POTENTIAL OF CARBON STORAGE OF RUBBER (*Hevea brasiliensis* MÜLL. ARG.) PLANTATIONS IN MONOCULTURE AND AGROFORESTRY SYSTEMS IN THE COLOMBIAN AMAZON

[POTENCIAL DE ALMACENAMIENTO DE CARBONO EN PLANTACIONES DE CAUCHO (*Hevea brasiliensis* MÜLL. ARG.) EN MONOCULTIVO Y SISTEMAS AGROFORESTALES DE LA AMAZONIA COLOMBIANA]

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SUMMARY

Carbon sequestration potential of rubber (*Hevea brasiliensis*) plantations was estimated in two production systems: monoculture and agroforestry system with copoazú (*Theobroma grandiflorum*), on farms of Florencia, El Doncello and Belén de los Andaquíes, in northeastern Colombian Amazon, department of Caquetá. The plantations were classified into three age classes, according to their productive stage: 1-7, 8-20 and > 20 years. The carbon storage was estimated using the methodology proposed by Andrade and Ibrahim (2003) and recommended by IPCC (2003). Tree carbon sinks were evaluated: above and below ground biomass, and necromass. The highest proportion of carbon storage was found in biomass, with 95 and 92% in monoculture plantations and agroforestry systems, respectively. In both types of production systems, carbon storage is a function of tree age and density. The carbon stored in monoculture plantations was higher than in agroforestry systems, due to a greater density of rubber trees in the first production system. This study confirms that rubber plantations have potential to capture and store atmospheric carbon. With this information, the issue of participating in carbon markets of the rubber production chain can be addressed, and therefore strengthen in the region's competitiveness and sustainability.

Keywords: Productive chain; timber stage; biomass; necromass; roots.

RESUMEN

Se estimó el potencial de captura de carbono de las plantaciones de caucho (*Hevea brasiliensis*) en dos sistemas de producción: monocultivo y sistema agroforestal con copoazú (*Theobroma grandiflorum*), en fincas de Florencia, El Doncello y Belén de los Andaquíes, del nororiente de la Amazonia colombiana, departamento del Caquetá. Las plantaciones se clasificaron en tres clases de edades, de acuerdo a su etapa productiva: 1-7, 8-20 y > 20 años. El carbono almacenado se estimó mediante la metodología propuesta por Andrade e Ibrahim (2003) y lo recomendado por el IPCC (2003). Se evaluaron tres sumideros de carbono: biomasa sobre el suelo y abajo del suelo y necromasa. Se encontró, la mayor proporción de carbono almacenado en la biomasa, con un 95 y 92% en plantaciones de monocultivo y en sistemas agroforestales, respectivamente. En ambos tipos de sistemas de producción, el almacenamiento de carbono es función de la edad y la densidad arbórea. El carbono almacenado en los monocultivos fue mayor que en los sistemas agroforestales, atribuyéndose este resultado a la mayor densidad de árboles de caucho en los primeros. Este estudio corrobora que las plantaciones de caucho presentan potencial para capturar y almacenar carbono atmosférico. Con esta información, se generan insumos para abordar el tema de participación en mercados de carbono de la cadena productiva del caucho en la región y así fortalecer su competitividad y sostenibilidad.

Palabras claves: Cadena productiva; fustales; biomasa; necromasa; raíces.

INTRODUCTION

Climate change refers to alterations, directly or indirectly attributed to human activities, affecting the atmosphere composition and which is additional to the climate variability observed over comparable periods of time (IPCC, 2001). This climate change on the planet is mainly due to the increase in the concentration of greenhouse gases (GHG) in the atmosphere, being a large proportion of them emitted by anthropogenic activities associated with land use change, deforestation, fossil fuels use, inadequate agricultural practices and extensive cattle-raising (Acosta *et al.*, 2001a; IPCC, 2008). These GHG cause an overall increase in air and ocean temperature, snow and ice melting, and hence cause sea level to rise (IPCC, 2008). Rainfall periodicity can vary and exceed the usual average. Concentrated droughts may occur which can increase the risk for forest fires and there will be a greater impact on local communities, due to the increasing loss of biodiversity and the reduction of water supply (IDEAM, 2001).

