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Reduction of emissions by avoided deforestation in andean high-land tropical forests

Reducción de emisiones por deforestación evitada en bosques tropicales alto-andinos

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ARTICLE DATA

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ABSTRACT

Deforestation and forest degradation, mainly in areas with high carbon density, is one of the most important source of greenhouse gases (GHG). The impact of deforestation on carbon storage in total biomass and its CO_2 emissions is analyzed in four land covers in the *Santuario de Fauna y Flora Iguaque* (SFFI), Boyacá, Colombia. A total of 32 temporal sampling plots (TSP) of 250m^2 was established to measure trees with diameter at breast height (dbh) ≥ 10 cm whereas 17 TSP of 36m^2 were established to measure total and stipe height of all frailejones (*Espeletia boyacensis* Cuatrec, *E. tunjana* Cuatrec and *E. cf. Incana*). Above and belowground biomass was estimated with allometric models, whereas carbon was calculated using the a fraction of 0.47. The sampling area was proportional to the area of each land cover: open heathlands and moorlands (OMH), dense heathlands and moorlands (DMH), broad-leaved forest with continuous canopy, not on mire (BFCC), natural grassland prevailingly without trees and shrubs (NSWT). BFCC and DMH showed higher carbon storage in biomass (55 and 27Mg C/ha, respectively). SFFI stored around 135.9Gg C, from which 25-38Gg CO_2e could be emitted to the atmosphere in the 20 next years if the deforestation rates continue. BFCC and OMH are the covers with the highest potential of CO_2 emissions to the atmosphere. Therefore, prioritizing the preservation of these ecosystems by Reducing Emissions from Deforestation and Degradation (REDD+) programs, is a key to counter the effects of climate change and ensure the supply of ecosystemic services that support local communities' livelihoods.

Keywords: Biomass; carbon stock; climate change; land cover; mitigation; sampling plots.

RESUMEN

La deforestación y degradación de bosques, principalmente en áreas con alta densidad de carbono, es una de las más importantes fuentes de gases de efecto invernadero (GEI). El impacto de la deforestación sobre el almacenamiento de carbono en biomasa total y sus emisiones de CO_2 es analizado en cuatro coberturas de la tierra en el Santuario de Fauna y Flora Iguaque (SFFI), Boyacá, Colombia. Un total de 32 parcelas temporales de muestreo (PTM) de 250m^2 fueron establecidos para medir los árboles con diámetro a la altura del pecho (dap) ≥ 10 cm. Mientras que 17 PTM de 36m^2 fueron establecidas para medir la altura total y de estípite de todos los frailejones (*Espeletia boyacensis* Cuatrec, *E. tunjana* Cuatrec and *E. cf. Incana*). La biomasa arriba y abajo del suelo fue estimada con modelos alométricos, mientras que el carbono fue estimado usando una fracción de 0.47. El área de muestreo fue proporcional al área de cada cobertura: arbustales abiertos (AA), arbustales densos (AD), bosque denso alto de tierra firme (BDATF) y herbazal denso de tierra firme no arbolado (HDTFNA). El BDATF y AD mostraron el mayor almacenamiento de carbono en biomasa total (55 y 27Mg C/ha, respectivamente). El SFFI almacenó cerca de 135.9Gg C, de los cuales 25-38Gg CO_2e podrían ser emitidos a la atmósfera en los próximos 20 años. El BDATF y AA son las coberturas con el mayor potencial de emisiones de CO_2 a la atmosfera. Por consecuencia, la priorización de la preservación de estos ecosistemas mediante programas de Reducción de Emisiones por Deforestación y Degradación (REDD+) es clase para contrarrestar los efectos climáticos y asegurar el suministro de servicios ecosistémicos que apoyen a los medios de vida de las comunidades locales.

Palabras clave: Biomasa; almacenamiento de carbono; cambio climático; cobertura del suelo; mitigación; parcelas de muestreo.

