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CO_2 Capture Capacity Measurement Using Multitemporal Analysis and Biophysical Variables in a Tropical Humid Forest in the Colombian Andes

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Abstract: This study analyzed the CO_2 capture potential for the Parque Natural Regional Serrania de las Quinchas buffer area in Colombia. For this purpose, multitemporal analysis for land covering for the years 1989, 2000, 2006, 2011, 2017 and 2021 was performed using the normalized difference vegetation index (NDVI) for each cover and land cover (LC) methodology. In the same way, aboveground biomass (AGB) was measured for representative parcels by measuring tree diameters and heights and applying adequate allometric models; carbon content in soils was measured too. The results showed that carbon content in soils is higher than that in aboveground biomass. Average values for the tree parcels were above 2 times the value recorded for average tropical humid forests, and one of them had a value 7 times this value. A very interesting potential for existing forest recovery was found for this area. Strategies for this include the development of sustainable practices, land use management, biodiversity preservation and the participation and leading of the local communities.

Keywords: spatiotemporal analysis; land cover; geographic information systems; aboveground biomass; carbon stock; remote sensing data; vegetation indices; Colombia

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1. Introduction

Climate change, attributed to the fast CO_2 concentration rise in the atmosphere, is one of the main environmental problems that humankind must face to achieve sustainability. It is caused mainly by fossil fuel use and changes in land use [1]. Colombia has an extensive coverage of natural forests that represent 52% of the total area of its continental surface, being the country with the third largest area of natural forests in South America. Also, the ecosystems related to these forests make the biodiversity of this country the second highest in the world. However, deforestation is the main problem related to CO_2 capture in this country. In the last two decades, 3.1 million hectares of forest have been deforested in the country. In general, it is estimated that it lost more than 6 million hectares of natural forests due to deforestation from 1990 to 2016 [2], and in 2022, deforestation rates were growing faster than ever before [3]. The soil cover in Colombia was 59% in protected areas in 2016 [2]. According to data from Mapbiomas Colombia [4], in 2022, Colombia was 58% covered by forest and 13% by natural areas different from forests. The growing livestock and agriculture activities due to population growth and bad practices generate conflicts of land use that are reflected in deforestation and deterioration processes of natural forests. Natural forests are one of the main sinks for CO_2, which accumulates in leaves, branches, roots, trunks and soil [5]. Therefore, forest preservation, reforestation and plantation have been found to be among the most suitable alternatives for CO_2 sequestration, and the CO_2 sequestration capacity depends on the forest type and management practices [1].

Strategies for reducing emissions due to deforestation and forest degradation are being implemented worldwide. Economic incentives such as CO_2 trading are an opportunity to generate income for local communities that are having problems finding a sustainable way to manage the forests in their territories. However, trading CO_2 derived from forest preservation requires detailed knowledge of a forest's state and its carbon stocks. A way to accomplish this is by using Corine Land Cover (CLC) and biomass data to establish how land cover changes affect the carbon stock in vegetation [6–10]. In the case of Colombia, some studies have been published. One of them is a study presented in [9] for forests located at different altitudes in the department of Antioquia, using CLC and biophysical variables. The Colombian Institute of Hydrology, Meteorology and Environmental Studies conducted a study to estimate the carbon content in Colombian forests in 2010 by statistical analysis using information provided by governmental and non-governmental institutions and national and international researchers [11]. This institute also performed an estimation of CO_2 emissions caused by deforestation in the period between 2005 and 2010 in Colombia [10]. A different methodology was used by the authors of [12] to estimate carbon stocks in the Colombian Amazon forest with high-resolution maps and LiDAR samples that were upscaled to a large area in the Colombian Amazon forest.

The Serrania de Las Quinchas Regional Natural Park (PNRSQ), located in the municipalities of Puerto Boyacá and Otanche, Colombia, is a protected area with conflicts regarding the change in its vegetation cover. This ecosystem, the last relict of the humid tropical forest of the Middle Magdalena, has followed a pattern of continuous deforestation, reaching an 80% loss of the native forest. Historically, this has been a conflict territory due to the presence of illegal activities related to illicit crops managed until 2013 by paramilitaries, specifically Autodefensas Campesinas de Puerto Boyacá, and there are some small areas of such activities currently present in the area. Currently, even though these activities have decreased, social problems persist due to the low income and unemployment of the population. The municipality of Otanche has, for example, a rate of multidimensional poverty of 79.2%, compared to an average of 54.9% in the department of Boyacá where it is located. Nowadays, productive and conservation activities are being promoted, among which the development of cocoa cultivation stands out, as well as other crops such as cassava and coffee, livestock and forest extraction. Other recently developed and potential activities include nature tourism, but it is undergoing only a very marginal development. Currently, the Environmental Management Plan of the PRNSQ has determined zoning intended for conservation; thanks to its great biological diversity, the PRNSQ has been declared a natural park, a Biodiversity Hotspot zone by NASA and a bird conservation area by the Alexander von Humboldt Institute [13]. However, the implementation of this plan has been difficult due to a lack of resources, institutional weakness and problems with the definition of land property rights [14].

An activity intended for this ecosystem conservation is related to forest conservation and its sustainable management. However, deforestation continues at a high rate due to the lack of income sources related to forest conservation. An interesting income source has proved to be carbon sequestration credits, but little information about their potential has been issued to date. For this, land cover may be used, but it has been shown that few variations in biomass have been explained by normalized difference vegetation index (NDVI) [15]. Therefore, more detailed information is needed to estimate aboveground biomass (AGB). Currently, in Colombia, a methodology framework for measuring biomass was issued by the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) and is based on in situ measurements such as height and diameter and allometric equations from previous studies conducted around the world [16].