GHG could be diminished by reducing CO_2 emissions and increasing terrestrial sinks (Segura and Andrade, 2008). Some agricultural practices, such as the implementation of agroforestry systems (AFS), are important alternatives for carbon capture and storage, especially in biomass and soil, increasing soil fertility, all of which has positive effects on the ecosystem productivity and sustainability (Orjuela, 2011; Orjuela and Andrade, 2011). AFS, by associating woody plants with crops, are an economical and ecological option for climate change mitigation (Albrecht and Kandji, 2003; Beer *et al.*, 2003; Swamy and Puri, 2005; Andrade, 2007; Segura and Andrade, 2008), which also involves the possibility of recognizing the economic value of carbon capture and storage as an environmental service (Ospina-Ante, 2003).

It has been shown that the rubber plantations (*Hevea brasiliensis* Müll. Arg) accumulate significant amounts of carbon in their biomass (Tsuruta *et al.*, 2000; Duran *et al.*, 2011). Moreover, the agroindustrial transformation process of rubber has great agro-ecological and socio-economic potential in Colombia, emerging as one of the most important productive lines in the Amazon region. This process generates rural employment, building social capital and fulfilling the protective-producer reforestation function in hydrographic basins and is an alternative development culture in illicit crops areas (SENA, 2006).

It is of fundamental importance to estimate with greater precision, the carbon capture and storage potential of *H. brasiliensis*. This information is key for assessing the ecosystemic service of carbon sequestration (Gobbi and Ibrahim, 2004; Andrade *et al.*, 2008), provides access to carbon sequestration economic incentives, generates additional revenue for the producer, and also contributes to the improvement of the production chain competitiveness and, hence, the life quality of local communities (Somarriba *et al.*, 2006). The aim of the study presented here was to estimate the carbon sequestration potential of rubber plantations in monoculture and agroforestry systems in the Colombian Amazon.

MATERIALS AND METHODS

The study was conducted in the Northeastern region of the Colombian Amazon, department of Caquetá, in the municipalities of Florencia, El Doncello and Belén de los Andaquíes (Figure 1). The Caquetá department is located at Southeast of Colombia, on the left bank of Caquetá river, at 2°58' N and 0°40' S, between 71°30' and 76°15' W (IGAC-INPA, 1993). The department has an average rainfall of 3,600 mm year^{-1}, a mean annual temperature of 25.1 °C and the relative humidity varies between 79.5 and 88.6%. Around 20% of the Caquetá is located in the Amazon piedmont at an altitude between 400 and 1,000 m.

Farm selection

The farms were selected in agreement with the *Asociación de Reforestadores y Cultivadores de Caucho del Caquetá* (ASOHECA), taking into account the producers' willingness and the availability of rubber plantations in monoculture and AFS with copoazú, in different stages of formation. Three age ranges were established in the rubber plantations: 1-7 years (stage of growing or unproductive trees); 8-20 years (production peak) and > 20 years (beginning of the decline in rubber production). A productive life of 40 years is estimated. Copoazú (*Theobroma grandiflorum* Willd. Ex Spreng Schum.) is one of the most promising and widespread fruit trees in the Amazonian region and is commonly associated with other crops or productive forest plantations such as rubber. Currently, this fruit tree is widely distributed in the Colombian Amazon departments with crop management and cultural practices similar to those used in cocoa. However, in spite of belonging to the genus *Theobroma*, copoazú has different characteristics in shape, size, internal structure and almond alveolar design (Cohen and Jackix, 2005).