INTRODUCTION

Agriculture, forestry, and other land uses (AFOLU) emit 10–12Pg CO_2e, around 25% of net anthropogenic greenhouse gas (GHG) emissions (Roe *et al.,* 2019). At the national level, it is estimated that carbon reserves in aboveground biomass of natural forests are of 6.4Pg C (Phillips *et al*., 2016). However, deforestation and forest degradation reduce carbon stock (FAO, 2020), being the main source of gross emissions in the country and the world: 36 and 17%, respectively (IDEAM *et al*., 2016). According to the FAO (2020), between 2011 and 2015, world emissions from forest degradation reached 0.7Pg CO_2e/year, caused by a loss of 5.9 hectares per year during the same period. Houghton and Nassikas (2017) estimated that World´s mountain tropical forests have a median of 62Mg C/ha, and they emitted 1.4Pg C/year between 2006 and 2015.

The tropical forests fix a massive amount of carbon and represent 90% of its flow between the atmosphere and Earth, so they are considered an essential part of the mechanisms for reduction of GHG concentrations and mitigation of climate change (FAO, 2020). Emission reduction derived from deforestation and forest degradation, framed in the context of the United Nations Convention on the Climate Change (CMNUCC), raises big financial expectations on the voluntary emission of carbon credits that strengthen the efforts of conservation and sustainable forest management and at the same time the compliance of national commitments acquired for the COP21 (Castro-Nunez *et al*., 2018; Pupo-Roncallo *et al.,* 2019).

According to Dannecker *et al*. (2016), voluntary carbon market in Colombia has been strongly encouraged in the latest years. With the application of carbon tax established on article 221 of Law 1819 (Congreso de Colombia, 2016), The Environment and Sustainable Development Ministry, by decree 926 from 2016, allowed access to non-causality of the tax by buying carbon credits certified under acknowledged standards; some of them are the Colombian Institute of Technical Norms and Certification –

Instituto Colombiano de Normas Técnicas y Certificación - (ICONTEC), the Verified Carbon Standard (VCS) and the Gold Standard (GS) (Espitia & Herrera, 2017). In the country, about 800,000 VCS carbon credits (1 carbon credit = 1 Mg CO_2e) have been generated and over 200,000 GS, from which 500,000 credits already sold have contributed to the promotion of energy efficiency, the restoration of approximately 10,000 ha of degraded soils and the conservation of around 20,000 ha of native forests (Dannecker *et al*., 2016). According to Furumo & Lambin (2020), the proliferation of zero-deforestation initiatives is creating opportunities for policy synergies and scaling up impacts.

Even though High-Andean tropical forests are known for their supply of ecosystem services, particularly hydrological (Immerzeel *et al*. 2020) and those derived from biodiversity conservation (Valencia *et al*., 2020), their participation in carbon storage is still very uncertain (Castañeda & Montes, 2017). The studies about carbon estimates in these ecosystems are few and divergent (Yepes *et al*., 2016; Peña & Duque, 2017; Segura *et al*., 2019) despite the great vulnerability they present (Bax & Francesconi, 2018; Pérez-Escobar *et al*., 2018). Between 1985 and 2005, a loss of 4.5 and 6.4% of the original extension of andean and sub-andean forests was estimated (Armenteras *et al*., 2003); however, recent reports show a recovery in the last years (Calbi *et al*., 2020). Colombia has 35 paramo complexes with legal resolutions that cover 2.6 million ha (2.3% of national surface) (Vergara-Buitrago, 2020). However, it is estimated that for 2032, this type of ecosystems will disappear from the Colombian landscape due to human interventions and accelerated climate change (WWF-Colombia, 2017).

The Santuario de Fauna y Flora Iguaque (SFFI) corresponds to one of the 59 natural areas that make the Colombian National System of Protected Areas (SINAP), and it is under the management of the Unidad Administrativa Especial del Sistema de Parques Nacionales Naturales (SPNN) – Special Administrative Unit of Natural National Parks. This protected area is considered of utmost importance as environmental good and services supplier, such as hydric resource supplier for the municipalities of Villa Leyva, Arcabuco, and Chíquiza in the department of Boyacá. The SFFI is a small zone of paramo and high-land Andean forests located in one of the most intervened area in the Cordillera Oriental of Colombia. This protected area has a high vulnerability to deforestation and degradation caused by the socioeconomical and demographical development of the zone (Valencia *et al*., 2020). This reserve is an important carbon reserve with an adequate forest management (Duque *et al*., 2021), for this reason its conservation is an important priority (Armenteras *et al*., 2003).

