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Original article

Quantification of carbon stored in two forests of the Sierra del Rosario Biosphere Reserve (Cuba): Implications for payment schemes for environmental services

Cuantificación del carbono almacenado en dos bosques de la Reserva de la Biosfera Sierra del Rosario (Cuba): Implicaciones para esquemas de pago por servicios ambientales

Quantificação do carbono armazenado em duas florestas da Reserva da Biosfera da Sierra del Rosario (Cuba): Implicações para sistemas de pagamento por serviços ambientais

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ABSTRACT

Tropical forests store approximately 25% of global terrestrial carbon, making them central actors in climate change mitigation and potential beneficiaries of Payments for Ecosystem Services. This research quantified the carbon stored in aboveground and belowground biomass of two forests at different successional stages: El Mulo, a regenerating forest, and Las Peladas a mature forest, both located in the Sierra del Rosario Biosphere Reserve, Cuba. Nine 500 m^2 plots were established, five in Las Peladas and four in El Mulo. Diameter at 1.30 m ≥ 5 cm and total height were measured for all tree individuals. Biomass was estimated using an allometric equation incorporating diameter and height. Estimated stored carbon was 34.65 t CO_2 ha^{-1} in El Mulo and 104.32 tCO_2 ha^{-1} in Las Peladas. dominated in El Mulo with 37.2% of total carbon, while *Matayba oppositifolia* (A. Rich.) Britton was key in Las Peladas with 22.4%. Economic valuation under a conservative range of 10–20 USD tCO_2^{-1} yielded a potential value per plot of up to 1,521 USD for Las Peladas, equivalent to a historical stock of 44,000–88,000 USD for the entire core area. The value of mature forests for carbon sequestration is confirmed, and differentiated management, annual monitoring of sequestration, and certification under voluntary standards are recommended to access carbon markets.

Keywords: forest biomass; allometric equations; carbon markets; ESP; tropical forest.

RESUMEN

Los bosques tropicales almacenan cerca del 25% del carbono terrestre global, lo que los convierte en actores centrales para la mitigación del cambio climático y en potenciales beneficiarios de Pagos por Servicios Ambientales. Esta investigación cuantificó el carbono almacenado en la biomasa aérea y subterránea de dos bosques con distinto estado sucesional. El Mulo con 280 ha, en regeneración, y Las Peladas con 214 ha de bosque maduro en la Reserva de la Biosfera Sierra del Rosario, Cuba. Se establecieron nueve parcelas de 500 m^2, cinco en Las Peladas y cuatro en El Mulo. Se midió el diámetro a 1,30 m ≥ 5 cm y la altura total de todos los individuos arbóreos. La biomasa se estimó mediante una ecuación alométrica que incorpora diámetro y altura. El carbono almacenado estimado fue de 34,65 tCO_2 ha^{-1} en El Mulo y 104,32 tCO_2 ha^{-1} en Las Peladas. *Prunus occidentalis* Sw. dominó en El Mulo con el 37,2% del carbono total, mientras que *Matayba oppositifolia* (A. Rich.) Britton fue clave en Las Peladas con el 22,4%. La valoración económica bajo un rango conservador, de 10–20 USD tCO_2^{-1}, arrojó un valor potencial por parcela de hasta 1 521 USD para Las Peladas, equivalente a un stock histórico de 44 000–88 000 USD para toda el área núcleo. Se confirma el valor de los bosques maduros en la captura de carbono y se recomienda manejo diferenciado, monitoreo anual de captura y certificación bajo estándares voluntarios para acceder a mercados de carbono.

Palabras clave: biomasa forestal; ecuaciones alométricas; mercados de carbono; PSA; bosque tropical.

