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Carbon storage in tree biomass dispersed in pastures in the arid Caribbean region of Colombia

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Abstract

Aim of study: To determine the importance in terms of carbon sequestration of dispersed trees in pasture lands as a greenhouse gas (GHG) mitigation measure.

Area of study: The study was carried out in the municipality of Agustin Codazzi (Cesar Department, Colombia), between October 2020 and March 2021.

Materials and methods: We characterized 43.57 hectares dispersed amongst sixteen plots and all trees with a diameter at breast height > 10 cm were measured. Allometric equations were used to estimate aboveground biomass storage and species were classified in terms of use: timber products (TP) and non-timber products (NTP).

Main results: A total of 750 trees were registered, 10 families and 28 species, of which NTP and TP represented 60.71% and 32.1% respectively. Aboveground carbon stock in trees in pastures was estimated at 7.15 + 4.8 Mg C ha^{-1}. The most abundant species were *Guazuma ulmifolia* Lam. and *Albizia saman* (Jacq.) Merr.

Research highlights: NTP species present a high potential for carbon storage and provide livestock assets. Placing value on carbon storage in rangelands can offset the low opportunity cost of trees in pastures by providing incentives for carbon storage, conservation, and recovery of threatened species.

Additional key words: trees diversity; species use; tropical dry forest; greenhouse gas mitigation; livestock; ecosystems services.

Abbreviations used: AGB (aboveground biomass); AGC (aboveground carbon); AGROSAVIA (Colombian Agricultural Research Corporation); BA (basal area); DBH (diameter at breast height); GHG (greenhouse gas); NTP (non-timber forest products); SPS (silvopastoral systems); TP (timber products).

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Introduction

Currently, the global forest area is equivalent to 4060 million hectares, 45% of which is in the tropical forest zone (FAO & UNEP, 2020). Tropical forest has registered significant losses, 420 million hectares since 1990, due to changes in land cover and conversion to other land uses. This is due to natural factors such as drought, fires, storms, and diseases, and anthropogenic causes such as clearing land for agriculture, overharvesting of timber, expansion of settlements, and infrastructural developments (Keenan et al*.,* 2015). According to Armenteras & Rodríguez (2014), the main precursors of deforestation in Latin America are associated with the expansion of the agricultural frontier including for livestock at 42.5% and population growth at 18.85%. These factors affect the provision of ecosystem services derived from tropical forests, functional diversity, and net carbon emissions due to deforestation and degradation (Houghton, 2012).

In Colombia, tropical dry forests (BsT) are considered a strategic ecosystem for the conservation of biodiversity and carbon storage. These forests represent 735,514 ha, 39.2% of which are in the Caribbean region, with average aboveground biomass (AGB) of 96.2 Mg C ha^{-1} (Phillips et al*.,* 2011). Ulloa (2016) reported that more than 98% of the pristine dry to sub-humid forest cover in Colombia has disappeared because of the degradation and conversion of forest formations to extensive cattle ranching.

Cesar Department, in the Colombian Caribbean region, is characterized by a livestock production of 1,529,131 head of cattle in a predominantly extensive grazing area of 1,062,415 ha (FAO & ADR, 2019). Livestock production is thus the most important agricultural activity and the precursor of deforestation, degradation, and increased greenhouse gas emission (GHG) processes. According to the GHG inventory of the Cesar Department, enteric fermentation and manure management from livestock production are responsible for 1229.66 kt CO_2-eq and 83.87 kt CO_2-eq, respectively (MADS, 2015), contributing to CH_4 and NO_2 emissions and global climate change (Gerber et al*.,* 2013).

The Cesar River Valley ecoregion has highly productive soils, where processes such as livestock, agriculture, agrobusiness and open-pit coal mining converge. For several decades these activities have generated negative externalities on natural resources. Elimination of tree cover, loss of topsoil, erosion processes, and compaction are examples of these processes. This deterioration is exacerbated by climate seasonality in the region; four months with low or non-existent rain days at the beginning of the year (CORPOCESAR, 2019). Although this situation presents serious limitations for the development of existing production systems, there is scope to implement consider sustainable production strategies as soon as possible to recover tree cover in agricultural and livestock. That is why an assessment strategy and recognition of the use of tree species can contribute to the restoration and sustainability of the territory.

Although livestock production systems generate deforestation processes and emit GHG, they also have the potential to conserve diversity and mitigate GHG through the implementation of silvopastoral systems (SPS) (Jose & Dollinger, 2019). SPS store carbon in aboveground biomass and soil organic carbon (Ibrahim et al*.,* 2007). The SPS integrates trees and shrubs associated with pastures and animals, into the same area, to improve the sustainability of the livestock system (Montagnini et al*.,* 2013). In Cesar Department, scattered trees in pastures stand out as the most important SPS.

