gonçalves B, ¿Mosquera-Losada MR (2022) Why do agroforestry systems enhance biodiversity? evidence from habitat amount hypothesis predictions. Frontiers in Ecology and Evolution, 9, 1–11. https://doi.org/10.3389/fevo.2021.630151
35. Schloerke B, Cook D, Larmarange J, Briatte F, Marbach M, Thoen E, Elberg A, Crowley J (2022) *GGally: Extensión a 'ggplot2'*. https://ggobi.github.io/ggally/, https://github.com/ggobi/ggally.
36. Schmitt-Harsh M, Evans TP, Castellanos E and Randolph JC (2020) Carbon stocks in coffee agroforests and mixed dry tropical forests in the western highlands of Guatemala. Agroforest Syst 86:141–157 (2012). https://doi.org/10.1007/s10457-012-9549-x
37. Siarudin M, Rahman SA, Artati Y, Indrajaya Y, Narulita S, Ardha MJ, Larjavaara M (2021) Carbon sequestration potential of agroforestry systems in degraded landscapes in west java, Indonesia. Forests, 12(6):714. MDPI AG. Retrieved from http://dx.doi.org/10.3390/f12060714

38. Six J, Paustian K (2014) Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. Soil Biol. Biochem. 68:A4–A9. https://doi.org/10.1016/j.soilbio.2013.06.014
39. Solis R, Vallejos-Torres G, Arévalo L, Caceres B (2022) Efeitos micorrízicos nos teores de proteína do solo relacionada à glomalina e de clorofila em cafeeiro na Amazônia peruana. Pesquisa Agropecuária Tropical, Goiânia, 52: e72303. https://revistas.ufg.br/pat/article/view/72303
40. Solis R, Vallejos-Torres G, Arévalo L, Marín-Díaz J, Ñique-Alvarez M, Engedal T and Bruun T (2020) Carbon stocks and the use of shade trees in different coffee growing systems in the Peruvian Amazon. The Journal of Agricultural Science 158:450–460. https://doi.org/10.1017/S0021859620000854
41. Soto-Pinto L, Anzueto M, Mendoza J, Ferrer GJ and de Jong B (2010) Carbon sequestration through agroforestry in indigenous communities of Chiapas, Mexico. Agroforestry Systems 78:39–51. https://doi.org/10.1007/s10457-009-9247-5
42. Suárez D (2004) Cuantificación Económica del servicio ambiental, almacenamiento de carbono en sistemas agroforestales de café en la Comarca Yassic sur, Matagela, Nicaragua (Thesis). Centro Agronómico Tropical de Investigación y Enseñanza-CATIE, Turrialba, Costa Rica. https://repositorio.catie.ac.cr/handle/11554/3735
43. Tedersoo L, Sepping J, Morgunov AS, Kiik M, Esop K, Rosenvald R et al (2023) Towards a co-crediting system for carbon and biodiversity. Plants, People, Planet. https://doi.org/10.1002/ppp3.10405
44. Tesfaye W, Seifu L (2016) Climate change perception and choice of adaptation strategies: Empirical evidence from smallholder farmers in east Ethiopia. International Journal of Climate Change Strategies and Management, 8(2):253–270. https://doi.org/10. 1108/IJCCSM-01-2014-0017
45. Tschora H, Cherubini F (2020) Co-benefits and trade-offs of agroforestry for climate change mitigation and other sustainability goals in West Africa. Global Ecology and Conservation. 6(1):22. https://doi. org/10.1016/j.gecco.2020.e00919
46. UNFCCC (2016) Report on the technical assessment of the proposed forest reference emission level of Peru submitted for publication in 2016. 22038. https://unfccc.int/documents/620399
47. Vallejos-Torres G, Tenorio-Cercado M, Gaona-Jimenez N, Corazon-Guivin M, Ormeño-Luna J, Paredes C, Saavedra J, Tuesta J, Tuesta O, Alguacil MM, Becerra A, Marín C (2022) Multiplication of arbuscular mycorrhizal fungi isolated from cocoa cultivated soils. Bioagro, 34(3):265-276. https://doi.org/10.51372/bioagro343.6
48. Walkley A and Black CA (1934) An examination of the Degtajareff's method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Science 37:29–38. https://doi.org/10.1097/00010694-193401000-00003
49. Wang YJ, He XH, Meng LL, Z YN, W QS (2022) Extraradical mycorrhizal hyphae promote soil carbon sequestration through difficultly extractable glomalin-related soil protein in response to soil water stress. Microb Ecol. https://doi.org/10.1007/s00248-022-02153-y
50. Wright SF, Upadhyaya A (1998) A survey of soils for aggregate stability and glomalin, a glycoprotein produced by hyphae of arbuscular mycorrhizal fungi. Plant and Soil, 198(1):97-107. https://doi.org/10.1023/A:1004347701584
51. Yohannes Y, Webb P (1999) Classification and regression trees, cart - a user manual for identifying indicators of vulnerability to famine and chronic food insecurity, IFPRI, Washington, USA, ISBN 0-89629-337-8. https://www.researchgate.net/publication/238649477
52. Zanne AE, López-Gonzalez G, Coomes DA, Ilic J, Jansen S, Lewis SL, Miller RB, Swenson NG, Wiemann MC and Chave J (2009) Data from: Towards a worldwide wood economics spectrum, Dryad, Dataset, https://doi.org/10.5061/dryad.234