RESUMO

As florestas tropicais armazenam cerca de 25% do carbono terrestre global, tornando-se atores centrais para a mitigação das mudanças climáticas e potenciais beneficiários de Pagamentos por Serviços Ambientais. Esta pesquisa quantificou o carbono armazenado na biomassa aérea e subterrânea de duas florestas em diferentes estágios sucessionais: El Mulo com 280 ha, em regeneração, e Las Peladas de floresta madura na Reserva da Biosfera Sierra del Rosario, Cuba. Nove parcelas de 500 m² foram estabelecidas, cinco em Las Peladas e quatro em El Mulo. Mediu-se o diâmetro a 1,30 m ≥ 5 cm e a altura total de todos os indivíduos arbóreos. A biomassa foi estimada por meio de uma equação alométrica que incorpora diâmetro e altura. O carbono armazenado estimado foi de 34,65 t CO_2 ha^{-1} em El Mulo e 104,32 t CO_2 ha^{-1} em Las Peladas. *Prunus occidentalis* Sw. dominou em El Mulo com 37,2% do carbono total, enquanto *Matayba oppositifolia* (A. Rich.) Britton foi chave em Las Peladas com 22,4%. A valoração econômica sob uma faixa conservadora de 10–20 USD t CO_2^{-1} resultou em um valor potencial por parcela de até 1.521 USD para Las Peladas, equivalente a um estoque histórico de 44.000–88.000 USD para toda a área núcleo. Confirma-se o valor das florestas maduras na captura de carbono e recomenda-se manejo diferenciado, monitoramento anual da captura e certificação sob padrões voluntários para acessar mercados de carbono.

Palavras-chave: biomassa florestal; equações alométricas; mercados de carbono; PSA; floresta tropical.

INTRODUCTION

Tropical forests store approximately 25% of global terrestrial carbon and are responsible for nearly 40% of the terrestrial carbon sink (Pan *et al.*, 2011). This capacity makes them central to the Nationally Determined Contributions (NDCs) of the Paris Agreement (IPCC, 2023) . However, deforestation and forest degradation continue to reduce this critical sink (FAO, 2020).

CO_2 sequestration has become one of the most important from a global mitigation perspective. In a forest ecosystem, carbon flows and stores include foliage, branches, roots, trunk, litter, and stable humus. Estimating biomass production and carbon sequestration by species allows us to understand the value of this environmental service and its relevance as a strategy for reducing atmospheric CO_2 concentration (Brown, 1997).

In this context, Payments for Environmental Services (PES) and voluntary carbon markets have emerged as financing mechanisms for the conservation and restoration of forest ecosystems (Sedjo and Sohngen, 2012).

In Cuba, carbon sequestration reports from the forestry sector (INAF, 2017) are primarily associated with standing timber stocks in natural and managed forests. However, few studies integrate floristic composition, biomass by species, stored carbon, and economic valuation in biosphere reserves.

The Sierra del Rosario Biosphere Reserve, declared by UNESCO on February 15, 1985, as the first of its kind in Cuba, encompasses several core areas, including the El Mulo and Las Peladas Nature Reserves. These areas represent the best-preserved ecosystems in the reserve according to the 2020-2025 Management Plan, although they exhibit contrasting histories of disturbance: El Mulo is a secondary forest undergoing active regeneration (selective logging until the 1980s), while Las Peladas is a mature forest with no significant intervention for over 60 years.

Understanding the capacity of these systems to store carbon and the differential role of tree species is essential for designing effective PES schemes and guiding management strategies differentiated by successional stage. This study analyzes how carbon storage varies between a mature forest and a regenerating forest in the Sierra del Rosario Biosphere Reserve, and which tree species contribute disproportionately to this service. It is based on the following hypothesis: the spatial variation in the amount of stored carbon is primarily determined by the abundance of a small group of dominant tree species, and this functional dominance is greater in the regenerating forest than in the mature forest. The objective of the study was to quantify the carbon stored in the El Mulo and Las Peladas nature reserves to estimate its potential economic value under a payment for ecosystem services scenario.

MATERIALS AND METHODS

Study area

The research was conducted at the El Mulo site (280 ha) and the Las Peladas site (214 ha), located in the Artemisa province of Cuba. Both sites have a humid tropical climate, with an average annual temperature of 24 °C and an average annual rainfall of 1,800 mm, with a dry season from November to April. The soils are red ferralitic, with a clay loam texture.