Forest stocks have been studied at a country level for the specific areas of Antioquia and Amazonas. Therefore, this study analyzes carbon stock for this unique ecosystem by using existing and previously applied methodologies adapted to Colombia, adding field measurements of aboveground biomass and carbon soil content. Additionally, temporary change in land cover because of land use conflicts is analyzed, and strategies for preservation and generation of income for communities based on ecosystem services are proposed.

2. Materials and Methods

2.1. Study Area

The buffer zone for the PNRSQ, in the municipality of Otanche, Boyaca Department, Colombia, was chosen as the study area. A digital elevation model (DEM) was downloaded from the United States Geological Service website, and the delimited area was determined from the environmental management plan of the National Natural Parks of Colombia entity. According to this information, the buffer zone was used as the study area. See Figure 1.

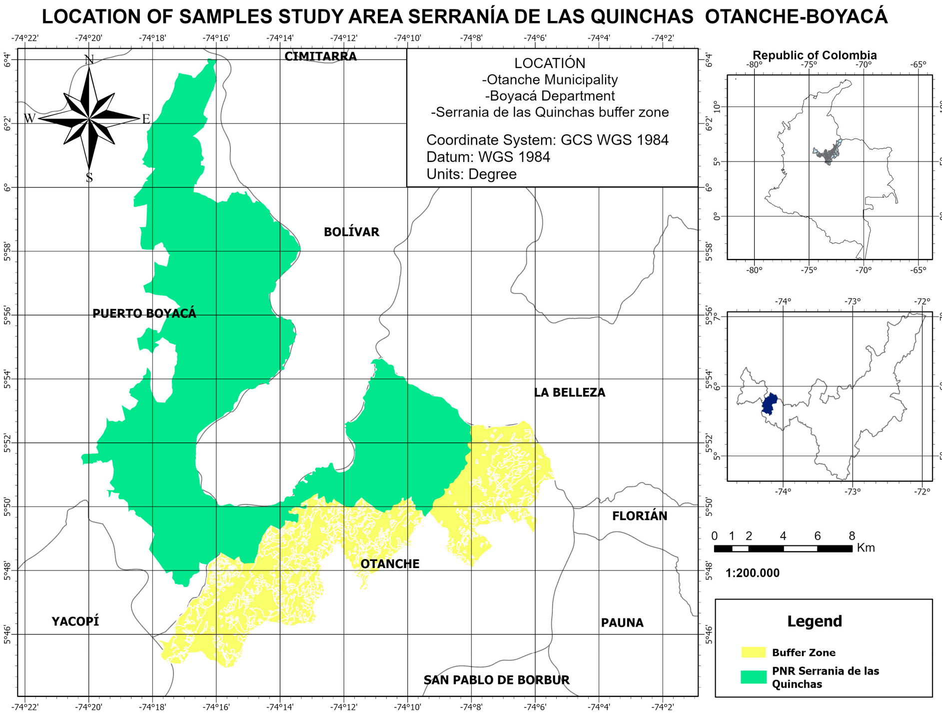

Figure 1. Study area.

2.2. Vegetation Cover

Multitemporal analysis for land cover was performed using satellite images for the years 1989, 2000, 2006, 2011, 2017 and 2021. The months of the images used correspond to the period from May to June and from October to November to avoid rainy periods for the study area. An atmospheric correction was made using the QGIS 3.28 software tool cloud masking. Normalized difference vegetation index (NDVI), which measures the vegetation cover areas using the near-infrared and visible red channel, was used. The following equation was applied:

$$\text{NDVI} = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}} \tag{1}$$

where the following definitions hold:

NDVI = Normalized difference vegetation index;

NIR = Near-infrared intensity;

Red= Visible red channel.

With the calculated NDVI for each cover, the land cover (LC) methodology was used to compare and classify vegetation cover properties. Using medium-resolution satellite images (Landsat), land cover maps were made at a scale 1:100,000 using ArcGIS 10.8 software. Subsequently, coverage was confirmed in the field through georeferencing. The classification method used was supervised classification through the selection of samples identified in the field and under five categories: dense forest, water bodies, fragmented forest with secondary vegetation, mosaic of pastures and crops and mosaic of crops and natural spaces. The supervised classification was carried out using the maximum likelihood algorithm for calculating the probability distributions for the classes, related to Bayes' theorem through the samples identified in the field.

The area for each land cover (LC) was calculated using ArcGIS 10.8 software. With this information, the change in each land cover over the years was calculated using the equation proposed by [17]:

$$TCLC = \frac{1}{T_2 - T_1} \times In\left(\frac{ATC2}{ATC1}\right) \quad (2)$$

where the following definitions hold:

$TCLC$ = Change rate of land cover over the years (%);
ATC_2 = Final land cover area at time 2;
ATC_1 = Initial land cover area at time 1.

2.3. Vegetation Cover Change Matrix

The identification of vegetation cover changes of the vector layers in the different years was carried out through a series of geoprocessing tools of intersection layers made using ArcGIS Pro 2.5 software. This series of geoprocessing is useful for analyzing changes between rural and urban land, agricultural border expansion, deforestation or changes between different types of cover, as was performed in the present study [18].

Vector layers with Corine Land Cover classification for years 1989, 2000, 2006, 2011, 2017 and 2021 were taken as input layers and analyzed by taking pairs of years, and thus, the global change between the initial year of analysis and the most recent year (1989–2021) was obtained, along with the changes between the years 1989 and 2000, 2000 and 2006, 2006 and 2011, 2011 and 2017, and 2017 and 2021. From the operations performed with these layers, tables were obtained that included the attributes of each shapefile, where the geometric area in hectares was recalculated.

A new comparative field called "Before-After" was created in the attribute table of the layer resulting from the intersection, which carried the information of the name of the coverages to be compared. For this purpose, the "Field calculator" tool was used, where the coverage fields of the couple of years analyzed were concatenated. The symbology was changed to red Tnes in these coverages where changes were identified between them.