Tables

Table 1. Forest composition of the types of coffee and secondary forest agroforestry systems.

Type of vegetation cover	Code	Altitude (masl)	Species	pH	N (%)	P (mg kg^{-1})
Coffee without shade trees	CWT	772	Coffee (*Coffea arabica*)	5.42	0.13	1.32
Coffee with *Inga sp.* Shade trees	CIs	783	Coffee (*Coffea arabica*) and guaba (*Inga* sp.)	5.72	0.18	1.32
Coffee with polyculture farming	CPo	704	Coffee (*Coffea arabica*), cedar (*Cedrela odorata*), avocado (*Persea americana*), cocoa (*Theobroma cacao*)	6.75	0.24	2.00
Secondary forest	SF	769	Shimbillo (*Inga* spp), atadijo (*Trema micrantha*), Shaina (*Colubrina grandulosa*), cetico (*Cecropia sciadophytla*), zapote (*Manilkara zapota*)	6.35	0.18	3.22

Table 2. Allometric equations used to estimate aboveground and belowground biomass.

Group of species	Barometric model	r^2	DBH range (cm)	References
Tropical rainforest	AGB = exp (−1.7689 + 2.377 × Ln (DBH))	0.96	2 ⩽ DBH < 5	Nascimento and Laurance (2002)
Tropical rainforest	$AGB = 0.0673 \times (\rho \times DBH^2 \times H)^{0.976}$		5⩽ DBH	Chave *et al*. (2014)
Inga sp.	$AGB = 0.01513 \times DBH^{3.0054}$	0.83	10 ⩽ DBH ⩽ 29	Castellanos *et al*. (2010)
Coffea arabica	$Ln (AGB) = -2.39287 + 0.95285 \times Ln(d_{15}) + 1.2693 \times Ln(H)$	0.63	$0 \leqslant d_{15} \leqslant 9$	Suarez (2004)
Roots	Y = exp (−1.0587 + 0.8836 × Ln(AGB))	0.84	-	Cairns *et al*. (1997)

AGB, aboveground biomass; Y, root biomass; DBH, diameter at breast height at 1.3 meters (cm); d15, diameter at 15 cm above ground (cm); H, height (m); and ρ, wood density.

Table 3. Carbon storage potential of coffee and secondary forest agroforestry systems by carbon component.