The vegetation consists of semi-deciduous forest on serpentine soil in El Mulo and mesophilic evergreen forest in Las Peladas. El Mulo was subject to selective logging of precious woods until the 1980s, while Las Peladas has not been disturbed for over 60 years, according to the 2020-2025 management plan.

Figure 1 shows the map of the reserve, the location of the two sites, and the sampling points at each site.

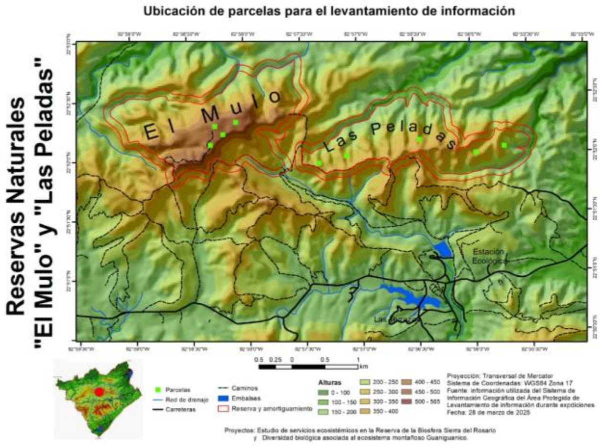

Figure 1. *- Map of the Sierra del Rosario Biosphere Reserve and location of the El Mulo and Las Peladas sites. The light green dots indicate the location of the sampling plots.*
Source: *Protected Area of Managed Resources. Sierra del Rosario Biosphere Reserve*

Sampling

Sampling was conducted in rectangular plots of 500 m² (20 × 25 m). The plots were distributed in a stratified manner according to the topographic and vegetation cover variations identified at each site. Initially, five points were selected in Las Peladas and four in El Mulo on the reserve map, assigning northwest coordinates and an identifying number to each point. In the field, each plot was located using GPS (± 3 m). When the topography prevented exact location, the plot was relocated to the closest possible location, and the new location was recorded. Trees coinciding with the vertices and those bordering each side were marked with paint.

Inclusion criteria: all tree individuals with a diameter at 1.30 m (DBH) ≥ 5 cm were measured. Palms, tree ferns, and standing dead individuals were not included.

Dendrometric and floristic measurements

Each individual was taxonomically identified using specialized keys and comparison with herbarium specimens. For each individual, the diameter at breast height (DBH) was recorded using a diameter measuring tape with a precision of 0.1 cm, and the total height (H) was measured with a Vertex hypsometer with a precision of 0.5 m in dense canopy plots, using a clinometer and measuring tape. To comply with the methodology, the measurements were converted to inches and feet.

The Ecological Importance Value Index (EIVI) formulated by Curtis and McIntosh (1951) was calculated for each species, based on the sum of the horizontal structure parameters: relative abundance, relative frequency, and relative dominance, expressed by basal area. Species with an EIVI > 0.5 were considered ecologically important.

Estimation of biomass and stored carbon

Aboveground biomass was estimated following the Planetary Carbon Standard (PSC) methodology (2023). Calculations were performed using the following formulas:

Aboveground biomass (AGB):

$$AGB = 0{,}25 * D^2 * H$$

Where:

- $D = D_{1.30}$ in inches
- H = total height in feet

Underground biomass (UBB): It was estimated as 20% of the AGB, in accordance with the IPCC recommendation (2006) for tropical forests:

BGB = 0.20×AGB

Total biomass (TB): TB = AGB + BGB

Total dry weight (PD) = TB x 0.725

Total carbon (CT) = PD x 0.5

Weight of CO_2 = CT x 3.67

All values were expressed in tons per hectare ($t\ ha^{-1}$) and per plot.