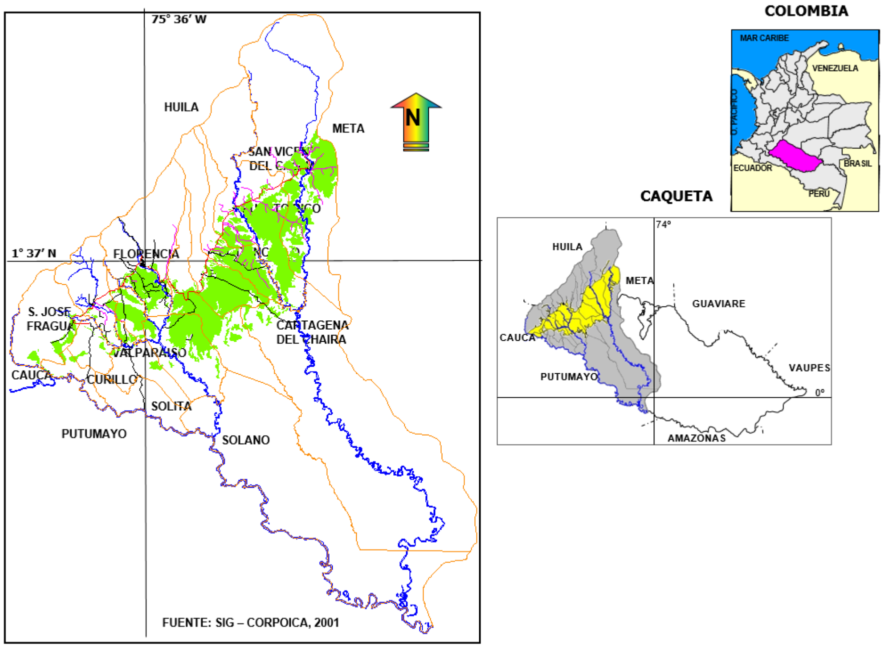

Figure 1. Details of study area.

Sampling techniques and evaluation of samples

Three sinks or carbon components were evaluated:
1) Necromass
2) Aboveground biomass
3) Belowground biomass (fine roots).

This research estimated carbon storage following the methodology proposed by Andrade and Ibrahim (2003) and methods recommended by IPCC (2003).

a) Temporary sampling plots

In each crop system selected, three temporary sampling plots, in rectangular shape, were established and measured, considering age range and location (municipality). A sample plot location map was made with a global positioning system (GPS). The sample plot was 250 m^2 in size considering at least 15 rubber trees (some reached a larger area due to the absence of some trees). The plots were delimited using wooden stakes and colored strings with reflective tape, as recommended by Delgadilla and Soltero (2006). In total, 48 sample plots were established and measured, corresponding to three ages in monoculture for two municipalities (27 plots), while in Florencia and El Doncello only two ages were placed in AFS (21 plots).

b) Carbon and biomass estimation
1. Necromass
Litter

Litter sampling was the first component measured, with the aim of reducing its disturbance. All material, found in 10 frames of 0.25 m^2 each, randomly located within each sample plot, was taken. The samples were fresh weighed and mixed to obtain a subsample of approximately 300 g per plot. In order to estimate dry material content, the subsamples were taken to the laboratory and dried in an oven at 65 °C until a constant weight was obtained.

Standing dead trees and fallen trunks

The standing dead trees were estimated with the method of biomass expansion factor and biomass models with correction according to the absence of part of the biomass. In this case, the diameter of trunk at breast height (dbh) and total height (th) were measured and the proportion of remaining crown, compared to a living tree, was estimated.