Type of vegetation cover	Carbon stocks (t/ha) in different components					
	AGC	HC	LC	BGC	SOC	Total
CWT	1.6 ± 0.2^{b}	0.7 ± 0.1^{b}	0.2 ± 0.1^{c}	0.6 ± 0.1^{b}	28.0 ± 10.7^{a}	31.1 ± 10.9^{c}
CIs	55.8 ± 17.4^{a}	3.7 ± 0.8^{a}	3.2 ± 0.9^{b}	$9,9 \pm 2.7^{a}$	45.7 ± 28.1^{a}	118.2 ± 14.5^{a}
CPo	21.2 ± 6.3^{b}	3.7 ± 0.5^{a}	5.9 ± 0.7^{ab}	3.5 ± 1.0^{b}	42.1 ± 7.2^{a}	76.5 ± 21.3^{b}
SF	75.8 ± 3.5^{a}	3.3 ± 0.5^{a}	$6.6 \pm 1,7^{a}$	$10,7 \pm 0.4^{a}$	35.8 ± 8.1^{a}	132.2 ± 7^{a}
Mean	38.3	2.9	4.0	6.2	37.9	89.5
CV	24.6	19.1	26.3	23.8	43.9	16.1
P value	<0.001***	<0.001***	<0.001***	<0.001***	0.3	<0.001***

CWT, Coffee without shade trees; CIs, Coffee with *Inga sp.* Shade trees; CPo, Coffee with polyculture farming; SF, Secondary Forest; AGC, aboveground carbon; HC, herbaceous carbon; LC, litter carbon; BGC, belowground carbon; and SOC, soil organic carbon.

Mean±standard deviation (n=4), different letters within the same column are statistically different according to Tukey test (*** at p < 0.001, ** at p < 0.01 and * at p < 0.05).

Table 4. The amount and proportion of carbon stored in coffee plants in the coffee agroforestry systems.

Type of vegetation cover	AGCC	BGCC	Total carbon stored in coffee plants (t/ha)	Proportion of carbon stored in coffee plants (%)
CWT	1.6 ± 0.15^{b}	0.57 ± 0.08^{b}	2.17± 0.22^{b}	7.46 ± 2.30^{a}
CIs	2.24± 0.05^{a}	0.73± 0.02^{a}	2.97 ± 0.07^{a}	2.54 ± 0.32^{b}
CPo	2.12 ± 0.09^{a}	0.69 ± 0.03^{ab}	2.82 ± 0.11^{a}	3.89 ± 1.08^{ab}
Mean	1.98	0.67	2.65	4.63
CV	5.25	7.39	5.5	31.94
P value	<0.001***	0.017*	0.00115 **	0.0162 *

CWT, Coffee without shade trees; CIs, Coffee with *Inga sp*. Shade trees; CPo, Coffee with polyculture farming; AGCC, Aboveground coffee carbon; and BGCC, belowground coffee carbon. Mean±Standard deviation (n=4), different letters within the same column are statistically different according to Tukey test (*** at P < 0.001; ** at P < 0.01 and * at P < 0.05).

Table 5. Total carbon stock and carbon dioxide (CO_2) equivalent sink in different coffee agroforestry systems and coffee plants.

	Total carbon stock (t/ha)		Equivalent CO_2 sink (t/ha)	
Type of vegetation cover	In the whole coffee agroforestry	In the coffee plants	In the whole coffee agroforestry	In the coffee plants
CWT	2.17	2.17	7.96	7.96
CIs	118.20	2.97	433.79	10.91
CPo	76.48	2,82	280.68	10.35
Total	**196.85**	**7.96**	**722.44**	**29.23**

CWT, Coffee without shade trees; CIs, Coffee with *Inga sp*. Shade trees; and CPo, Coffee with polyculture farming.