Economic valuation of stored CO_2

A price range of 10 to 20 USD per tonne of CO_2 was used (tCO_2), based on averages from the voluntary carbon market for forest restoration and conservation projects in Latin

America (Ecosystem Marketplace, 2023). This range is conservative, as projects with high-quality certification (Verra, Gold Standard) can reach prices of USD 25–40 tCO_2.

For each plot, the following was calculated:

$$Valor\ (USD)\ =\ CO_2\ almacenado\ (tCO_2)\ \times\ Precio\ (USD\ tCO_2)$$

Important note: This calculation represents the value of the historical carbon stock accumulated over the life of the trees, not the annual carbon uptake. The historical stock serves as an indicator of the site's potential, but PES schemes and carbon markets generally pay for net annual uptake, the increase in biomass per year. Access to these markets requires annual monitoring using permanent plots.

Statistical analysis

Student's t-test for independent samples, after verifying normality with Shapiro-Wilk and homogeneity of variances with Levene, in order to compare the carbon means between El Mulo and Las Peladas.

Spearman correlation coefficient between the abundance of the dominant species and total carbon per plot. The significance level was set at α = 0.05. The analyses were performed using InfoStat software (Di Rienzo *et al.*, 2020).

RESULTS

General characterization of the sites

Table 1 presents the general characteristics of the two evaluated sites. Species diversity, as expressed by the Shannon-Wiener index (H'), is slightly higher at Las Peladas (1.38 vs. 1.24), although evenness (J') is similar (0.85 vs. 0.83). The number of species is notably higher at Las Peladas (41) than at El Mulo (32), despite El Mulo having a greater total number of individuals (881 vs. 522). Total basal area and total volume are considerably greater at Las Peladas, reflecting its status as a mature forest with larger trees (Table 1).

Table 1. *- Characterization of species diversity by site*

Parameter	The Mule	The Bald Ones
Total number of individuals	881	522
Total number of species	32	41
Shannon H'	1.24	1.38
Shannon J'	0.83	0.85
Total basal area (m^2)	5.12	24.87
Total volume (m^3)	68.19	205.31
Basal area (m^2 ha-1)	25.6	341.0
Volume (m^3 ha-1)	99.48	821.0

Floristic composition and Ecological Importance Value Index (EIVI)

Tables 2 and 3 present the floristic lists of each study area, as well as the ecological contribution of each species according to its IVIE (Tables 2 and 3).

Table 2. *- Contribution by species according to IVIE in El Mulo (IVIE > 0.5)*

Scientific name	IVIE
Prunus occidentalis Sw.	1.5966
Hibiscus costatus A. Rich.	1.3220
Dendropanax arboreus (L.) Decne. & Planch.	1,1459
Syzygium jambos (L.) Alston	1.1296
Guarea guidonia (L.) Sleumer	1,0947
Palicourea crocea (Sw.) Roem. & Schult.	1.0920
Trophis racemosa (L.) Urb.	1.0814
Trichilia havanensis Jacq.	1,0741
Cinnamomum verum J.Presl.	1.0636
Casearia sylvestris subsp. *myricoides* (Griseb.) JE Gut.	1.0263
Erythroxylum areolatum L.	1.0198
Oxandra lanceolata (Sw.) Baill.	0.8589
Nectandra coriacea (Sw.) Griseb.	0.8059
Sideroxylon foetidissimum Jacq. subsp. *foetidissimum*	0.7859
Pisonia aculeata L.	0.7822
Licaria triandra (Sw.) Kosterm.	0.5241

In El Mulo, 16 species have an IVIE > 0.5, indicating a distribution of ecological importance in a relatively high number of species, although with a clear dominance of *Prunus occidentalis* (the highest value).