Studies of SPS in the tropics have shown an important aboveground carbon (AGC) storage regarding natural forests. Natural pastures with scattered trees and forage banks store between 70 and 120 Mg C ha^{-1} (Ibrahim et al., 2007), while pastures with a high density of trees in the dry tropics of Nicaragua conserve 6.3 Mg C ha^{-1} (Cárdenas et al., 2019) compared with natural regeneration processes in cattle farms in the Department of Caquetá, Colombia, reach values of 32.32 Mg C ha^{-1} (Rojas-Vargas et al*.,* 2019).

The IPCC (2007) estimates AGC of 141 Mg C ha^{-1} in the tropical forests while Ibrahim et al*.* (2007) reported values of 90.78 Mg C ha^{-1} and 115 Mg C ha^{-1}, respectively, in secondary dry forests present in cattle farms in Costa Rica and Nicaragua. In Colombia AGC storage in tropical dry forest and humid forest estimated from 46.17 Mg C ha^{-1} of 124.27 Mg C ha^{-1} respectively (AGB values multiplied by emission factor 0.48) (Phillips et al*.,* 2011).

In addition to contributing to AGC storage, SPS where trees are dispersed in pastures, improve the productivity of the livestock production system through the conservation of biodiversity and landscape connectivity (Chacón & Harvey, 2013), the conservation of soils and water (Ríos et al., 2008), and the provision of timber products (TP) and non-timber forest products (NTP) for commercial or subsistence purposes. Improving the profitability of production systems whilst contributing to animal welfare (Harvey et al*.,* 2011) has been seen through the production of forage and fruits of high nutritional quality for cattle feeding (Casasola et al*.,* 2001), whilst the provision of wood, fence posts, and firewood reduces the impact on forests (Harvey et al*.,* 2011) together.

The objective of this study was to determine the AGC storage present in the dispersed trees in pastures in the arid Caribbean, Colombia.

Material and methods

Study area

The study was carried out in the municipality of Agustín Codazzi, in Cesar Department, which ranks third at the

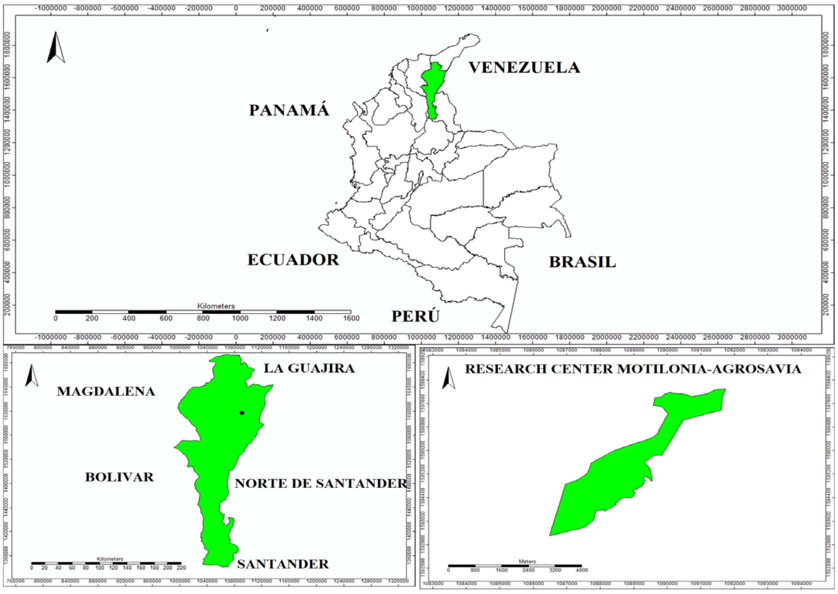

Figure 1. Location of the experimental sites, Cesar Department, Colombia.

departmental level in livestock production in Colombia, with 89,789 bovines according to records of the Colombian Agricultural Institute (ICA, 2021). The municipality of Agustín Codazzi is in the Colombian dry Caribbean region and is characterized by the development of extensive cattle ranching in mostly naturalized pastures.

The sample area was established in pastures with traditional management practices, located at Motilonia Farm within the Research Center of the Colombian Agricultural Research Corporation (AGROSAVIA) located in the municipality of Agustín Codazzi, Cesar (Fig. 1) (10°00´09.03 N-73°14´55.88 W) at an elevation of 103 m.a.s.l. The Center has an annual precipitation of 1581 mm (1980-2019 period), average annual temperatures of 29°C, average relative humidity of 69.7% and sunshine of 6.9 hours day^{-1}. The soils have a sandy, loamy texture, neutral pH, and low soil organic matter content. The natural vegetation corresponds to a tropical dry forest (Phillips et al., 2011). The research center presents various production systems, among which livestock farming stands out.

Livestock production systems are characterized by dispersed trees in pastures association with naturalized grasses (*Hyparrhenia rufa* (Nees) Stapf and *Bothriochloa pertusa* (L.) A.Camus) for grazing dual-purpose cattle (beef and dairy production) with an average load of 2.0 livestock units per hectare for an occupation period between 30 and 45 days.