Figures

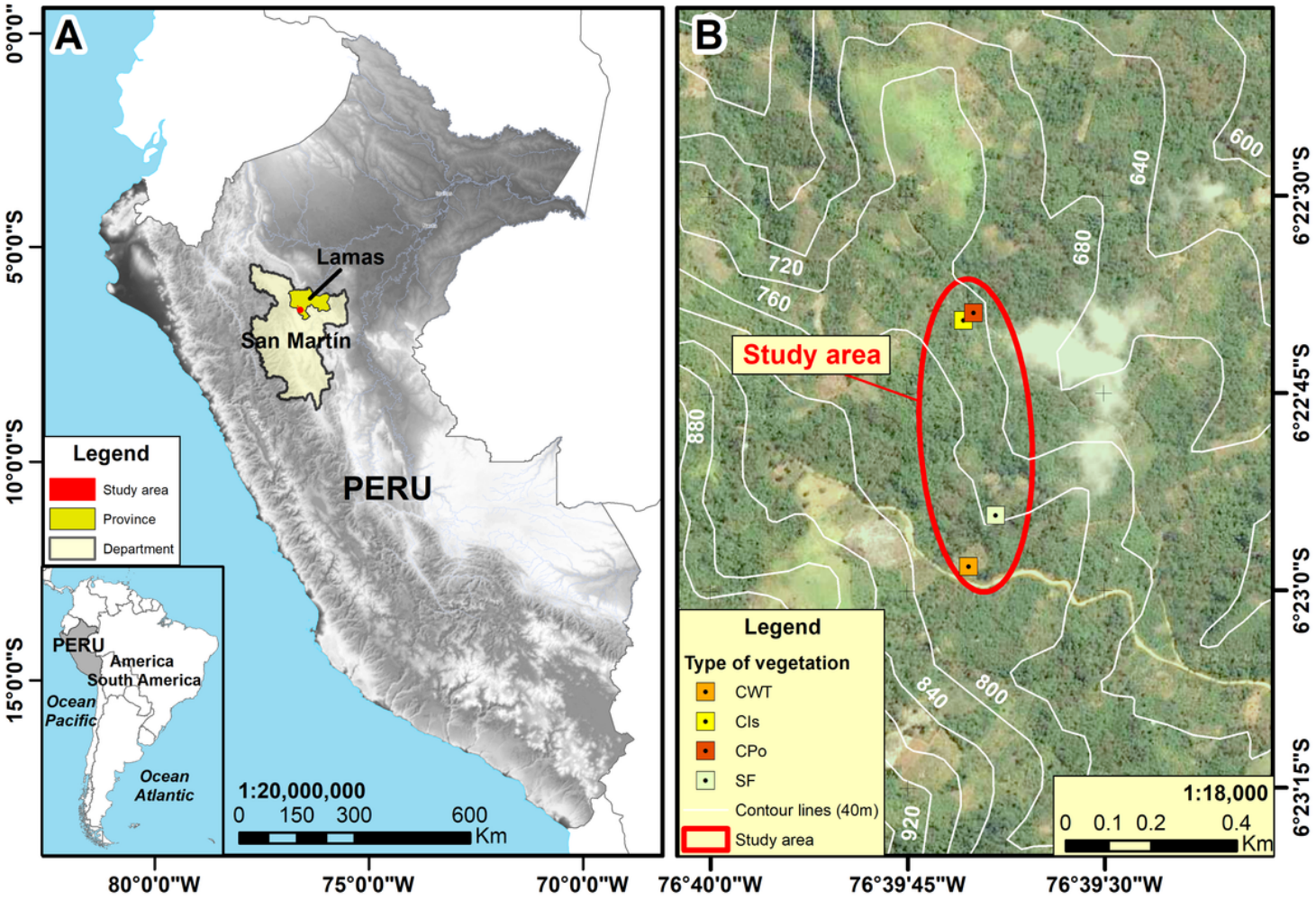

Figure 1

Map of the study area showing the distribution of the sampled plots.