The volume of the trunks or fallen dead trees was estimated with the line intersect method (IPCC, 2003), which consists in establishing two perpendicular transects of 50 m each by plot. The diameter of all the pieces (>1 cm) that touched any transect was measured. The volume of fallen timber was estimated with the equation:

$$V = \frac{\pi^2 \ x \ (D_1^2 + \ D_2^2 + \ldots + D_n^2)}{8 \ x \ L}$$

Where:
V : Volume of fallen timber (m^3 ha^{-1})
D_1, D_2, D_n : Diameter of each piece intercepted by the line (cm)
L : Transects length (m)

The timber volume was converted to dry matter assigning a specific gravity to each piece. In order to do so, the machete method, recommended by IPCC (2003), was used. This method consists on hitting the piece with a machete, defining a class of density: high (consistent), medium (intermediate) and low (rotten), and assigning an specific gravity to each density class: 0.23, 0.42 and 0.60 g cm^{-3}, respectively (Segura, 2005).

2. Above-ground biomass
Herbaceous material

This component was estimated in 10 frames of 0.25 m^2 each, which were randomly distributed within the plot. All herbaceous biomass was collected, cutting the herbaceous material (plants < 1.5 m in height) that was found inside the frame. The collected material was fresh weighed and a subsample of about 250 g was taken to estimate the dry matter content in the laboratory (65 °C until a constant weight was obtained).

Woody components

All rubber and copoazú trees that were found in the temporal sampling plot were measured (th and dbh in rubber and trunk diameter at 30 cm height -D_{30}- in copoazú). Aspects such as the presence of twisted, bifurcation, buttressed, or inclined trunks in sloped terrains were considered when measuring the trees.

The woody component biomass was estimated using allometric models that were developed for these species. The above-ground biomass of 1-7 years trees was estimated with the biomass model developed by Duran *et al.* (2011):

$$AB = -0{,}59 + 0{,}34 \ x \ dbh^2$$

Where:
AB : Aboveground biomass (kg $tree^{-1}$)
dbh : Trunk diameter at breast height (cm)

The allometric model created by Moreno *et al.* (2005) was applied to rubber trees of 8-20 and >20 years age:

$$AB = 0{,}00411 \ x \ CBH^{2{,}596}$$

Where:
AB : Aboveground biomass (kg $tree^{-1}$)
CBH : Trunk circumference at breast height (cm)

Given that no allometric models for copoazú tree have been developed, its aboveground biomass was estimated using an allometric model developed by Andrade et al (2008) for cacao trees (*Theobroma cacao* L.) in Costa Rica:

$$\boldsymbol{AB = 10^{(-1{,}625 + 2{,}63 \ x \ Log(D_{30}))}}$$

Where:
AB : Aboveground biomass (kg $tree^{-1}$)
Log : Base 10 logarithm
D_{30} : Trunk diameter at 30 cm height (cm)

3. Below-ground biomass

In each established plot, three sampling points for fine roots were located, using pits. Fine roots (diameter < 2 mm) biomass was estimated by removing three monoliths (one for each side: south, east and west) of 1000 cm^3 (10 x 10 x 10 cm) at depths of 0-10, 10-20 and 20-30 cm. The roots were extracted from each soil sample manually and were taken to the laboratory for oven drying at 65 °C until constant weight.

4. Carbon storage estimation

Biomass and necromass was converted into carbon by multiplying by 0.5, which is a factor proposed by IPCC (2008).

Information analysis

The results obtained in this study were analyzed with descriptive statistics (mean, standard deviation and standard error) using the Infostat statistical software 2010 version (Di Rienzo *et al.*, 2010).

RESULTS AND DISCUSSION

General Information Regarding Sampled Individuals

In a total of 1.3 ha sampled area, a total of 880 trees was found, of which 774 were *H. brasiliensis* trees and 106 were *T. grandiflorum* individuals The sampled trees were in a good phytosanitary state; some individuals had deciduous behavior due to they were naturally defoliated, which is a usual behavior of this species, according to Torres-Arango (1999). The sampled rubber tree individuals belonged to the clones: FX 25, FX 3864, IAN 710, IAN 873 and FX 4098.