Sampling of dispersed trees in pasture

Sample plots similar characteristics - that contained trees - were selected: slope < 5%, similar grass composition and herd management practices, and a size between 2.0 and 5.0 ha. The pastures were delimited by geo-referencing with a GPS. In these pastures, 16 sample plots were selected randomly, each with an average area of 2.73 ± 0.82 ha for a total of 43.57 ha. Within each of the sample plots, all dispersed trees in pastures with a diameter at breast height (DBH) ≥10 cm were registered with species, genus, and family of each individual recorded (Harvey et al., 2011). The DBH (cm) was measured using a tree diameter tape (long. 10 m) and their heights (H, m) were estimated using a Vertex IV digital hypsometer (Haglöf, Langsele, Sweden) (Harvey et al., 2011; Chacón & Harvey, 2013; Martínez-Encino et al., 2013). The botanical identification in the field was carried out from the common name of the species and later cross-referenced with the flora of the territory (Collantes et al., 2019; García et al., 2019). A list of species was prepared from the data obtained with standardized botanical nomenclature using: the Angiosperm Phylogeny Group IV tool, the International Plant Names Index (https://www.ipni.org) and World Flora Online (http://www.worldfloraonline.org).

Assessment of the economic importance of trees

To estimate the importance of trees in production systems, the taxa studied were grouped into TP and NTP, and into species of commercial importance (CM) or subsistence crops (SUB) (Selaya et al., 2017). If a species provided both the TP and NTP, it was included only in the main use category (Selaya et al., 2017). To estimate its potential use, 12 use categories were defined for trees in pastures (Cajas-Girón & Sinclair, 2001; Harvey et al., 2011; Rao et al., 2015). Timber uses are related to the production of beams, planks, boards, strips, and construction materials, in addition to other uses like fuel for cooking food (firewood and charcoal); non-timber uses like feeding cattle (fruits, fodder), human and fauna feed-

Table 1. Floristic characterization, number of trees, diameter at breast height (DBH) and height (H) in pasture dispersed trees of studied area (Caribbean region, Colombia). Average (Ave.) and standard error are shown (N=16 plots).

Species	No. of trees	DBH (cm			H (m)		
		Ave.	Min.	Max.	Ave.	Min.	Max.
Guazuma ulmifolia Lam.	352	23.01 + 16.36	10	200	10.17 + 2.60	4	18
Albizia saman (Jacq.) Merr.	124	76.88 + 30.73	11	154	14.62 + 2.34	8	22
Maclura tinctoria (L.) D. Don ex Steud.	54	17.50 + 8.47	10	63	9.51 + 2.57	4	18
Cordia alba (Jacq.) Roem. & Schult.	40	15.12 + 5.38	10	36	6.52 + 1.66	4	11
Leucaena leucocephala (Lam.) de Wit	25	16.21 + 5.56	10	32	12.22 + 2.37	9	18
Attalea butyracea (Mutis ex. L.f.) Wess. Boer	24	51.52 + 13.55	24	73	13.85 + 2.01	10	17
Acacia farnesiana (L.) Willd.	19	17.94 + 6.77	10	41	9.79 + 1.43	8	12
Enterolobium cyclocarpum (Jacq.) Griseb.	11	26.59 + 25.6	11	99	11.33 + 4.92	6	25
Tabebuia rosea (Bertol) DC	11	23.73 + 7.28	15	40	14.82 + 2.96	10	18
Pithecellobium dulce (Roxb.) Benth.	11	16.61 + 6.13	10	27	8.62 + 1.73	6	12
Albizia guachapele (Kunth) Dugand	10	89.83 + 23.29	62	146	15.39 + 1.18	13	17
Ceiba pentandra (L.) Gaertn.	8	87.00 + 63.3	12	158	13.53 + 3.02	8	18
Albizia niopoides (Benth.) Burkart	8	57.94 + 35.44	13	110	16.88 + 4.39	10	24
Cecropia peltata L.	7	16.69 + 5.77	12	28.5	11.38 + 3.31	5	16
Sterculia apetala (Jacq.) H.Karst.	7	45.46 + 31.46	12	90	12.54 + 3.38	8	16
Prosopis juliflora (Sw.) DC.	7	16.07 + 3.63	10.5	21.3	8.57 + 2.44	6	13
Gliricidia sepium (Jacq.) Walp.	6	38.18 + 5.11	30	45	13.33 + 1.97	12	17
Cordia gerascanthus L.	6	16.00 + 4.82	12	25	12.17 + 1.60	10	14
Ficus insipida Willd.	4	57.67 + 31.36	17.2	93.5	14.40 + 4.67	8.60	20
Spondias mombin L.	3	70.67 + 37.17	40	112	17.00 + 2.00	15	19
Lecythis minor Jacq.	2	50.00 + 14.14	40	60	18.50 + 2.12	17	20
Tabebuia ochracea A.H. Gentry	2	44.50 + 0.71	44	45	13.75 + 0.35	13.50	14
Platymiscium pinnatum (Jacq.) Dugand	2	20.25 + 2.47	18.5	22	10.00 + 2.83	8	12
Crescentia cujete L.	2	21.15 + 1.63	20	22.3	5.50 + 0.71	5	6
Erythrina fusca Lour.	2	12.25 + 0.35	12	12.5	7.25 + 0.35	7	7.25
Acacia sp.	1	20.00	-	-	15.00	-	-
Ficus dendrocida Kunth	1	24.40	-	-	9.00	-	-
Anacardium excelsum (Bertero ex Kunth)	1	10.00	-	-	10.20	-	-