Table 3. *- Contribution by species according to IVIE in Las Peladas (IVIE > 0.5)*

Scientific name	IVIE
Matayba oppositifolia (A. Rich.) Britton	1,170
Rondeletia odorata Jacq. subsp. *odorata*	1,074
Bursera simaruba (L.) Sarg.	0.887
Erythroxylum areolatum L.	0.857
Cyathea arborea (L.) Sm.	0.852
Clusia rosea Jacq.	0.848
Coccoloba uvifera L.	0.687
Chrysophyllum oliviforme L. subsp. *oliviform*	0.673
Genipa americana L.	0.666
Calophyllum antillanum Britton	0.657
Syzygium jambos (L.) Alston	0.654
Sideroxylon foetidissimum Jacq. subsp. *foetidissimum*	0.652
Byrsonima lucida (Mill.) DC.	0.631

In Las Peladas, 13 species exceeded the IVIE threshold > 0.5. Unlike El Mulo, the IVIE values are more balanced among the dominant species, with no single species having double the value of the second.

CO_2 storage

El Mulo Site: Figure 2 shows the species that contribute most to CO_2 storage, more than 1.0 tCO_2. Prunus *occidentalis* stands out with 12.90 tCO_2, representing 37.2% of the site's total carbon of 34.65 tCO_2 ha^{-1}. It is followed by *Hibiscus costatus* with 3.87 tCO_2 and Dendropanax *arboreus* with 3.32 tCO_2. The species highlighted are also among the most important according to the IVIE (Figure 2).

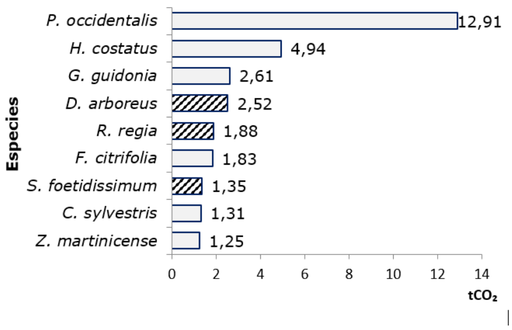

Figure 2. *- Value in tCO_2 (> 1.00) per species in El Mulo*

Las Peladas site: Figure 3 shows the species with the highest CO_2 storage. Matayba *oppositifolia* accumulates 23.41 tCO_2, 22.4% of the site's total of 104.32 tCO_2 ha^{-1}. Other important species are *Pithecellobium* spp., with 8.56 tCO_2, Cojoba *arborea* with 7.23 tCO_2, and Casearia *laetioides* with 6.98 tCO_2. Unlike El Mulo, the carbon distribution is more equitable; at least eight species exceed 5 tCO_2 (Figure 3).

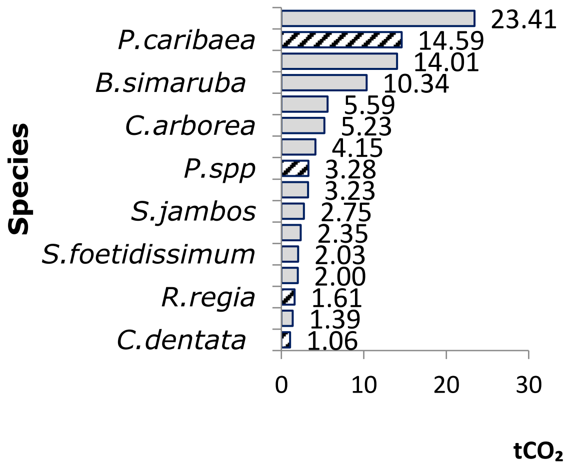

Figure 3. *- Value in tCO_2 (> 1.00) per species in Las Peladas*

Total biomass by species

El Mulo: The average total biomass (TB) was 9.70 t ha-1, *with Prunus occidentalis* contributing 9.702 t ha-1, a value very similar to the site average, reflecting its dominance. The species with the lowest biomass was *Trichostigma octandrum* with 0.00018 t ha- 1.

Las Peladas: The average total biomass was 17.59 tha-1, with *Matayba oppositifolia* reaching 17.597 t ha -1, also very close to the site average. The species with the lowest biomass was *Amyris balsamifera* with 0.0073 t ha-1.