The rubber plantations in monoculture and AFS have a planting distance of 7 x 3 m. AFS older than 7 years were not established with a planned distribution, since only the fruit component between rubber lines was included. However, some young plantations (1-7 years), were established in double rows of rubber, with planting distances of 4 m between rows, 3 m between plants and 10 m between each double line, in the middle of which the copoazú trees were planted. Plantations established in monoculture showed a higher density of rubber trees (Table 1) than in AFS, because in most of the sampled plots, it was found that the producer includes the fruit component when rubber tree losses are obtained due to phytosanitary problems, which allows maintaining its productivity per hectare.

Table 1. Population density of rubber plantations in monoculture and agroforestry systems (AFS) in the Colombian Amazon.

Age (years)	**Production System**		
	Monoculture	**AFS**	
	Rubber	**Rubber**	**Copoazú**
	Density (trees ha^{-1})		
1 - 7	662	673	232
8 - 20	582	572	126
> 20	563	501	199

Carbon storage in herbaceous plants

Carbon storage in herbs showed no significant differences (p>0.05) between systems, with averages of 1.5 Mg C ha^{-1} for both systems (Table 2). The low carbon content of this component can be attributed to the low amount of photosynthetically active radiation transmitted to the herbaceous layer, where only shade tolerant species can grow (Acosta *et al.*, 2001b). Moreover, in older plantations, herbs are subjected to constant weed control and eventually grazing by cattle.

Table 2. Carbon stored in herbs present in rubber plantations in monoculture and agroforestry systems (AFS) in the Colombian Amazon.

System	**Age (years)**		
	1 - 7	**8 – 20**	**> 20**
	Mg C ha^{-1}		
Monoculture	1.46 ± 0.10 a	1.56 ± 0.11 a	1.49 ± 0.16 a
AFS	1.65 ± 0.06 a	1.59 ± 0.08 a	1.35 ± 0.08 a

Values correspond to the mean ± standard error. Same letters indicate no statistical differences among systems (p > 0.05).

Carbon storage in necromass

Carbon storage in necromass showed that in AFS more of this element is captured, which could be initially attributed to the extra and constant leaf litter contribution by copoazú. The estimated carbon in this component corresponds to 6.7% of the total stored in the AFS, while in monocultures corresponds to 2.6%.

Litter stored on average 2.6 Mg C ha^{-1} in rubber plantations in agroforestry (Table 3), exceeding reports such as Orjuela (2011) and Orjuela and Andrade (2011), who found that litter stores 1.8 Mg C ha^{-1} in fallows of five years in Caquetá, Colombia. Similarly, Ferreira (2001) found that litter stored 1.8 Mg C ha^{-1} in 1-7 years secondary forests, 1.9 Mg C ha^{-1} in 8-20 years secondary forests, and 2.6 mg C ha^{-1} in >20 years secondary forests, in San Carlos, Nicaragua.

Table 3. Carbon stored in necromass of rubber plantations in monoculture and agroforestry systems (AFS) in the Colombian Amazon.

System	**Component**	**Age (years)**		
		1 - 7	**8 – 20**	**> 20**
		Mg C ha^{-1}		
Monoculture	Litter	3.34 ± 0.62 a	1.25 ± 0.16 b	1.18 ± 0.26 b
	Fallen trunks	0.84 ± 0.46 a	1.23 ± 0.59 a	0.29 ± 0.17 a
	Standing dead trees	0.00 (NA) a	0.00 (NA) a	0.03 ± 0.03 a
AFS	Litter	3.25 ± 0.96 a	2.14 ± 0.46 a	2.49 ± 0.40 a
	Fallen trunks	3.80 ± 3.29 a	3.61 ± 1.63 a	2.33 ± 0.95 a
	Standing dead trees	0.00 (NA) a	0.59 ± 0.59 a	0.78 ± 0.78 a

Values correspond to the mean ± standard error. NA: Not Applicable. Same letters indicate no statistical differences among systems (p > 0.05).