Finally, in order to identify the number of hectares that changed between the different types of cover, a consolidation of the areas was carried out using the "summarize" tool, where the result was a table that showed the number of hectares that changed between the different covers.

2.4. Sample Plots

Three sample plots were chosen for measuring biophysical properties in forests in the study area; places located in different mapping units were chosen to check differences in species, height and diameter of the trees due to different soil properties. However, according to [16], aboveground biomass could also change depending on the forest management, especially if the forest has unplanned exploitation. Therefore, care was taken in choosing three plots with few human interventions; however, once there, it was difficult to find a totally preserved area. Evidence of selective deforestation was found almost everywhere, classifying these plots as an intervened primary forest. According to the Colombian protocol for estimating biomass [16], plots must be chosen in all present cover lands, and in different soil, climate and altitude conditions. In this research, 3 plots of approximately 0.25 ha each were chosen. The compartments chosen for carbon estimation were aboveground biomass and soil. Their location is shown in Figure 2, and their properties are shown in Table 1.

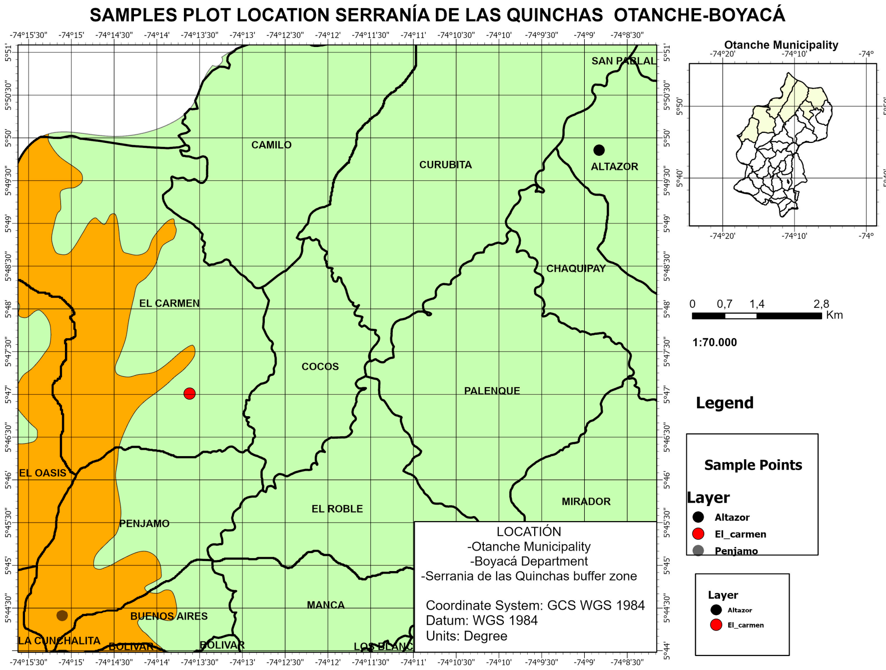

Figure 2. Sample plot locations.

Table 1. Characteristics of sample plots.

Zone	Altazor	El Carmen	Cunchalita
Coordinates	5°49′51″ N–74°08′50″ W	5°47′01″ N–74°13′37″ W	5°44′25″–74°15′06″ W
Holdridge Life Zone	Humid Forest	Humid Forest	Humid Forest
Soil units	MVAfp	MPAfp	MPAfp
Altitude (masl)	1449	892	1678
Precipitation (mm/year)	2820	3246	2430
Average temperarure (°C)	25	28	22
Total area (m^2)	2420	3111	2250
Total tree number/plot	164	141	103

All the sample plots were located in the humid forest Holdrige Life Zone, and the soil units were MVAfp and MPAfp. MVAfp soils are, according to the soil classification, eroding structural mountains of moderate to strongly broken relief, with slopes between 12 and 50%, affected by diffuse runoff to a light degree and stoniness; they are deep, imperfect to well-drained soils, with clayey textures, light and extremely acidic reactions, very high base saturation and aluminum saturation greater than 60%, and fertility from low to high. MPAfp soils belong to the Asociación Typic Dystrudepts—Humic Dystrudepts—Lithic Udorthents and are characterized by a very humid ambient climate, defined by an average temperature of 20 °C and a rainfall ranging from 2000 to 4000 mm. The topography is moderately steep, with slopes of 50 to 75% and stoniness on the surface [19].

2.5. Forest Biomass Estimation

For forest biomass estimation, areas for each land cover determined by CLC methodology as explained in Section 2.2 were used. Theoretical biomass contents were used based on the correlation and data from [11,20]. Also, an average of the carbon stock calculated based on field measurements performed in this study was used. For this, the following procedure was followed: The aboveground biomass content for the 3 parcels was estimated using field measurements by the indirect method calculated by allometric equations reported by [21]. This method was developed for different life zones and allows the estimation of aboveground biomass in a wide environmental gradient in Colombian ecosystems. These models were validated with field measurements and nowadays are the best approximation for calculating AGB in Colombian tropical forests. In our study, all the trees with a diameter higher than 10 cm were measured for each parcel. The diameter at chest height was measured, and height was calculated after measuring angles using a clinometer. Biomass was estimated by an allometric equation for tropical humid forests using tree height, diameter and density measurements, as established by [21]:

$$Ln(AGB) = a + B_1 Ln\left(D^2 H\rho\right) \tag{3}$$

where the following definitions hold:

AGB = Aboveground biomass in kg;
D = Diameter at 1.30 cm from the soil, in cm;
H = Height of the tree, in m;
ρ = Density of the timber in g/cm^3;
A, B_1 = Model parameters for humid tropical forests.