ing (fruits, seeds, and nectar), making crafts (seeds, fibers), medicines (latex and resins) and providing environmental and cultural services like shade, water protection, living fences, and cultural symbols. The identification of uses by species was carried out through semi-structured surveys (García-Flores et al*.,* 2019). Livestock producers, agricultural technicians, and botanical experts were surveyed. The respondents were in six departments in the Caribbean region. Additionally, the information was complemented with literature reviews on the use of scattered trees in paddocks in the dry tropics. To facilitate the analysis, species were grouped according to their uses, TP and NTP, in three density classes (Pitman et al., 2001): dominant species with a density > 2 individuals ha^{-1}, common species between 1 and 2 individuals ha^{-1}, and rare species with less than 1 individual ha^{-1}.

Aboveground carbon stock estimate

The AGB stock content in trees with DBH > 10 cm dispersed in pastures was estimated. The estimation of the biomass was carried out using two allometric equations: Eq. (1) for tree species (Chave et al., 2014), and Eq. (2) for palm species (Frangi & Lugo, 1985), equations widely used in agroforestry systems in the dry tropics (Chacón & Harvey, 2013).

$$AGB = 0.0673 \times (\rho DBH^2 HT)^{0.976} \quad (1)$$

$$Y = 10 + 6.4 \times HT \quad (2)$$

where: AGB, aboveground biomass (kg); DBH, diameter at breast height (cm); HT, total height (m); ρ, wood density (g cm^{-3}); Y, aboveground biomass (kg).

Table 2. Taxa classification according to their major uses nontimber, timber and minor or unknown use in relation to abundance, basal area (BA) and estimated aboveground carbon (AGC). Taxa were sampled in 16 plots location in dispersed tree in pasture, dry Caribbean region, Colombia.

Use category	No. of taxa	Stems abundance		BA		AGC	
		Absolute	Total (%)	Absolute (m²)	Total (%)	(Mg C)	(%)
Species or genera primarily used for TP	9	98	13.00	11.38	9.30	20.60	6.60
Species or genera primarily used for NTP	17	647	86.30	109.66	89.63	288.50	92.51
Species with minor or unknown use	2	5	0.70	1.31	1.07	2.80	0.89
Total	28	750	100	122.34	100	311.84	100

TP: timber products. NTP: nontimber products.

DBH, total height, and specific wood density were used as predictor variables. The specific wood density values for trees in the Colombian Caribbean region were used (IPCC, 2007; Álvarez et al., 2013) as well as the database of the World Agroforestry Center (http://db.worldagroforestry.org//wd). When a species was not listed, the average wood density for the family was calculated and assigned to the unknown species (Dawoe et al., 2016).

AGC was estimated by multiplying the AGB with carbon fraction by 0.48 (IPCC, 2007). AGC stored in species was transformed into carbon dioxide equivalents (CO_2-eq) by multiplying by the factor 3.67 (Watson et al., 2000). To calculate the income of the carbon sequestered in the aboveground biomass of trees in pastures based on the limits in market prices, we used a reference price of 5 USD per 1.0 Mg CO_2-eq according to the National Planning Department of Colombia (Sousa et al., 2018).

Data processing and analysis

Nonparametric analysis of variance and descriptive statistics were used for data analysis. Welch's t-test was applied to identify statistical differences ($p<0.05$) among economically important taxa grouped as dominant, common, or rare, derived from the main category density, considering the response variables AGB, basal area (BA), and density of taxa. The comparison of averages was conducted using Games-Howell post hoc tests. This analysis was performed on the statistical software SPSS IBM trial v 2.0.

Simple linear regressions between the density of taxa (independent) and AGC (dependent variable) were used, and a scatter plot was developed based on the density of taxa and mean DBH to understand the relationships between these variables. In addition to regressions to show the relationship between AGC with respect to tree density and BA, equations were developed for projecting carbon contents in aerial tree biomass with SAS statistical software v 9.4 (SAS Institute Inc., 2022).

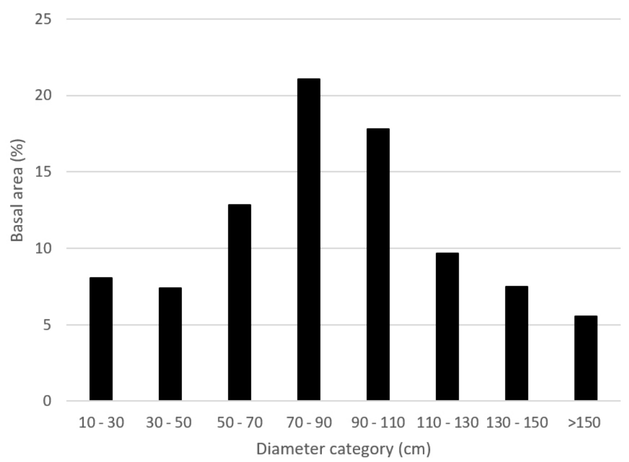

Figure 2. Diameter categories in relation to basal area in dispersed tree in pastures, arid Caribbean region of Colombia.