Carbon stored per site

Table 4 presents the statistical descriptors of carbon stored by site

Table 4. *- Results of the estimation of carbon stored in the El Mulo and Las Peladas sites of the Sierra del Rosario Biosphere Reserve*

Place	Media tCO_2 ha-1	Standard Deviation	95% CI
The Mule	34.65	5.82	28.1 – 41.2
The Bald Ones	104.32	13.45	89.4 – 119.2

Statistical comparison

The Student's t-test showed a statistically significant difference between the two sites ($T = 8.94$; $df = 7$; $p < 0.001$). Spearman's correlation between the abundance of the dominant species and total carbon per plot was high at El Mulo ($r = 0.89$; $p = 0.02$) and moderate at Las Peladas ($r = 0.62$; $p = 0.09$), supporting the hypothesis of greater dominance in the regenerating forest.

Estimation of potential economic compensation

Tables 5 and 6 present the monetary values per plot under the three price scenarios, 10, 15 and 20 USD per tCO_2. A conservative range of 10 to 20 USD per ton of CO_2 was used.

Table 5. - Potential economic compensation in El Mulo (historical stock)

Parcel	Low price ($10)	Average price ($15)	High price ($20)	Total per plot
P1	77.65	116.47	155.30	349.42
P2	47.51	71.27	95.02	213.80
P3	106.20	159.30	212.40	477.89
P4	115.18	172.77	230.36	518.32
Total	346.54	519.81	693.08	1,559.44

Table 6. *- Potential economic compensation in Las Peladas (historical stock)*

Parcel	Low price ($10)	Average price ($15)	High price ($20)	Total per plot
P1	235.23	352.85	470.47	1,058.55
P2	332.15	498.22	664.30	1,494.67
P3	33.51	50.27	67.03	150.81
P4	338.12	507.18	676.24	1 521.54
P5	104.28	156.42	208.56	469.26
Total	1,043.29	1,564.94	2,086.58	4,694.81

The preliminary estimate for the entire core area, considering a price of USD 10-20 tCO_2^{-1}, would represent:

- Las Peladas (214 ha): USD 44,000 – 88,000.
- El Mulo (280 ha): USD 31,000 – 62,000.

These amounts represent the value of historically stored carbon, not annual carbon sequestration. In carbon markets and PES schemes, payment is based on the net annual increase in biomass (annual sequestration). To access these payments, it is essential to establish an annual monitoring system with permanent plots. The values presented here serve as a baseline for the site's potential.

DISCUSSION

The results obtained in the core areas El Mulo and Las Peladas not only quantify the ecosystem service of carbon storage, but also provide empirical evidence to address central debates in contemporary tropical forest ecology: the relationship between diversity and functioning, the disconnect between floristic and functional recovery, and the implications for PES schemes.

One of the most current debates revolves around which factor is more decisive for carbon storage: the identity of the dominant species or numerical diversity. Liang *et al.* (2016) demonstrated a positive and consistent relationship between species richness and forest productivity on a planetary scale. On the other hand, Poorter *et al.* (2016) proposed that aboveground biomass is determined by multiple factors, including species richness, forest structure and environmental variables, and that in secondary forests the identity of long-lived pioneer species may be more important than diversity *per se*.

The data from this research offer a perspective that integrates both positions along a successional gradient:

El Mulo (regenerating forest): It exhibits a marked functional hyperdominance. A single species, *Prunus occidentalis,* concentrates more than a third of the site's total carbon (37.2%). This pattern reflects what Fauset *et al*. (2015) noted regarding "hyperdominance" in the carbon cycle of Amazonian forests, and is consistent with the idea that, in early secondary forests, a few fast-growing species capitalize on carbon storage.

Las Peladas (mature forest): Although *Matayba oppositifolia* is the dominant species (22.4% of carbon), there are at least eight species with a DBH greater than 20 cm and five species with heights greater than 10 m. The community is more diverse and equitable, and total productivity (104 tCO_2 ha^{-1}) is three times higher than that of El Mulo. This pattern is consistent with the findings of Liang *et al.* (2016) and with the hypothesis of niche complementarity: in mature forests, greater diversity allows for a more complete use of resources and, therefore, greater carbon storage.