After the biomass was calculated for each tree, all the trees' aboveground biomass values were summed and then multiplied by 0.5 to obtain C content, as established by the IPCC [22].

2.6. Soil Biomass Estimation

Due to the soil heterogeneity in the area, different contents of organic carbon could be found at different depths. However, according to the characteristics presented by the Humic Dystrudepts soils, which are the soils that predominate in the studied area, where the organic thickness is mainly found in the surface, horizon A has a thickness of 20 to 25 cm, according to the organic carbon sample, the organic carbon sample was taken at 30 cm, taking advantage of the fact that the concentration of organic carbon is between 90 and 95% of the total organic carbon characteristic of the carbon content of soils in the first horizon. Consequently, the first soil layer (30 cm depth) was analyzed. For each plot, a trial pit was made for a soil survey, with dimensions of 30 cm $\times$ 100 cm $\times$ 100 cm, and samples were taken with a cylinder and sent for laboratory analysis of total organic carbon content and pH. Total organic carbon was measured by the Walkly Black humid combustion method, following the methodology described in [16]. Total organic carbon content per area was calculated by the following equation:

$$TC = D \times \left(\frac{C_c \times m}{V}\right) \tag{4}$$

where the following definitions hold:

TC = Total organic carbon content per area in the analyzed soil layer (kg/m^2);
D = Analyzed soil layer depth (m);
C_c = Organic carbon concentration (g/kg);
m = Mass of the analyzed material (kg);
V = Sample taken volume (m^3).

3. Results

3.1. Vegetation Cover Multitemporal Analysis

NDVI values were calculated for the area and classified into five classes: dense forest, water bodies, fragmented forest with secondary vegetation, mosaic of pastures and crops and mosaic of crops and natural spaces. The area percentage values are shown in the Table 2, proportion values are shown in Figure 3, and total values in Figure 4. Figure 5 shows the maps with the areas by each coverage for years 1989-2021

Table 2. Area, percentage of the total, calculated by CLC methodology.

Year	Dense Forest	Water Bodies	Fragmented Forest with Secondary Vegetation	Mosaic of Pastures and Crops	Mosaic of Crops and Natural Spaces
1989	55.8%	3.5%	37.7%	2.5%	0.6%
2000	67.4%	1.3%	29.7%	1.1%	0.4%
2006	59.1%	2.6%	33.8%	1.1%	3.3%
2011	60.2%	3.0%	33.9%	0.5%	2.4%
2017	66.0%	2.6%	26.6%	4.2%	0.6%
2021	66.1%	1.0%	26.4%	4.7%	1.8%

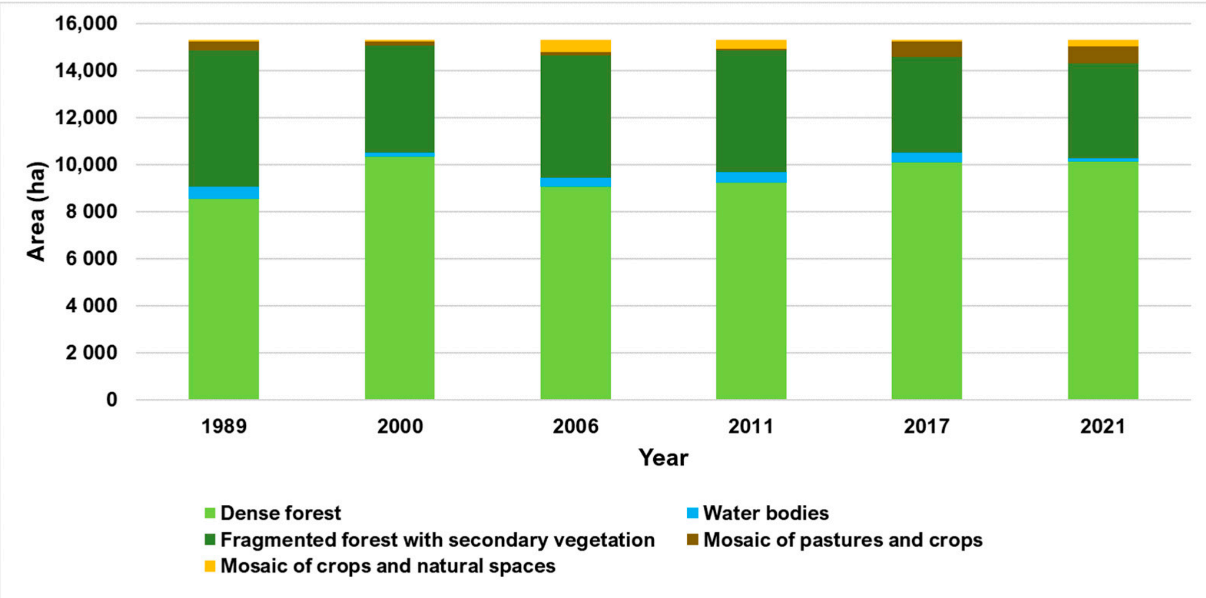

Figure 3. Proportion of vegetation covers. Total areas (ha) (1989–2021).