Results

Economic importance of trees

In the sample plots, we recorded 750 trees with DBH >10 cm, 28 species belonging to 10 plant families. The species *Guazuma ulmifolia* and *Albizia saman* were the most abundant with 352 and 124 trees respectively, followed by *Maclura tinctoria* and *Cordia alba* with 54 and 40 trees respectively. Finally, 18 species with less than 10 trees were sampled (Table 1). In total we identified 28 species used for commercial and/or subsistence purposes. Species used mainly as NTP represented 60.7%, while 32.1% were used as TP. In terms of abundance, 86.3% of all the trees registered were used for NTP, representing a BA of 89.63% and an AGC of 92.5%. TP species represented 13.1%, with a BA of 9.3% and an AGC of 6.6%. Two species with unknown use represented an abundance of 0.7%, AB 1.07%, and AGC 0.89% (Table 2).

The proportion of BA (%) to DBH classes (cm) in species grouped as NTP, TP, and unknown uses was the following: the NTP species had a normal distribution within the DBH classes, with a greater proportion (38.6%) of BA in

Table 3. Species with non-timber and timber uses classified according to their importance for commercial, subsistence or unknown uses. Taxa were sampled in 16 plots location in dispersed tree in pasture, dry Caribbean region Colombia.

Use importance	No. of taxa	Stems abundance		BA		AGC	
		Absolute	Total (%)	Absolute (m²)	Total (%)	(Mg C)	(%)
Commercial							
Species or genera primarily used for NTP	1	24	3	5	4	1	0.30
Species or genera primarily used for TP	7	83	11	10	8	18	5.60
Species with minor or unknown use	0	0	0	0	0	0	0
Subsistence							
Species or genera primarily used for NTP	16	623	83	104	85	288	92.20
Species or genera primarily used for TP	2	15	2	2	1	3	1.00
Species with minor or unknown use	0	0	0	0	0	0	0
Unknown							
Species or genera primarily used for NTP	0	0	0	0	0	0	0
Species or genera primarily used for TP	0	0	0	0	0	0	0
Species with minor or unknown use	2	5	1	1	1	3	0.90
Total	28	750	100	122	100	312	100

NTP: nontimber products. TP: timber products. BA: basal area. AGC: estimated aboveground carbon.

the classes of 70-90 cm and 90-110 cm. The TP species also presented normal distribution inside the DBH classes with percentages of BA between 0.52 and 3.05%; the classes of 130-150 cm and >150 cm stood out, representing 5.42%. Finally, the class of 'unknown uses' presented the lowest contribution in proportion to BA and was distributed in two DBH classes, 50-70 cm and 90-110 cm (Fig. 2).

Species that are important for subsistence usage, in addition to being related to NTP use, represented 65% of all species, their abundance was 85% and AGC was 93.2%. On the other hand, species with commercial importance represented 25% of the taxa and were associated with TP with an abundance of 14% and AGC of 5.63%. Outstanding in the category of commercial importance, was a NTP palm species, *Attalea butyracea* (Mutis ex L.f.) Wess. Boer), which is used for winemaking and construction (Table 3).

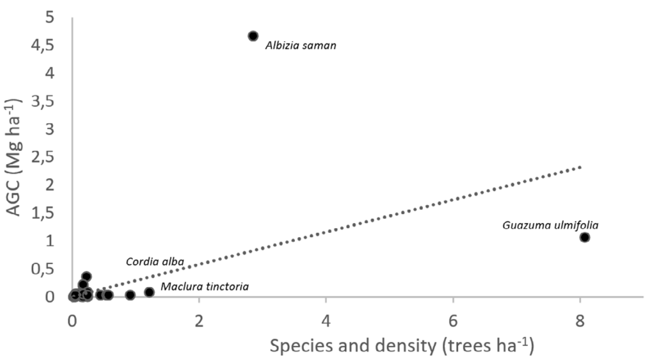

Figure 3. Relationship between tree density and above ground carbon storage (AGC) of species used mainly for non-timber and timber products dispersed in tree in pastures, arid Caribbean region, Colombia.

Relationship between density categories and carbon stock

Species with dominant density and rare in the NTP main use category had an abundance of 63.5% and represented 22.8% of the trees sampled, while the TP main use category was associated with the group of common and rare species with an abundance of 7.1% and represented 6.0% of the trees sampled. The dominant species, represented by *A. saman* and *Guazuma ulmifolia,* stored 79.9% of the AGC, while the common and rare ones together stored 30.1% (Table 4).