Carbon storage in the woody component

As expected, carbon storage increases with the age of the plantations (Table 4), as described by Alegre *et al.* (2001), Callo-Concha *et al.* (2001) y Lapeyre *et al.* (2004). In other words, older plantations showed the highest carbon storage values, which is related to biomass accumulation product of the balance between photosynthetic activity and respiration (Segura and Andrade, 2008).

Younger plantations (1-7 years) stored on average 4.3 Mg C ha^{-1} in monoculture and 4.2 Mg C ha^{-1} in AFS. These findings are similar to those reported by Duran *et al.* (2011) who found that ASOHECA plantations, in the same age range, stored on average 4.2 Mg C ha^{-1}. The 8-20 years age range, in AFS stored 44.8 Mg C ha^{-1}; this result is close to that reported by Yquise-Pérez *et al.* (2009), who found 54.3 Mg C ha^{-1} in forest species of 10 years in AFS with *Paspalum conjugatum* Berg. For the rubber plantations in monoculture included in this study, the amount of carbon in this compartment was 57.2 Mg ha^{-1}. The oldest plantations (> 20 years) contained 121.5 and 97.2 Mg C ha^{-1} in monoculture and AFS, respectively. These same researchers found that *T. cacao* in AFS with forest species of 25 years, stored 111.7 Mg C ha^{-1}.

Carbon storage in belowground biomass

In this compartment, most of the carbon storage was found in the first 10 cm of soil depth (Table 5), which is related to the greater abundance of herbs' root systems. The stored carbon at this depth was 1.2 Mg C ha^{-1} in AFS and 1.5 Mg C ha^{-1} in monoculture; while at 10 to 20 cm depth 0.23 Mg C ha^{-1} in AFS and 0.30 Mg C ha^{-1} in monoculture was found; in the last depth 0.14 Mg C ha^{-1} was estimated for both production systems. In monocultures, more carbon storage was found in fine roots than in AFS, possibly attributed to crop management in the region, where monoculture plantations are subjected to a constant weed control, which in turn stimulates a greater production of roots.

Orjuela (2011) and Orjuela and Andrade (2011) found on five years of formation fallows in the Colombian Amazon, an average of 1.6 Mg C ha^{-1} in the first 10 cm of soil depth and 0.5 Mg C ha^{-1} at depths of 10 to 20, and 20-30 cm. Yquise-Pérez *et al.* (2009) found in rubber plantations of 30 years of age in the department of Huanuco (Peru), a storage of 0.35 Mg C ha^{-1} in the first 20 cm of soil depth, which is a lower result than that found in this study. In the same way, Poroma (2012) found 0.1 Mg C ha^{-1} in the first 20 cm of soil depth, in cacao orchards in Waslala, Nicaragua.

Table 4. Carbon stored in the woody component of rubber plantations in monoculture and agroforestry systems (AFS) in the Colombian Amazon.

System	Species	Age (years)		
		1 – 7	**8 – 20**	**> 20**
		Mg C ha^{-1}		
Monoculture	**Rubber**	4.33 ± 0.48 a	57.16 ± 6.26 a	121.52 ± 19.34 a
AFS	**Rubber**	4.12 ± 1.19 a	44.38 ± 12.32 a	96.62 ± 14.03 a
	Copoazú	0.03 ± 0.02	0.44 ± 0.17	0.60 ± 0.25

Values correspond to the mean ± standard error. Same letters indicate no statistical differences among systems (p > 0.05).

Table 5. Carbon stored in fine roots at different depths in rubber plantations in monoculture and agroforestry systems (AFS) in the Colombian Amazon.