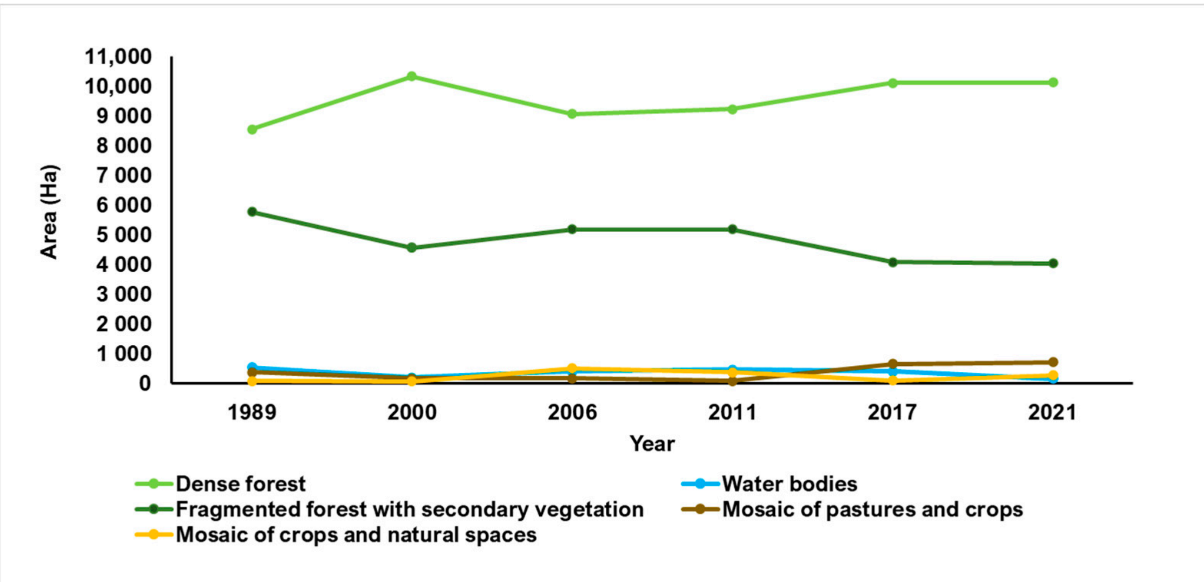

Figure 4. Variation in vegetation covers over time. Total areas (ha) (1989–2021).