The main goal of this study was to estimate the carbon stock in total biomass and the potential emission of CO_2 for deforestation in the Santuario de Fauna y Flora Iguaque (SFFI) in Boyacá, Colombia. This information will grant key elements for the estimation of the potential carbon credits for a future REDD+ project in this zone, which would help its preservation and improve livelihoods of the local people.

MATERIALS AND METHODS

Description of the study area. SFFI is located in the Iguaque–Guantiva–La Rusia paramo and forests corridor of the center-west of the Cordillera Oriental of Colombia between the departments of Boyacá and Santander. The area covers 6750 ha of paramo, sub-paramo, oak groves, Andean and High-Andean forests that cover the municipalities of Villa de Leyva, Arcabuco, Chíquiza and Sáchica (Colombia), in the geographic coordinates 5°36´02” - 5° 44´38”N, and 73°22´57” - 73°31´20”W (Figure 1a). The SFFI has altitudes between 2400 and 3890m, whose regional distribution starts at the height of Villa de Leyva and extends towards NE to La Rusia paramo (Santander). This area is a cloudy wet forest between the thermal levels of cold and paramo. In the south of the area, the dry weather conditions of Villa de Leyva dominate, meanwhile in the North, it is notoriously more humid, with a humidity gradient ranging between 650 and 2800 mm/year.

Identification of the land cover in SFFI. The four most dominant land covers of the study area were defined: open heathlands and moorlands (OMH), dense heathlands and moorlands (DMH), broad-leaved forest with continuous canopy, not on mire (BFCC), natural grassland prevailingly without trees and shrubs (NSWT) (Figure 1b). This process was carried out by using cover and land use maps of the National Natural Parks, following the CORINE Land Cover methodology adapted for Colombia during 2010 and 2012 at a 1:100000 scale (Perea-Ardila *et al.*, 2021) (Table 1).

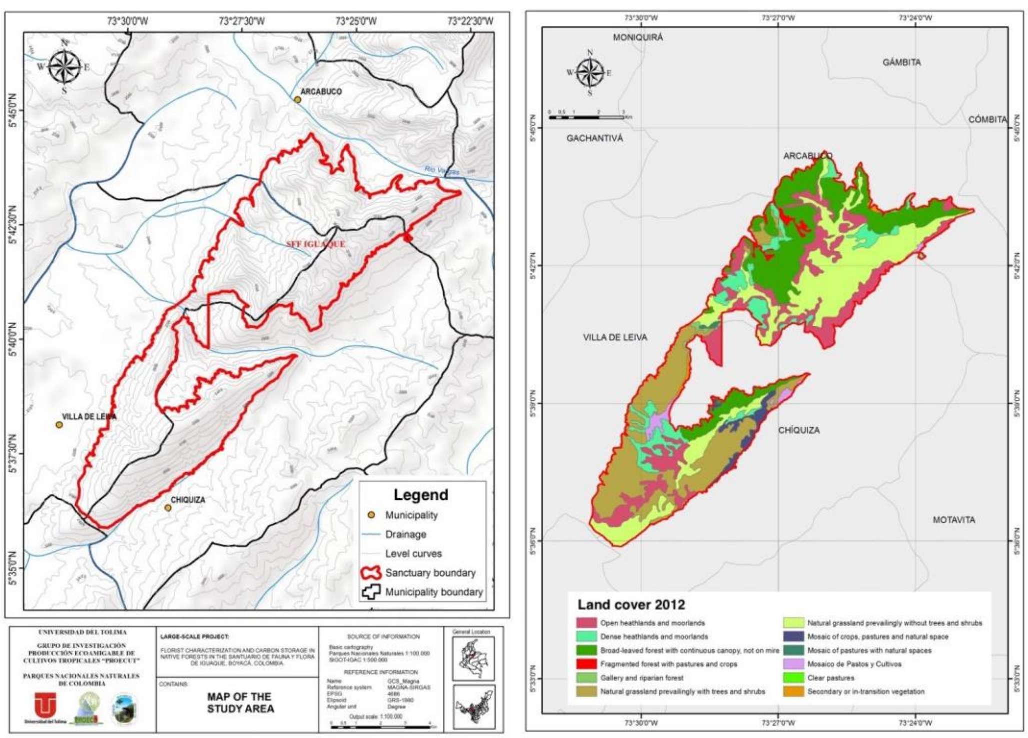


Figure 1. Location of study area (left) and land cover (right) of the Santuario de Fauna y Flora Iguaque in Boyacá (Colombia). Source: Perea (2017).