Welch's t-test showed that there were no significant differences among the dominant, common, and rare groups in terms of abundance F (2, 1.34) = 1.55, p = 0.44, BA F (2, 2.54) = 1.50, p = 0.37, and AGC biomass F (2, 1.33) = 2.09, p = 0.42 (Table 5).

Potential of trees in pastures for aboveground carbon

The species, *A. saman* and *G. ulmifolia* recorded the highest contribution of AGC (4.65 and 1.06 Mg C ha^{-1}) and were dominant inside the pastures, with a density of 2.84 and 8.07 trees ha^{-1}, respectively. In addition, *Albizia guachapele* and *C. pentandra* contributed to carbon storage with 0.35 and 0.23 Mg C ha^{-1} respectively (Table

Table 4. Species with main non-timber and timber uses classified as dominant (density > two tree ha^{-1}), common (one or two tree ha^{-1}), or rare (less than one tree ha^{-1}). Taxa were sampled in 16 plots location in dispersed tree in pasture, dry Caribbean region, Colombia.

Density category	No. of taxa	Stems abundance		BA		AGC	
		Absolute	Total (%)	Absolute (m²)	Total (%)	(Mg C)	(%)
Dominant							
Species or genera primarily used for NTP	2	476	63.50	88.70	72.50	249.30	79.90
Species or genera primarily used for TP	0	0	0	0	0	0	0
Species with minor or unknown use	0	0	0	0	0	0	0
Common							
Species or genera primarily used for NTP	0	0	0	0	0	0	0
Species or genera primarily used for TP	1	53	7.10	1.57	1.30	4.30	1.40
Species with minor or unknown use	1	4	0.50	1.28	1.00	2.70	0.90
Rare							
Species or genera primarily used for NTP	15	171	22.80	20.96	17.10	39.20	12.60
Species or genera primarily used for TP	8	45	6.00	9.81	8.00	16.30	5.20
Species with minor or unknown use	1	1	0.10	0.03	0.02	0.10	0
Total	28	750	100	122.35	100	311.83	100

NTP: nontimber products. TP: timber products. BA: basal area. AGC: estimated aboveground carbon.

S1 [suppl]), while *Sterculia apetala* and *Tabebuia rosea* present low carbon storage with 0.06 and 0.03 Mg C ha^{-1} respectively. Also, some species such as *A. saman, G. ulmifolia, Acacia farnesiana, Gliricidia sepium, Crescentia cujete* and *Cordia alba,* among others, are economically important in the local market or are used on farm as firewood or for agricultural and/or housing constructions (Table S1 [suppl]).

The regression analysis between species density and AGC stock showed a positive relationship ($R^2 = 0.23$, $F = 7.59$, $p<0.0106$). However, there was a prominent outlier in this relationship: *A. saman* was the species that presented

Table 5. Welch's t-test for density (trees ha^{-1}), basal area (BA, m^2 ha^{-1}), and above ground carbon (AGC, Mg ha^{-1}) biomass of non-timber and timber taxa for the density categories. Mean, standard deviation (SD), degrees of freedom (df1 and df2), and significance at $p < 0.05$ per variable are shown.

Categories	N	Mean	SD	Welch test F distributed	df1	df2	p value
Density							
Common	2	0.65	0.79	1.55	2.00	1.34	0.44
Dominant	2	5.46	3.70				
Rare	24	0.20	0.21				
BA							
Common	2	0.03	0.00	1.50	2.00	2.54	0.37
Dominant	2	1.01	0.72				
Rare	24	0.02	0.04				
AGC							
Common	2	0.07	0.02	1.33	2.00	2.09	0.42
Dominant	2	2.86	2.54				
Rare	24	0.05	0.08				

Table 6. Carbon dioxide equivalents (CO_2-eq) content (Mg ha^{-1} and USD ha^{-1}) of species with non-timber and timber uses grouped in density categories. Density category were sampled in 16 plots location in dispersed trees in pasture in arid Caribbean region, Colombia.

Density category	AGB (Mg ha^{-1})	AGC (Mg ha^{-1})	CO_2-eq (Mg ha^{-1})	CO_2-eq (USD ha^{-1})
Dominant				
Species or genera primarily used for NTP	11.92	5.70	21.00	105.00
Species or genera primarily used for TP	0.00	0.00	0.00	0.00
Unknown taxa and use	0.00	0.00	0.00	0.00
Common				
Species or genera primarily used for NTP	0.00	0.00	0.00	0.00
Species or genera primarily used for TP	0.20	0.10	0.40	1.80
Unknown taxa and use	0.13	0.10	0.20	1.10
Rare				
Species or genera primarily used for NTP	1.87	0.90	3.30	16.50
Species or genera primarily used for TP	0.78	0.40	1.40	6.90
Unknown taxa and use	0.00	0.00	0.00	0.00
Total	14.90	7.15	26.30	131.30

NTP: nontimber products. TP: timber products. AGB: aboveground biomass. AGC: aboveground carbon (Mg ha^{-1}).

the highest AGC stock of the species set but it reached this carbon stock whit a low relative density (2.8 trees ha^{-1}) (Fig. 3). The explanation for this outlier is the very high median DBH of 76.88 $\pm$ 30.73 cm and an abundance of 16.5%. The strongly skewed population structure of this species also caused it to be the species with the highest DBH values in this study. Finally, *G. ulmifolia* showed the second highest value of AGC due to the highest density (dominant) with 8.1 trees ha^{-1} and an average DBH of 23.01 $\pm$ 16.36 cm (Fig. 3).