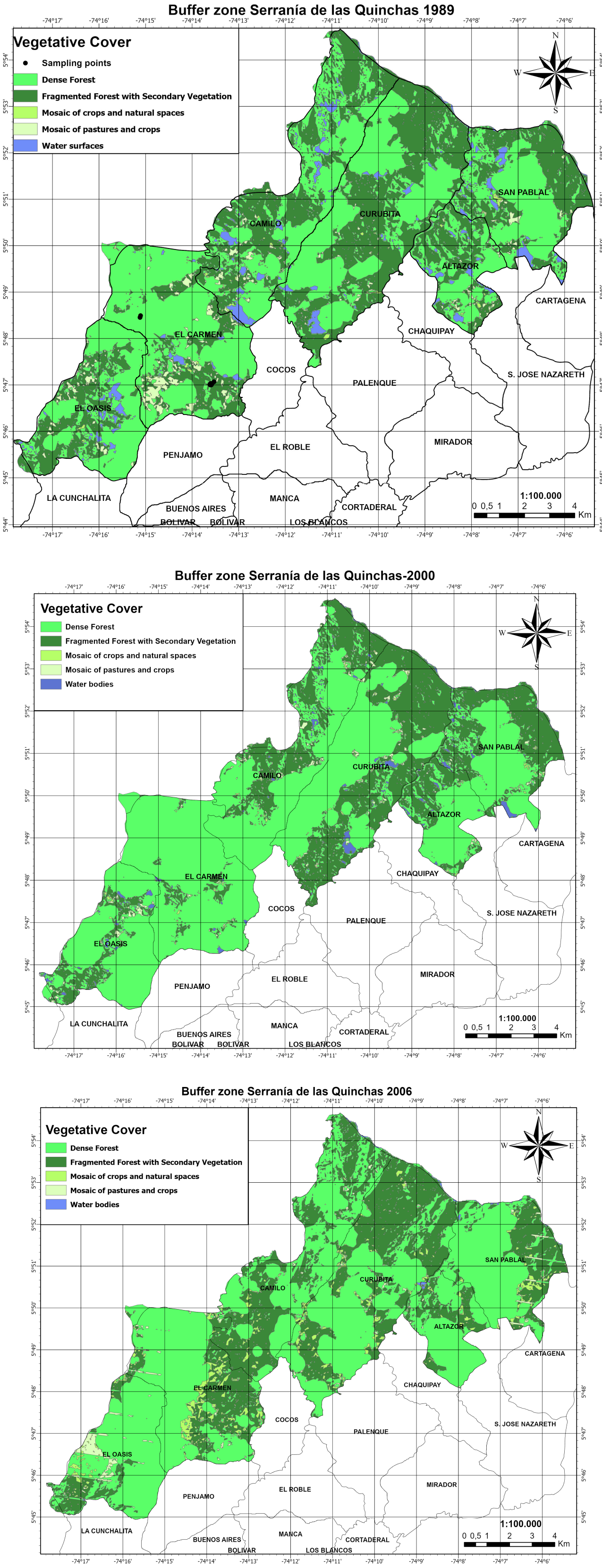

Figure 5. *Cont.*

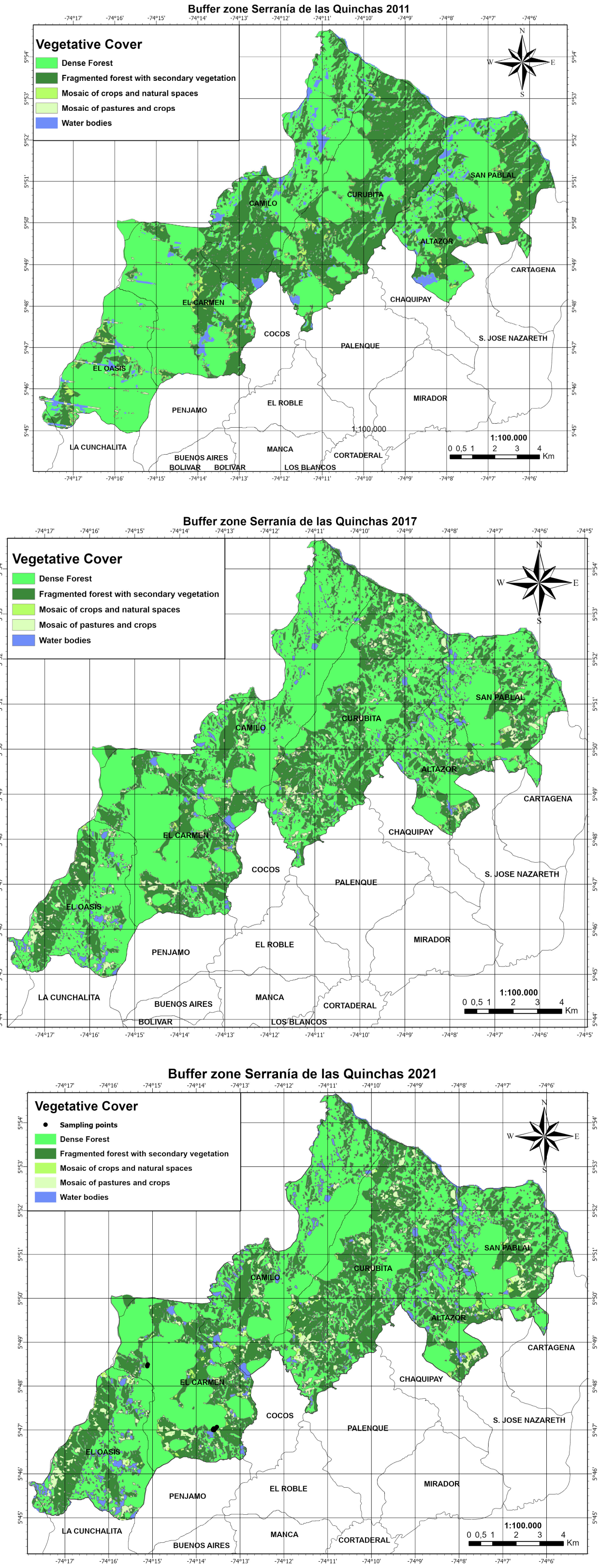

Figure 5. Variation in vegetation covers over time—maps.

3.2. Forest Biomass and Carbon Stock Estimation

Aboveground biomass estimation was performed by field measurements in three parcels located in Cunchalita, El Carmen and Altazor (Table 1), with studied areas of 0.24, 0.31 and 0.22 ha, respectively. Each plot had 103, 141 and 164 trees with the required characteristics as explained in Section 2.4, and densities were 468.2, 453.4 and 677.7 trees/Ha. Carbon contents were 119.6 Tn C/ha, 54.8 Tn C/ha and 948.3 Tn C/ha, respectively, with an average of 374.3 Tn C/ha. As shown in Figures 6 and 7, Altazor, the plot with the highest carbon content per area, was the parcel with the highest number of high-diameter trees and also had taller trees, and El Carmen was the plot with the highest number of low-diameter trees. The three parcels were located in the dense forest cover.

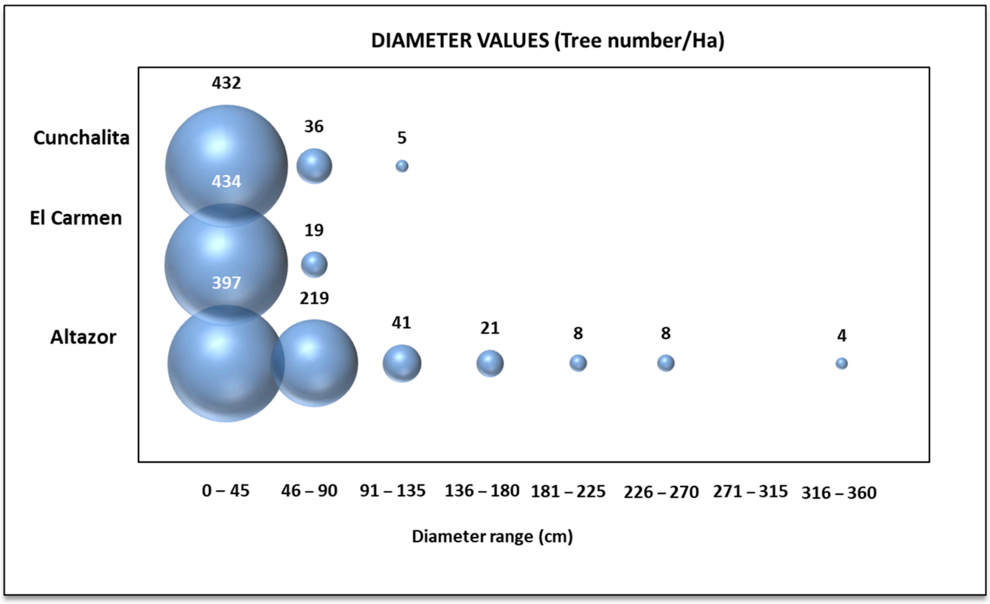

Figure 6. Tree diameter values.