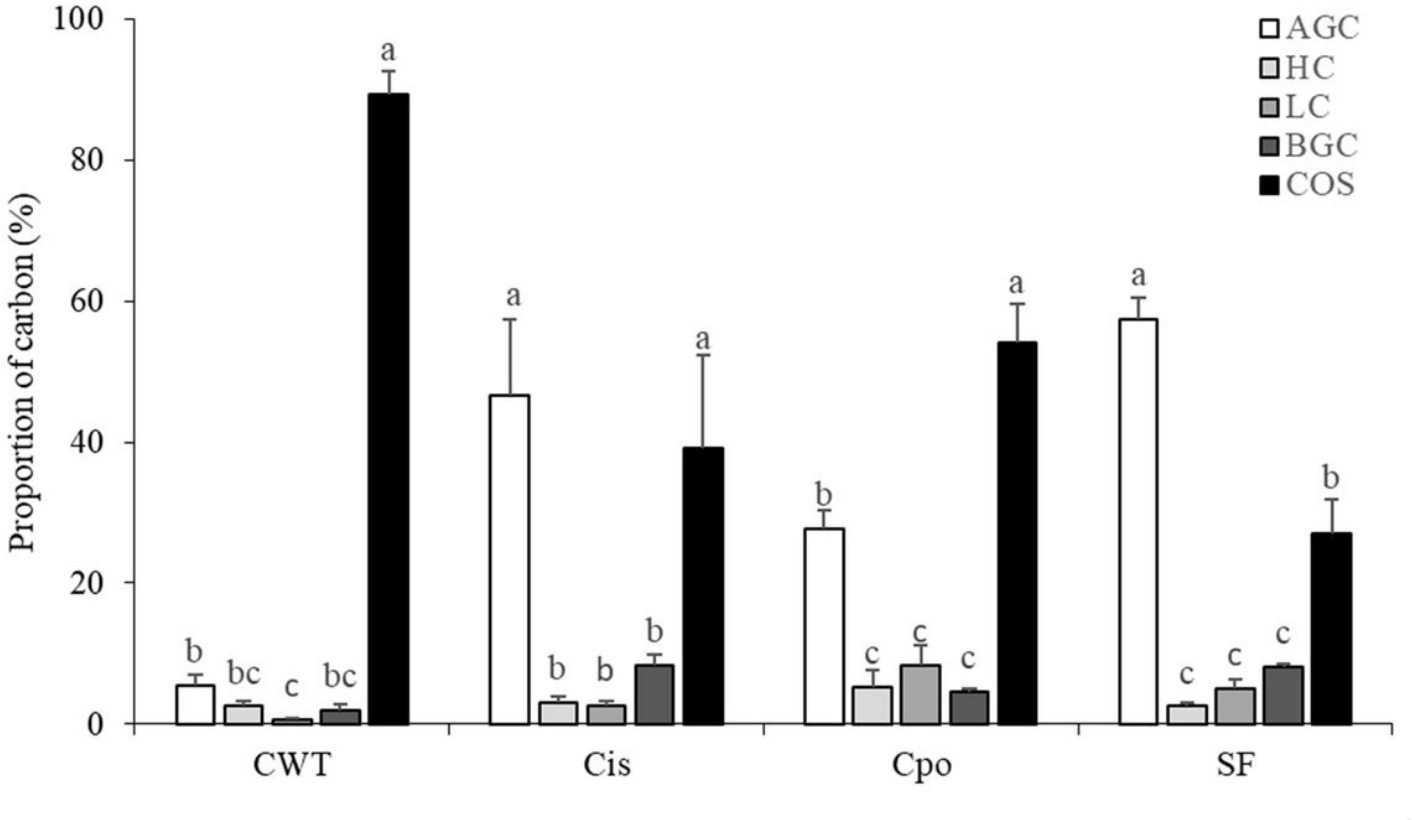

Figure 2

The percentage proportion of carbon components stored in the different types of vegetation cover. AGC, aboveground carbon; HC, herbaceous carbon; LC, leaf litter carbon; BGC, belowground carbon; SOC: soil organic carbon. CWT: Coffee without shade trees. CIs: Coffee with Inga sp. Shade trees. CPo: Coffee with polyculture farming. SF: secondary forest.