Table 1. Land cover between 2010 and 2012 of the Santuario de Fauna y Flora Iguaque, Boyacá, Colombia.

Land cover	Code	Area		Temporal sampling plots
		ha	%	
Natural grassland prevailingly without trees and shrubs (NSWT)	321111	1755.8	5.4	17
Open heathlands and moorlands (OMH)	222	227.8	7.7	9
Dense heathlands and moorlands (DMH)	221	95.1	0.6	5
Broad-leaved forest with continuous canopy, not on mire (BFCC)	3111	1477.8	1.4	18

Source: Perea (2017).

Sampling design. A total of 32 temporary sampling plots (TSP) of 250 m^2 were set for sampling all individuals with breast-height diameter (dbh) ≥ 10cm in OMH, DMH and BFCC, whereas 17 TSP of 36m^2 were established to measure total and stipe height of all *Espeletia* spp individuals in NSWT (Table 1). Land covers were used as strata or treatments with different number of samples (Table 1) randomly established. The TSP were randomly and proportionally established in every land cover, located in representative places of each area.

Estimation of total biomass and carbon storage. Aboveground biomass was estimated by Andrade *et al*. (2020), using the allometric model (Equation 1) proposed by Lerma & Orjuela (2014), for high-land Andean forest species dominated basically by *Baccharis* sp., *Miconia* sp. and *Weinmannia auriculata* between 5 and 67cm of dbh and 4.22 and 25.5m in height.

$$Ln\ (Ab) = -1.85 + 2.11 * Ln(dbh) \qquad \text{Equation 1}$$

Where;

Ab: Total aboveground biomass (kg/tree)
dbh: Trunk diameter at breast-height (cm)

The allometric model developed (Equation 2) by Jaramillo (2014) was used for estimating aboveground biomass of *Espeletia boyacensis* Cuatrec, *E. tunjana* Cuatrec and *E. cf. incana*. It was used because it fitted the architecture of the *Espeletia* genus and the climatic conditions of this study.

$$Ln\ (Ab) = 0.46 + 1.00 * Ln(hst) \qquad \text{Equation 2}$$

Where;

Ab: Total aboveground biomass (kg/plant)
hst: Stipe height (m)

Afterwards, the general model (Equation 3) was used to estimate belowground biomass (Cairns *et al*., 1997). Biomass was converted into carbon using the 0.47 fraction; then the estimated carbon was determined for the total area of each land cover in SFFI. Finally, carbon was converted into CO_2 using the 3.67 conversion factor, which is the stoichiometric relation.

$$Bb = e^{(-1.0587+0.8836*Ln(Ab))} \qquad \text{Equation 3}$$

Where;

Bb: Belowground biomass (Mg/ha)
Ab: Aboveground biomass (Mg/ha)

CO_2 avoided emissions. Avoided emissions refer to CO_2 production that is not caused by effect of controlling deforestation. GHG potential emissions due to deforestation were estimated for 20 years. The reference situation was assumed as the change of carbon storage when applying two annual deforestation rates of 0.26 and 0.40%, corresponding to the loss of Andean region forests between 2012 and 2013 (Galindo *et al*., 2014) and from Colombia between 1990 and 2015 (FAO, 2020). The project was considered when carbon is kept in biomass because deforestation is eliminated. It was considered that after the deforestation process, carbon in biomass gets to a lower level as Navarrete *et al*. (2016) argued (9.3Mg C/ha). Total carbon storage in SFFI was estimated annually taking every deforestation rate and using Equation 4 without considering the land use systems with the lowest carbon stock.

$$C_{i+1} = C_i * \left[\frac{100-D}{100}\right] \quad \text{Equation 4}$$

Where;