The study identified that AGC stock in dispersed trees in pastures was 7.15 $\pm$ 4.8 Mg C ha^{-1}, density of 17.42 $\pm$ 13.93 trees ha^{-1} and BA of 2.69 $\pm$ 1.76 m^2 ha^{-1}. We found that the higher the density of trees and a greater BA the larger AGC stock is expected. Linear regression tests showed a relationship between AGC in the trees, density, and BA when these variables were tested together (R^2= 0.95, $p<0.0001$). The relationship between AGC and tree density was lower, yet statistically significant (R^2= 0.43, $p<0.0001$). Finally, the regression between AGC with BA was highly significant (R^2= 0.95, $p<0.0001$). With these results, prediction equations were developed for carbon storage in pastures regarding density and BA (Table S2 [suppl]).

Estimated economic value of aboveground carbon in units of CO_2-eq

The estimated economic value of carbon on the ground in units of CO_2-eq, based on the categories of tree density and species grouped according to their main uses (NTP, TP, and unknown), was estimated in the aboveground biomass of trees in pastures and equivalent to 26.3 Mg CO_2-eq ha^{-1}. In economic terms, at a reference price of 5.0 USD per Mg CO_2-eq (Sousa et al., 2018) it corresponds to a monetary value of 131.33 USD ha^{-1} (Table 6). The NTP dominant species, represented by *A. saman* and *G. ulmiflora* stored 21 CO_2-eq (Mg C ha^{-1}), which is equivalent to 105 USD ha^{-1}. The NTP and TP rare species stored 3.3 and 1.4 CO_2-eq (Mg C ha^{-1}), while the main timber use species contributed the least to the soil carbon stock in forested pastures (Table 6).

Discussion

Trees dispersed in pastures of a tropical arid forest can contribute to the conservation of this ecosystem. This study assessed 28 species with a density of 17.42 $\pm$ 13.93 trees ha^{-1}. Of the species listed, 65% are important for subsistence and are associated with potential NTP uses such as live fences and medicines, shade and food resources such as fodder and fruit for cattle. Similar results regarding species richness, abundance, and use were reported by Cajas-Girón & Sinclair (2001) in four micro-regions of the Colombian Caribbean region (Litoral, Golfo de Morrosquillo, Sabanas, and Valle del Sinú). These authors found that between 70 and 90% of the trees in cattle ranches were used primarily for timber and forage. Among the timber species reported are *T. rosea*, *S. apetala* and *Albizia caribaea*. In the same way that this study, 83% of producers reported high dependence on forage trees such as *A. saman* and *Cassia grandis*, *G. ulmifolia* and *C. cujete* for animal feed during the grass shortage period.

In a characterization of trees in pastures of a tropical dry forest zone in the Department of Tolima, among a set of 21 species identified in pastures, Serrano et al. (2014) reported that *G. ulmifolia* was the species with the greatest abundance and BA (25.3% and 26%, respectively); it is used as timber for fence posts and as feed and shade for livestock. Meanwhile, in the characterization of trees dispersed in pastures in four livestock landscapes of Central America (Matiguás and Rivas in Nicaragua, and Cañas and Río Frío in Costa Rica), Harvey et al. (2011) found a mean richness between 22.9% to 45.9%, density between 7.9-33.4 trees ha^{-1} and average DBH between 18.56 and 44.32 cm.

The most abundant species in our study were *G. ulmifolia* (46%), *A. saman* (16.53%), *M. tinctoria* (7.2%) and *C. alba* (5.33%). The abundance of *G. ulmifolia* in pastures is associated mainly with the supply of forage and fruit as an option for cattle in times of forage shortages (Manríquez-Mendoza et al., 2011). In addition, its characteristic as a pioneer species contributes to its permanence in pastures mainly by anthropic selection (Villa-Herrera et al., 2009). Tree diameter varied between 10 and 90 cm, similar to values reported by Zapata-Arango (2010) for trees in pastures in Muy Muy and Matiguás, Nicaragua, with an average of 35.1 cm; by Esquivel-Mimenza et al. (2011) in Guanacaste, Costa Rica with an average of 58.9 cm; and by Chamorro et al. (2018) in tropical dry forest conditions in Nicaragua with averages of 30.3 cm. These different studies indicate that *G. ulmifolia* has similar ecological characteristics in those places and its dominant density may be associated with its excellent natural regeneration capacity, due to its abundant fruit production (~17.5 kg tree^{-1} with 40 to 80 seeds fruit^{-1}; Leyva, 2003) and its easy propagation through consumption of the fruit by birds and mammals, mainly bats and cattle.