System	Depth (cm)	Age (years)		
		1 - 7	**8 - 20**	**>20**
		Mg C ha^{-1}		
Monoculture	**0 – 10**	0.88 ± 0.14 a	2.38 ± 0.19 a	1.28 ± 0.13 a
	10 – 20	0.17 ± 0.03 a	0.42 ± 0.06 a	0.31 ± 0.04 a
	20 – 30	0.08 ± 0.02 a	0.18 ± 0.03 a	0.17 ± 0.03 a
AFS	**0 – 10**	0.70 ± 0.10 a	1.60 ± 0.15 b	1.20 ± 0.17 a
	10 – 20	0.14 ± 0.03 a	0.32 ± 0.05 a	0.22 ± 0.03 a
	20 – 30	0.14 ± 0.06 a	0.16 ± 0.02 a	0.12 ± 0.02 a

Values correspond to the mean ± standard error. Same letters indicate no statistical differences among systems ($p > 0.05$).

Total carbon storage

The total carbon storage of the studied plantations, specifically in the aboveground biomass compartment, is higher in rubber plantations in monoculture than in AFS with copoazú (Table 2), which is mainly due to differences in tree density, being it 31% higher in monoculture plantations compared with the AFS studied. In relation to this, Salgado and Flores (2004) emphasize that the ability to capture and store carbon depends on the species used, tree density, silvicultural management, ecological conditions, site quality and possible leakages.

The plant aboveground sub-compartment was the largest reservoir of carbon: 95.4 and 91.7% of the total carbon stored in monoculture plantations and AFS, respectively (Figure 2); which is explained by its high content of timber biomass. The necromass sub-compartment, held 2.6 and 6.7% of the total carbon stored in monoculture and AFS, respectively. The fine root component held 1.9 and 1.6% of the total carbon stored in monoculture and AFS, respectively.

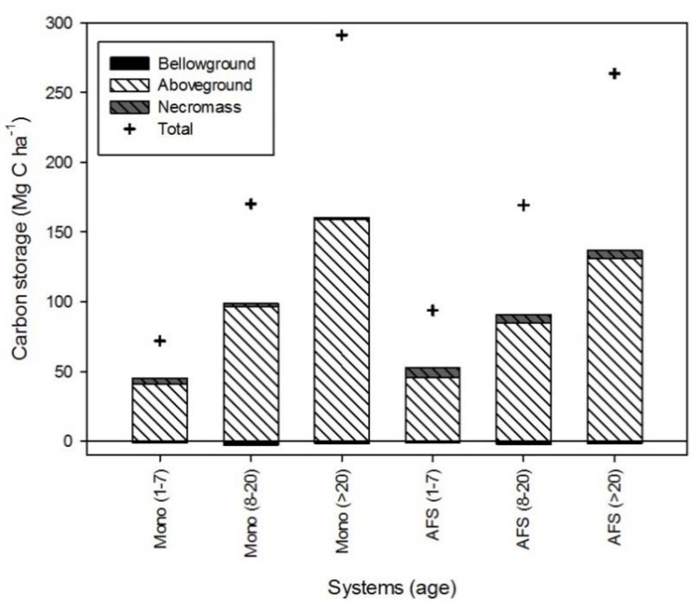

Figure 2. Carbon stored in rubber plantations in monoculture (Mono) and agroforestry systems (AFS) in the Colombian Amazon.

CONCLUSIONS

Rubber production systems in monoculture fixed 3.7% more atmospheric carbon than those in AFS with copoazú. The major carbon storage is found aboveground in the plant sub-compartment. However the difference between the densities of rubber trees sampled in monoculture and AFS showed, in the same way, the difference in total carbon storage. This is related to the fact that in the region rubber plantations are very heterogeneous and present tree loss because of various reasons, such as damages in the trunk by termites and fungi.

It is confirmed that plantations of *Hevea brasiliensis* in the Colombian Amazon, have great potential for carbon capture and storage, making it possible to find options to strengthen the competitiveness and sustainability of the rubber production chain of the in the region. This can be a first step to access to compensation mechanisms (payment for ecosystem services: PES), which could generate additional revenue to the producer and hence help to improve the life quality of local communities.

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