C_{i+1}: Carbon storage in year i + 1 (Gg C);

C_i: Carbon storage in year i (Gg C);

D: Deforestation rate (%/year)

Data analysis. CO_2 avoided emissions by controlling deforestation were estimated as the difference between the project situation (no deforestation) and the reference situation with the two deforestation rates. Estimations of carbon stock to the time by deforestation rates were developed in an Excel spreadsheet. Data of carbon stock was analyzed with a one-way non-parametric analysis of variance with a Kruskal-Wallis test due to no normality according to Shapiro-Wilks test. Differences between pairwise means of land covers were analyzed with a Dwass-Steel-Critchlow-Fligner test. All statistical analyses were carried out in Jamovi software.

RESULTS AND DISCUSSION

The weighted average of carbon stored in total biomass in SFFI was 29.2Mg C/ha, with some differences between land cover (Table 2). Broad-leaved forest with continuous canopy, not on mire (BFCC) is the cover that statistically presented the highest carbon stored in total biomass ($p < 0.05$), which was more than twice than estimated in dense heathlands and moorlands (DMH) and open heathlands and moorlands (OMH). Natural grassland prevailingly without trees and shrubs (NSWT) has stored just 5.0Mg C/ha (Table 2). SFFI had a carbon stock in biomass of 135.9Gg C, which represents 499Gg CO_2 that has been captured from the atmosphere and conserved in the land uses.

Carbon stored in total biomass of OMH, DMH and BFCC of the SFFI is higher than the one estimate by Peña *et al*. (2011) for disturbed and non-disturbed paramo ecosystems in the Chingaza National Natural Park (17.3 and 22.4Mg C/ha, respectively). It is in the range reported by Castañeda & Montes (2017) for Andean paramo (13.2 and 183.0Mg C/ha) and disturbed and non-disturbed forest of Los Nevados National Natural Park (23.6 and 113.7Mg C/ha; Peña *et al*. 2011). These results are evidence of the potential of these ecosystems to capture and conserve carbon. Thus, FAO (2020) estimated that Colombian forests stored around 112.9Mg C/ha in 2020.

Table 2. Carbon storage in total biomass in different land cover in Santuario de Fauna y Flora Iguaque (SFFI), Boyacá, Colombia.

Land cover	Area (ha)	Carbon (Mg C/ha)	Total carbon stored in SFFI		Total Emission (Gg CO_2)*	
			Gg C	Gg CO_2	0.26%	0.40%
Broad-leaved forest with continuous canopy, not on mire (BFCC)	1477.8	55.5±4.5 a	81.9	300.7	5.3	23.2
Dense heathlands and moorlands (DMH)	595.1	27.0±8.5 ab	16.0	58.9	0.0	4.5
Open heathlands and moorlands (OMH)	1227.8	23.7±6.4 b	29.1	107.0	0.4	8.2
Natural grassland prevailingly without trees and shrubs (NSWT)	1755.8	5.0±4.6 c	8.8	32.2	0.6	2.5
Total	**5056.5**	**29.2**	**135.9**	**498.8**	**5.3**	**38.4**

Carbon values correspond to mean ± standard error. Different letters indicate statistical differences among coverage types ($p < 0.05$). 1Mg = 10^6g; 1 Gg = 10^9g. * Corresponds to a 20-year period.

Estimates of carbon in biomass in SFFI forests (BFCC) were higher (55.5Mg C/ha) than 48.2Mg C/ha in the forests of 12, 30 and 40 years of the Botanic Garden of Colombian Pacific (Torres *et al*., 2017) and similar to the findings reported by Phillips *et al*. (2016) for Colombian Andean forests (48.1 at 129.4Mg/ha) and by Segura *et al*. (2019) for native forests from the Anaime paramo (32.2 and 144.9Mg/ha). Conversely, these results differ greatly from the estimates on oak groves in the south of Colombian Andes (234.9Mg C/ha; Yepes *et al*. 2016), low-mountain wet forest (128.8Mg C/ha; Phillips *et al*., 2016), and the estimates from Segura-Madrigal *et al*. (2020) for oak forests in Santa Isabel (125.0Mg C/ha). These differences can be caused by the local conditions, mainly in terms of altitude, because SFFI is higher up than the areas where these studies were carried out.