The second species with the highest abundance value was *A. saman* with 16.5% of the trees reported. These results differ from those reported by Harvey et al. (2011) with an abundance of 5% of scattered trees in pastures in Matiguás, Nicaragua, and by Esquivel et al. (2011) with an average DBH of 57.3 cm and a density of 8.1 trees ha^{-1} in Guanacaste, Costa Rica. The high presence of *A saman* could be related to its wide distribution from Mexico to Bolivia, giving it a frequent occurrence in the tropical dry forest (Cascante et al., 2002). In addition, its rapid growth, high capacity to colonize open fields, and provision of fruits for animal consumption and shade, make it an interesting species for livestock systems (Aparajita & Rout, 2010). In addition, *A. saman* is also used for cultural purposes (Durr, 2001) and as a source of timber (Cascante et al., 2002).

Although we found that species with timber as their main use were less abundant than non-timber species, their density values were like those reported by Esquivel et al. (2011) for *T. rosea* and *T. ochracea* (0.56 and 0.17 trees ha^{-1} respectively). Timber species continue to have an important value in cattle ranches. Villanueva et al. (2006) highlighted the preference of cattle producers in Esparza, Costa Rica, to conserve species with timber and firewood uses on their pastures out of 61.8% and 55.9% of the reported species. Esquivel et al. (2011) reported 50% of the species categorized as timber, 27% as fodder, and 27% as fruit in Guanacaste, Costa Rica (tropical dry forest).

The increase in grazing areas has led to loss of much of the carbon previously stored in the aboveground biomass (Hoosbeek et al., 2018). However, silvopastoral uses increase the carbon storage potential of pasturelands worldwide (Jose & Bardhan, 2012) and mitigates GHG (Hoosbeek et al., 2018). The value of AGC dispersed trees in pastures of 7.15 $\pm$ 4.8 Mg C ha^{-1} was similar to data reported by other authors in tropical dry forest conditions. Cárdenas et al. (2019) reported values of 6.3 Mg C ha^{-1} in pasturelands with a high density of trees in Matiguás, Nicaragua; Chacón & Harvey (2013) reported AGB values (multiplied by 0.48) between 2.54 and 6.48 Mg C ha^{-1} in four Central American agro-landscapes; Rojas et al. (2009) reported values between 4.4 Mg C ha^{-1} and 5.8 Mg C ha^{-1} in Guanacaste, Costa Rica in pasturelands associated with *Diphysa robinoides* and *Pithecellobium saman*, respectively; and Aryal et al. (2018) reported AGB values between 10.75 and 12.72 Mg C ha^{-1} in pasturelands of Chiapas, Mexico.

Differences in tree species composition, tree density per hectare, soil type, and management practices may explain variations in the carbon stocks of these systems (Cárdenas et al., 2019). Studies on silvopastoral systems in Colombia have reported higher carbon storage values in trees than this study. For example, Montagnini et al. (2013) reported AGB values between 13.65 and 28.07 Mg C ha^{-1} in trees in pasturelands in the watershed of the La Vieja River in Colombia. Giraldo et al. (2006) reported AGB values between 12.22 and 19.51 Mg C ha^{-1} and a density of 100 trees ha^{-1} in a 9-year-old silvopastoral system of *Acacia mangium*. Phillips et al. (2011) estimated a value of 48.1 Mg C ha^{-1} for the tropical dry forest of the Caribbean region.

The potential of trees in pastures for biodiversity conservation, landscape structural connectivity, and the provision of ecosystem services has been evidenced (Montagnini et al., 2013; Jose & Dollinger, 2019) in the face of deforestation and degradation of tropical forests converted to extensive cattle production (Graesser et al., 2015). For example, large areas in Cesar are in the process of desertification with a 69% level of affectation (MAVDT, 2005) and the deforested area was estimated to be 15,655 ha in 2007 (IDEAM, 2010). These scenarios have a negative impact on the conservation of natural resources, provision of ecosystem services, and sustainability of livestock systems. Conversely, the conservation of these species can contribute to the improvement of the landscape, which is considered an ecosystem service (Cordero et al., 2008), favoring small farmers and improving their living conditions in rural areas (FAO, 2018).

The PES (Payment for Environmental Services) is an important conservation strategy at the national level (Díaz et al., 2019) and is focused on areas and ecosystems identified in the Colombian Registry of Ecosystems and Environmental Areas (REAA) and the national registry of protected areas (RUNAP), and although it is empowered to implement the incentive in Colombia, the implementation is still insufficient (DNP, 2018).

Silvopastoral systems of dispersed trees in pasture store an important amount of carbon in the above-ground biomass, as has been reported in other similar agro-ecological conditions. Trees in pastures are mainly used for non-timber uses, such as providing shade, fodder, and fruit for cattle. The species *G. ulmifolia* and *A. saman* represent the species with the highest carbon storage due to their wide distribution, abundance, and large BA. Finally, pasture production in wooded systems is important in GHG mitigation and climate change adaptation strategies by providing timber and non-timber goods and services to animals and producers.

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