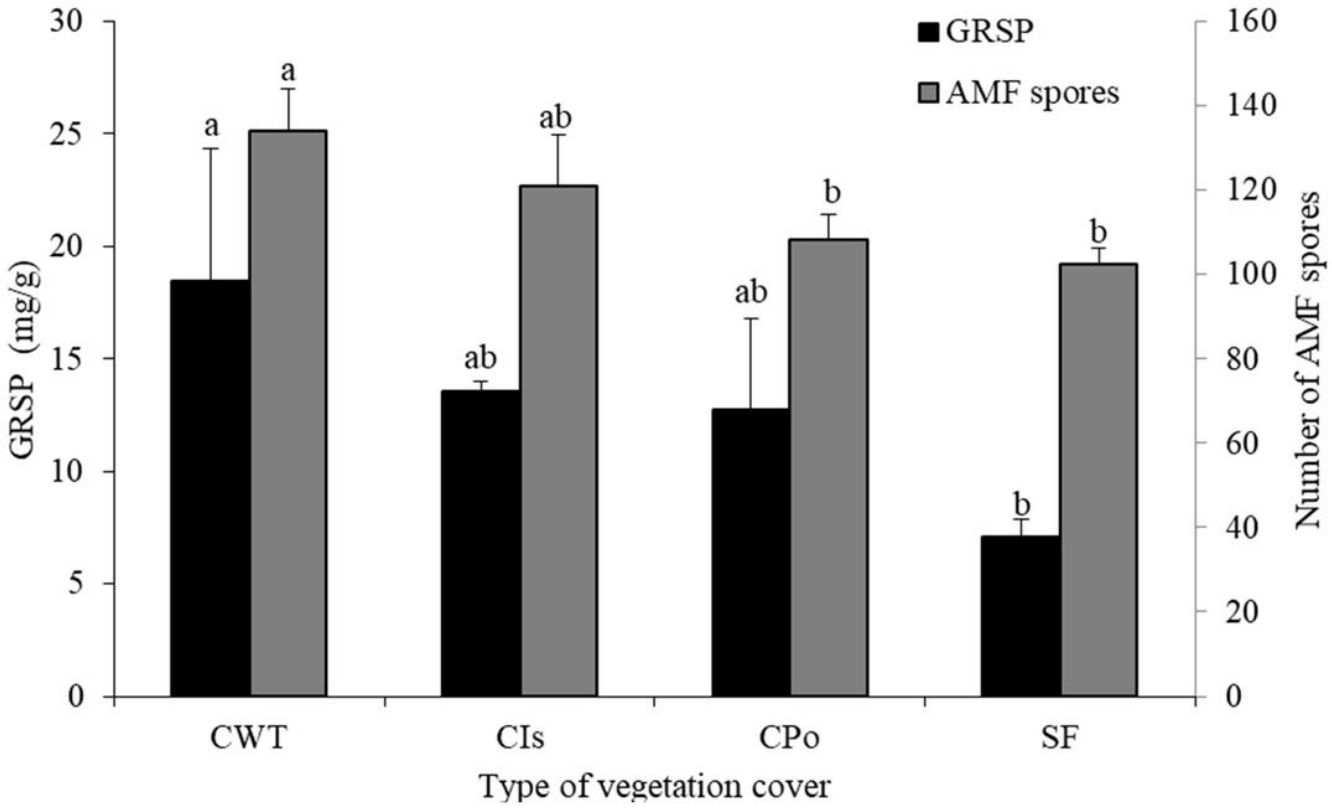

Figure 3

Glomalin and number of AMF spores in different types of vegetation cover. Letters above bars indicate significant differences according to Tukey's test ($P \leq 0.05$). CWT: Coffee without shade trees. CIs: Coffee with Inga sp. Shade trees. CPo: Coffee with polyculture farming. SF: secondary forest.