Concerning NSWT, a low content of carbon in biomass is observed, which is a typical paramo coverage mainly dominated by grass, frailejon shrubs and bushes that contribute mostly to soil organic carbon storage (SOC) than in total biomass, as stated by Castañeda and Montes (2017) and Benavides *et al*. (2017). Even though in this study only carbon stored in aboveground and belowground biomass was considered, it is possible that if SOC were included, this cover could contribute to support the addition of SFFI ecosystems to the carbon markets, as reported in Santa Isabel (Colombia) by Rojas *et al*. (2018).

Considering the total area of SFFI, BFCC is the most important carbon reserve, given that its 1477.8ha have 81.9Gg C in biomass, which might emit around 300.7Gg CO_2 if it is deforested (Table 2). In contrast, NSWT is the least important despite having a big amount of carbon stored in their total biomass (8.8Gg C) (Table 2). In case of having the simulated annual rates of deforestation (0.26 and 0.40%, respectively), between 25.3 and 38.4Gg CO_2 would be emitted during the next 20 years (Table 2). It is expected that at the end of the simulated period, carbon stocks would be 133.5 and 137.3Gg C, which correspond to 92 and 95% of the stored in 2021 (Figure 2). Carbon stocks under the four tested cover are projected to reduce through time as deforestation rate increases. BFCC and OMH will be the coverages that require the most attention in conservation projects given that the most significant emissions would happen in these coverages if deforested at the rates studied (between 5.4 and 23.2Gg CO_2) (Table 2; Figure 3).

SFFI stored around 0.5Tg CO_2 in 5056ha, while the forests from the Reserve of Semillas de Agua del Páramo de Anaime contained 3.2Tg CO_2 in 9250ha (Segura *et al*., 2019), which represent 0.2 and 1.3%, respectively of the total in very wet mountain forests (bmh-M) of Colombia (242 Tg CO_2; Phillips *et al*., 2016). This difference in carbon stock per area unit must be mostly due to the diametric distribution of species, climate conditions and the anthropic intervention (Duque *et al* 2021). Conservation of SFFI native forests could avoid large emissions, which would contribute to mitigate climate change, apart from generating other environmental services, such as hydric regulation and those derived from biodiversity conservation. Initiatives to conserve tropical montane forests are important strategies to maintain these ecosystems which have the second greatest deforestation rate (1.55%/year) (Armenteras *et al*. 2017).

One of the main land covers of SFFI, in terms of reduction of GHG emissions, are BFCC and OMH; however, deforestation threatens with turning these forest ecosystems into a source of emission of CO_2, which is why it is necessary to promote their conservation. The results of this study could be useful as estimates *ex ante* for proposing future REDD+ projects that would potentiate carbon conservation of the ecosystems present there.