Recovery of floristic composition vs. recovery of carbon stock

The data clearly show that floristic composition recovers more rapidly than carbon stock. El Mulo, with 32 species (78% of the 41 species present in Las Peladas), has already reached high floristic diversity, probably thanks to seed dispersal from nearby fragments of mature forest. However, its carbon stock (34.65 tCO_2) ha^{-1}) is only 33.2% of the stock of Las Peladas (104.32 tCO_2 ha^{-1}).

This decoupling between floristic and functional recovery is consistent with long-term succession studies in the Neotropics (Rozendaal *et al.* , 2019) . While seed dispersal and regeneration can rapidly re-establish the presence of many typical species within 20–40 years, it takes decades or centuries (80–200 years) for these individuals to reach the diameters and heights necessary to match the carbon stocks of a mature forest.

CO_2 storage values obtained are consistent with results from studies conducted in similar ecological contexts. Perea-Ardila *et al.* (2021), in Colombia in preserved high-Andean forests, reported an average storage of 134.3 tCO_2 ha^{-1} . Chave *et al.* (2014) and Poorter *et al.* (2016) in Costa Rica and Panama in mature tropical rainforests report values of 100-120 tCO_2 ha^{-1} , in both cases quite similar to those of Las Peladas. This indicates that the mature forest of Sierra del Rosario is representative of well-preserved tropical rainforests in the region.

Cuba, Ramírez-López and Chagna-Ávila (2019), in Eucalyptus grandis plantations, obtained values of 100–150 tCO_2 ha^{-1} for mature plantations and *30–60* tCO_2 ha^{-1} for young plantations. Las Peladas (104 tCO_2 ha^{-1}) is equivalent to a mature plantation, while El Mulo (34.65 tCO_2 ha^{-1}) is equivalent to a young plantation. This parallel is remarkable and validates the interpretation of the successional stage of both sites, demonstrating that the reserve's natural forests, even during regeneration, have a storage potential comparable to or greater than that of commercial plantations.

Implications for payment schemes for environmental services

The economic valuation, using a conservative range of 10-20 USD per $tCO_2^{-1,}$ yielded values per plot of up to 1,521 USD in Las Peladas. Extrapolated to the entire core area of 214 ha, the historical stock would have a value of 44,000-88,000 USD. However, as has been emphasized, carbon markets do not pay for carbon already stored, but rather for the additional carbon captured annually as a result of conservation or restoration activities.

For the Sierra del Rosario Reserve to access these markets, several steps are required, including establishing permanent monitoring plots to measure net annual carbon capture. A conservative estimate for neotropical secondary forests is 3–5 tCO_2 ha^{-1} $year^{-1}$ (Poorter *et al* ., 2016). If Las Peladas were to capture 5 tCO_2 ha^{-1} $year^{-1}$, the 214 ha would generate 1,070 tCO_2 $year^{-1}$, equivalent to USD 10,700–21,400 annually.

For the future of the protected area, it would be feasible to pursue certification under international standards (Verra, Gold Standard, Climate Action Reserve). This would increase the price to 25-40 USD per tCO_2 but would require initial verification costs and ongoing monitoring. Incorporating soil carbon into future valuations could also significantly increase the total value of the ecosystem services.

Another aspect to consider could be designing a PSA scheme differentiated by successional stage: for El Mulo (regeneration), PSAs could finance active restoration activities enriching the area with species of ecological and economic value, while for Las Peladas (mature), PSAs should compensate for the opportunity costs of not extracting timber from valuable species such as *Swietenia mahogoni* and *Brya ebenus.*

CONCLUSIONS

The mature forest Las Peladas stores three times more carbon with 104.32 tCO_2 ha^{-1} than the regenerating forest El Mulo, 34.65 tCO_2 $ha^{-1.}$

The potential economic value of the historical carbon stock in Las Peladas is USD 44,000-88,000, at prices of USD 10-20 tCO_2 - [1], and in El Mulo it is USD 31,000-62,000.

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