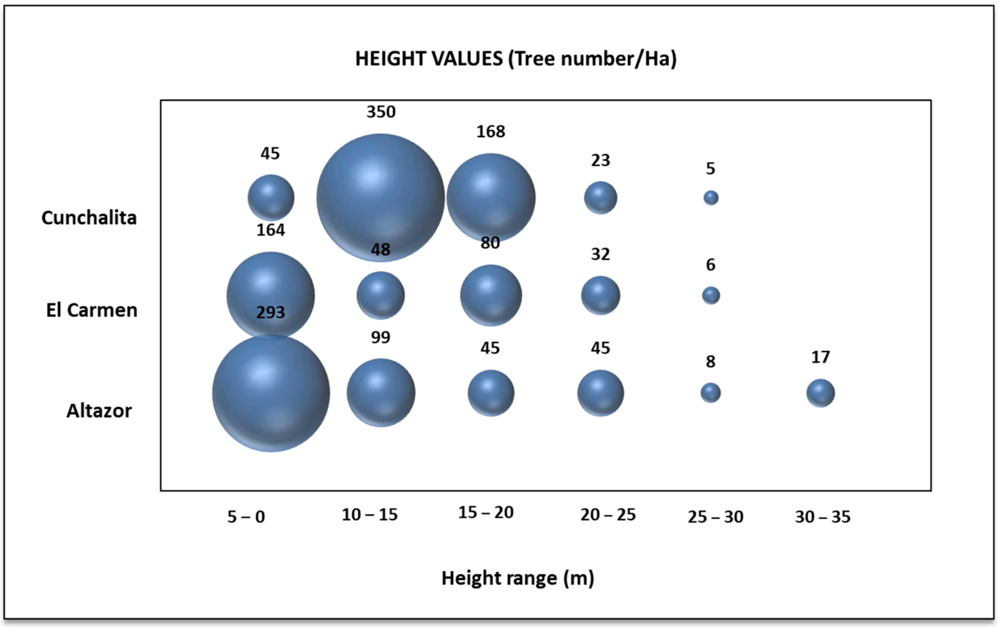

Figure 7. Tree height values.

3.3. Carbon Stock in Soil

Tables 3 and 4 show the values for carbon content in the three parcels analyzed; an average of 897.19 Tn/ha was obtained. Organic C is expressed as a percentage of the total weight of the soil.

Table 3. Carbon stock in analyzed parcels and Colombian tropical humid forests.

Location/Clasification	C (Tn/ha)	Source
Cunchalita	140.3	Authors
El Carmen	70.4	Authors
Altazor	1023.0	Authors
Natural forest—tropical humid forest	132.1	[10]
Colombian tropical humid forests	131.87	[20]
Average Colombian forests	113.45	[23]
Amazon forests	273.1	[24]

Table 4. Carbon stock in analyzed parcels.

Location	Soil Type	Organic C (%)	pH	Density (g/mL)	Total C/ha
Cunchalita	Humic Dystrudepts	6.33	6.22	1.77	1120.41
El Carmen	Typic Dystrudept	1.46	4.18	1.96	286.16
Altazor	Humic Dystrudepts	6.33	6.31	2.03	1284.99

3.4. Deforestation Rates and Carbon Stock Changes

Table 5 shows the carbon stock in land coverages used for estimation in this study.

Table 5. Carbon stock in land coverages according to [10].

Cover	Carbon Stock (Tn/ha)
Shrublands	23.8
Forest plantation	89.9
Secondary vegetation	19.6
Heterogeneous agricultural areas	5.8
Permanent crops	28.9
Transitory crops	4.2
Grasslands	14.1
Pastures	6.4
Water surfaces	0.0
Aquatic vegetation	0.0
Built-up areas	0.0
Other areas without vegetation	0.0
Burned areas	0.0

Figure 7 shows the results for carbon total stock and its distribution by land coverages for the studied area in the years 1989–2021. In part (a), the case in which 131.87 TnC/ha was used for dense forest [20], the maximum carbon stock was 1′453.460.32 Tn obtained in 2000. For 2021, it was 1′421.248.35 Tn. In general, in the analyzed period (1998–2021), there was an increase of 14.3% in the carbon stock in all the vegetation covers, and an 18.5% increase in the carbon stock in the dense forest cover. By 2021, 94% of the total carbon stock was in the dense forest coverage. Figure 8 (left) shows the conservative estimation, using the carbon stock for Colombian tropical humid forests reported by [20]. Figure 8 (right) takes into account an average of the carbon stock obtained in the tree parcels analyzed in this study. In this case, a value of 411.3 Tn C/ha for dense forest was used, resulting in the total carbon stock for 2021 being 4′245.792.012 Tn, 3 times that for conservative estimates, and by 2021, 98% of the total carbon stock was in the dense forest coverage.

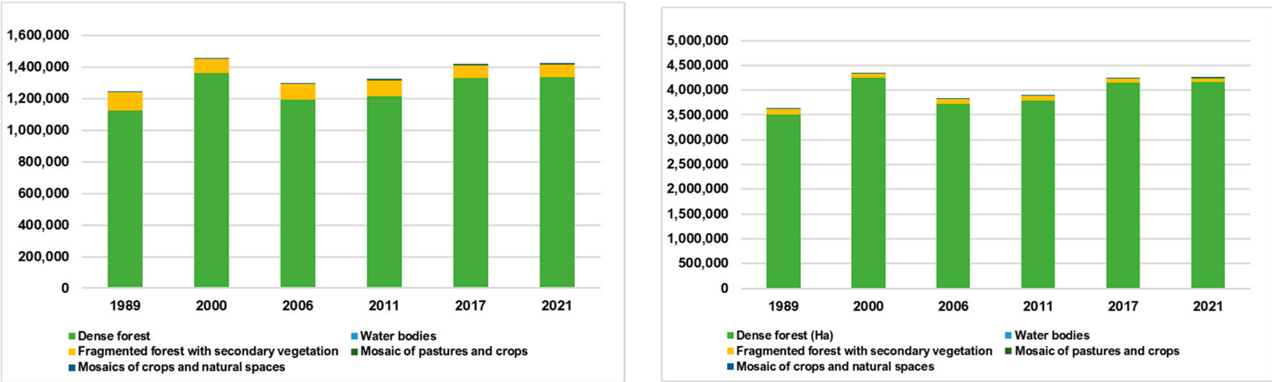

Figure 8. Carbon stock (Ton) by land coverage, 1989–2021. (**Left**) Estimates using stock C values reported by [10]. (**Right**) Estimates using stock C average values obtained by author's field measurements.