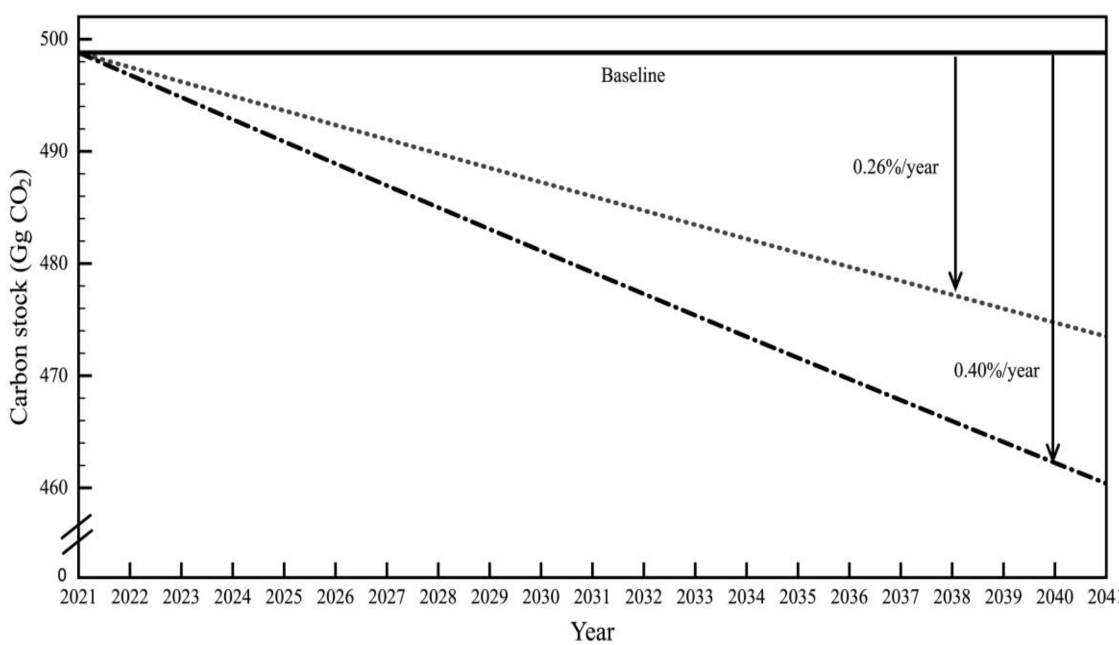
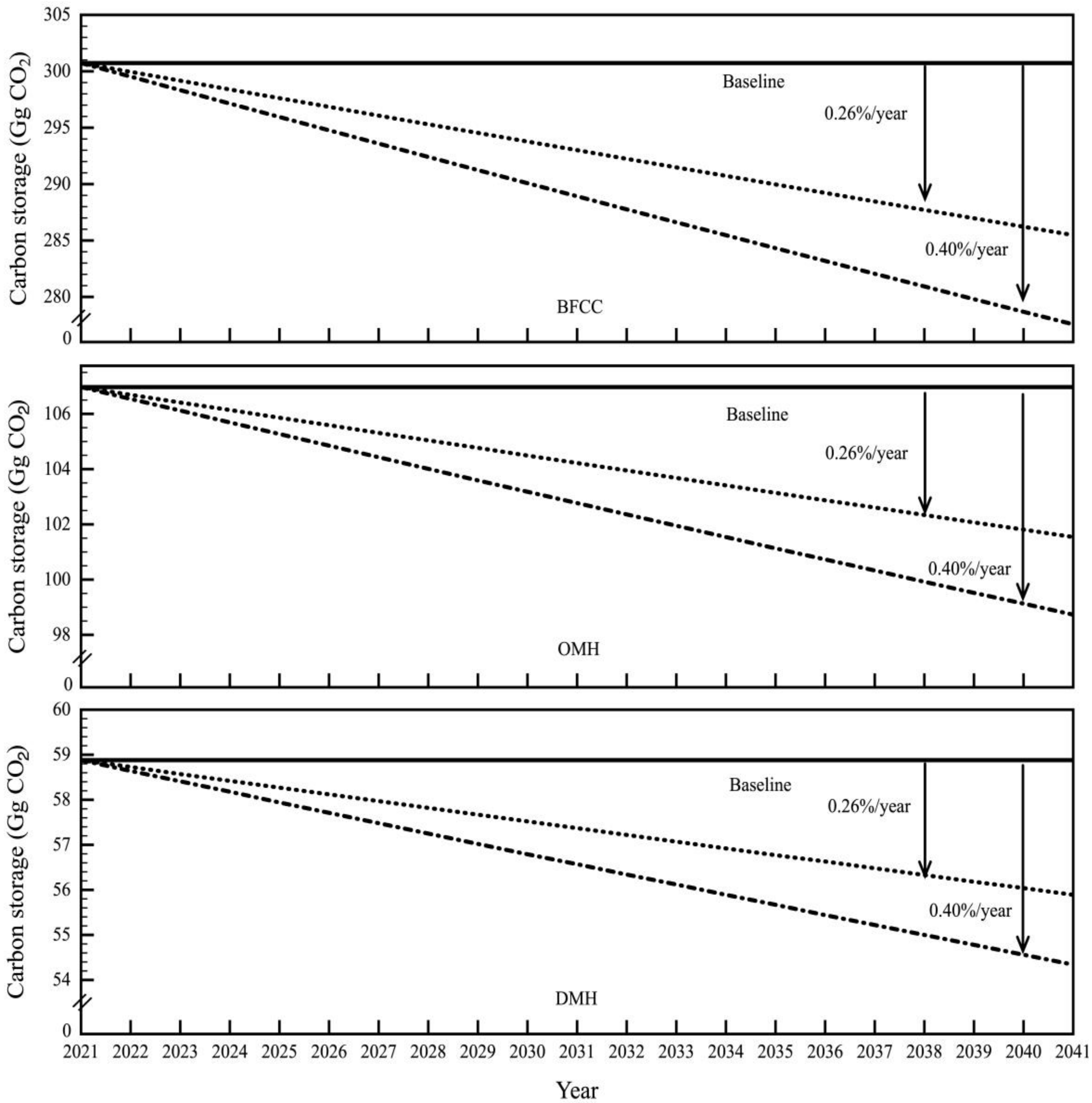