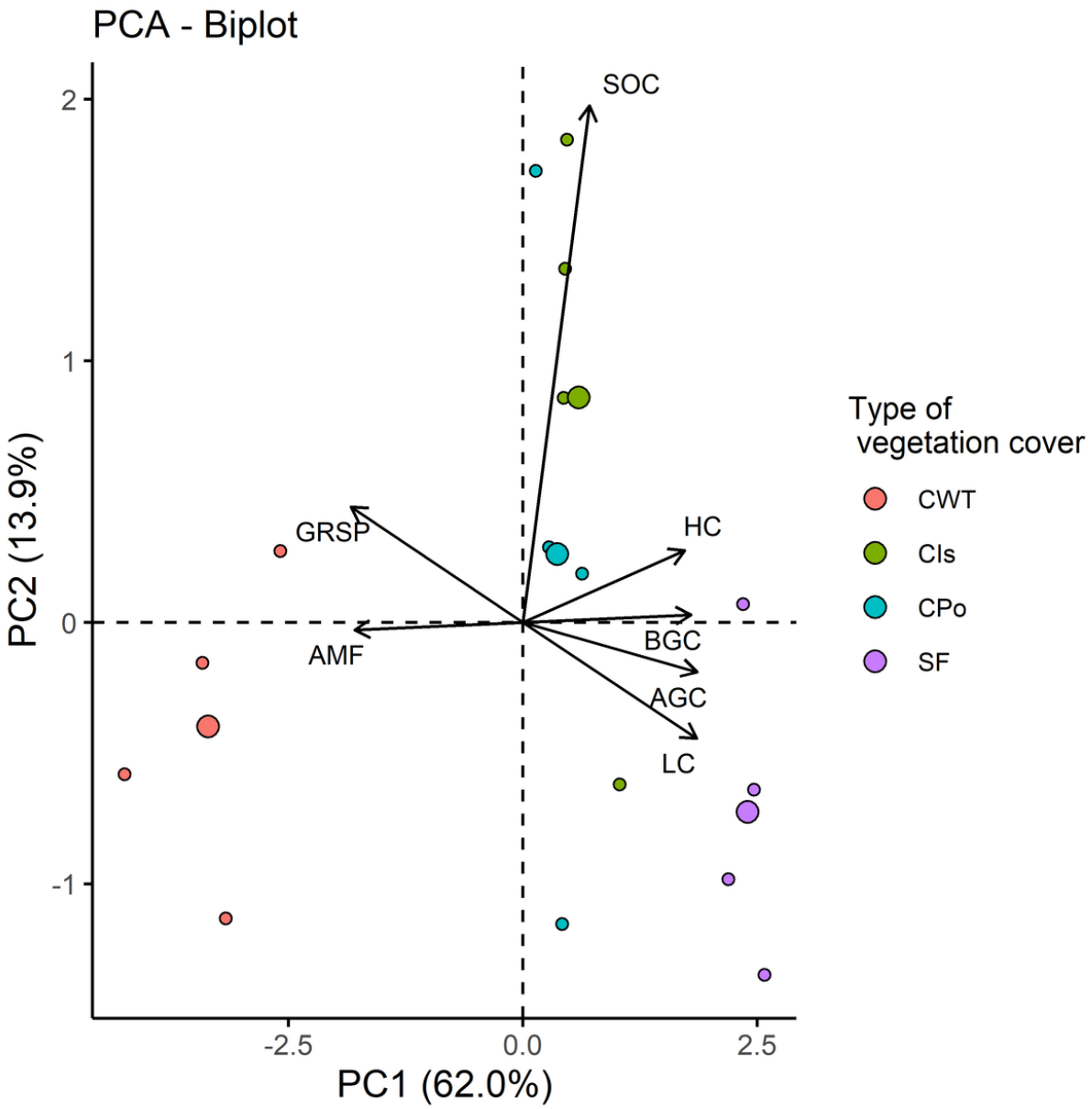

Figure 4

Multivariate analysis of carbon, Glomalin and mycorrhizal components in different vegetation cover systems. Carbon components include AGC, aboveground carbon; HC, herbaceous carbon; LC, leaf litter carbon; BGC, belowground carbon; SOC: soil organic carbon; GRSP: Glomalin content; AMF: number of HMA spores. CWT: Coffee without shade trees. CIs: Coffee with Inga sp. Shade trees. CPo: Coffee with polyculture farming. SF: secondary forest.