Figure 2. Projection of carbon storage in total biomass of Santuario de Fauna y Flora Iguaque, Boyacá, Colombia during 20 years under the annual rates of regional and national rates (0.26 and 0.40%/year, respectively). The arrows indicate CO_2 emissions that could be reduced in case of eliminating deforestation rates.



BFCC: broad-leaved forest with continuous canopy, not on mire; OMH: open heathlands and moorlands; DMH: dense heathlands and moorlands.

Figure 3. Projection of carbon storage in total biomass in land covers of Santuario de Fauna y Flora Iguaque, Boyacá, Colombia under the annual regional and national rates of deforestation. The arrows indicate CO_2 emissions that could be reduced in case of eliminating deforestation.

Deforestation measurements will help governments and decision makers to improve their reports for international initiatives, such as REDD+ and develop policies for the sustainable management of forests and for reducing deforestation (Armenteras *et al*., 2017). Protected areas are another strategy to reduce deforestation. In this sense, Cuenca *et al*. (2016) estimated that protection decrease forest losses in around 6%.

Although REDD+ are gaining more importance in Colombia and other tropical countries, there are some risks of this type of projects, such as overestimating emission reductions, which can be detrimental to the reliability of mitigation from forests (Neeff, 2021). More countries are including uncertainty in their reference levels and using more sophisticated methods to estimate and control error propagation (Yanai *et al.,* 2020). Spatial and temporal scale needs to be considered for evaluating environmental robustness of estimations of emissions reductions (Schwartzman *et al*., 2021). Omission of land changes cause large errors in reduction estimations, which can be reduced with efficient forest stratification (Olofsson *et al.,* 2020). Remote sensing and geographic information system approaches, such as Object Oriented Classification, Maximum Likelihood Classification and Vegetation Indices Classification are now used (Laura & Darmawan, 2020; Perea-Ardila *et al.,* 2021) to increase accuracy and reduce monitoring costs. At the same time, Neeff (2021) proposes to use discount factors to be cautious in estimations of carbon.

CONCLUSIONS

SFFI most dominant land cover is NSWT and BFCC (34.7 and 29.2%, respectively). However, BFCC and OMH are the most important concerning their carbon content in biomass (81.9 and 29.1Gg C, respectively), which is why their conservation should be prioritized.

SFFI stores around 499Gg CO_2, which in 20 years could produce emissions between 25 and 38Gg CO_2 if deforestation rates stay between 0.26 and 0.40% per year. This shows the potential that the forests of this protected area have in carbon capture, and therefore, their importance in complying with national commitments acquired in COP21. Not only does deforestation influence the loss of biodiversity, but it also represents a strong source of CO_2 emissions towards the atmosphere, product of the loss of forest biomass, mainly BFCC and OMH.

Despite the development of the national REDD+ strategy, conservation and improvement of carbon forest and sustainable management of the forests in the country become a good alternative that should be encouraged in national policies. Reduction of emissions reported in this study could become carbon credits and be commercialized under REDD+ project standards to encourage conservation of this kind of ecosystems and at the same time contribute to mitigate climate change effects.

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native forests in the Santuario de Fauna y Flora de Iguaque, Boyacá, Colombia)", code 380120516.

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