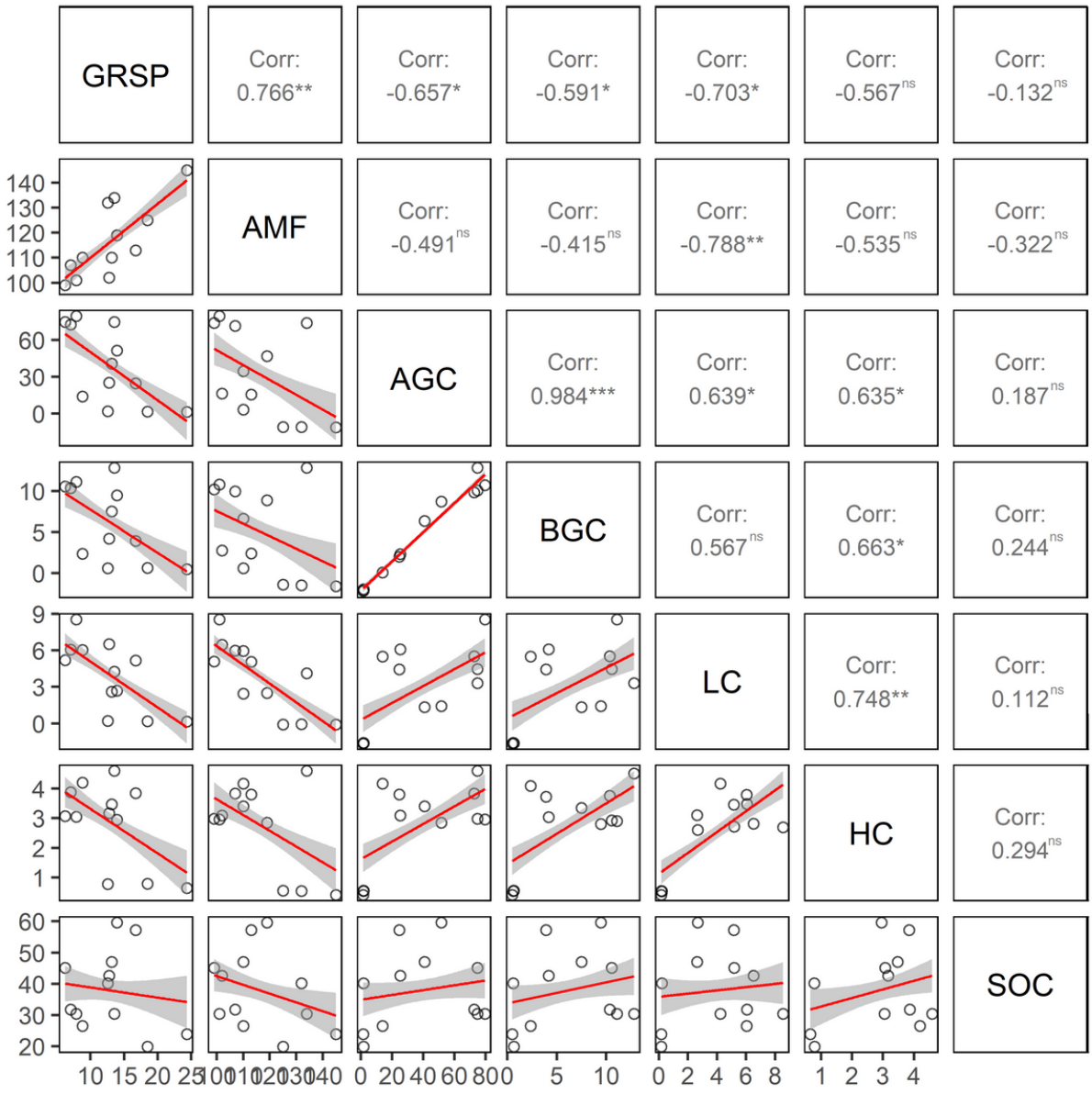

Figure 5

Correlation coefficients between Glomalin and mycorrhizae with carbon components. Carbon components include AGC, aboveground carbon; HC, herbaceous carbon; LC, leaf litter carbon; BGC, belowground carbon; SOC: soil organic carbon; GRSP: Glomalin content; AMF: number of arbuscular mycorrhizal fungal spores.