4. Discussion

Variation in vegetation covers calculated by CLC methodology over time, as shown in Figures 3 and 4, showed that for 2021, dense forest area increased 18.5% since 1989. Fragmented forest with secondary vegetation areas diminished by 30.1% in the same period, and the areas with crops, pastures and natural spaces grew by 112.4%. Natural primary forests are being preserved and increased by the recovery and consolidation of some forests with secondary vegetation, but also, agricultural areas are growing at the expense of secondary forests. This conversion of forests and grasslands to cropland or permanent pasture is a common activity in the tropics and one of the main problems for this area [10]. Previous studies show that tropical humid forests in Colombia were 45,377,140.32 ha of a total of 60,548,267.97 in 2010 and also that for 2000–2005, the forest area lost was 137,000 ha/year, a decrease of 0.3% per year [10]. For the period 2010–2022, according to MapBiomaps Colombia data, forest areas decreased a total of 3.4%, 0.28% per year, showing a constant path over the years. Worldwide emissions from deforestation are 1.8 GT/yr; this activity is the main driver for carbon release into the atmosphere, showing the potential of afforestation as a sink of CO_2 [25].

As shown in Figure 5, although dense forest areas are growing in the PNRSQ buffer area, they are more dispersed, and areas that were continuous dense forests in 1989 are now a mix of dense forest and secondary forest, showing an extracting activity with posterior recovery; some cases recover to a state very similar to that of the native forest, but in smaller continuous areas.

On the other hand, the average value for carbon content in aboveground biomass for the three parcels was 411.3 Tn C/ha, a high value compared to all of the reported carbon stock values in the literature for Colombian humid forests. In the study presented in [20], researchers used topographic, climate and remote sensing variables at several points to explain the aboveground biomass in Colombia based on field measurements and a correlation made by the Random Forest model in R. Their model is based on the premise that there is a sensitivity of the optical reflectance to variations in the structure of the vegetation canopy. The statistical model results showed that the Ombrothermal Index (IOd3), average annual rainfall and mid-infrared band (MODIS MCD43A4 Band 6) were the main variables affecting aboveground biomass in the Colombian forests analyzed. They reported the median carbon content per area in Tn C/ha for natural regions, and for the Andes, the reported value was 120 Tn C/ha. They also reported median values for the Holdridge Life Zones; and for tropical humid forests, the reported value was 131.87 Tn C/ha. In their report by departments, Boyaca had an average of 114.62 Tn C/ha. They reported that values calculated by the Random Forest model underestimated carbon content for forests with a high carbon content. The value reported in their study for tropical humid forests was used to estimate the whole forest carbon content to make these values comparable with other similar studies and have a conservative estimation. Other studies reported lower carbon contents; for example, 82.5 Tn/ha was reported by [10] for very humid tropical forests in Colombia, and 113.45 Tn/ha was reported by [23] as the total mean value for the forests of the entire country; higher values such as 273.1 ± 9.8 Tn/ha have been reported for Colombian Amazon forest [24].

For the Cunchalita parcel, carbon aboveground biomass content was in agreement with values reported in the literature for humid tropical forests in Colombia, and El Carmen had a lower carbon content. On the other hand, the Altazor parcel had a very high carbon content (1023 Tn/ha), 7 times the average for tropical humid forests in Colombia, showing that this forest is into the category of very well-preserved forests in this area and that the potential for carbon sequestration in this ecosystem is very high.

5. Conclusions

This study contributes to the understanding of the pattern of forest fragmentation and influence of the land cover changes. Finding the areas where changes have occurred helps to understand and prioritize actions in forest management, conservation and biodiversity policies in this area. The results show that dense forest has grown since 1989 and the carbon stock in all the vegetation covers increased by 14.3% from 1989 to 2021, using literature data for tropical humid forests.

The carbon stock by land coverage in the period between 1989 and 2021 was estimated by means of GIS. The average values found in the literature for land coverages were used, and in the case of dense tropical humid forests, a calculation was performed using biophysical variables from chosen plots in the area. Those variables included tree diameter, density and species. Values for these variables were obtained by field trip techniques and posterior application of allometric models adapted to Colombian forests. Carbon content in soils was measured by sampling in plots and measurements in the laboratory. The measured average carbon content in AGB was 374.3 Tn C/ha, well above the average for the content reported for humid tropical forests in Colombia. Using the AGB values obtained in this study, the carbon stock average is 3 times this value. On the other hand, the carbon content in soils was 897.19 Tn/ha, 2.4 times that found in the AGB. In total, an average of 1271.49 Tn C/ha (AGB+ soil) was found, and a pattern of dense forest recovery over time is being achieved, but in a more dispersed way than in the past. Global strategies for carbon storage potential in forests are oriented mainly to existing forests that must be allowed to recover (61%); the remaining (39%) are for forests that have been fragmented. The results found in this study show that the recovery of fragmented forests has led to an increase in dense forest area, and also that well-preserved forests have an outstanding capacity for carbon storage. In this area, strategies must consider sustainable practices that consider the local communities in the first place. Among these strategies are agroforestry, silviculture and permaculture practices. However, forest recovery must be primarily related to a biodiversity-positive effect and has to do with complex local social, political and economic conditions.

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References

1. Nunes, L.J.R.; Meireles, C.I.R.; Gomes, C.J.P.; Ribeiro, N.M.C.A. Forest contribution to climate change mitigation: Management oriented to carbon capture and storage. *Climate* **2020**, *8*, 21. [CrossRef]
2. Rey, C.A.; Rojas, M.; Guerrero, R.; Lagos, A.M.; Franco, O.; Becerra, M.T.; Vargas, D.M.; García, P.; Hoffmann, R.; Retrepo, M. *Bosques Territorios de Vida*; MinAmbiente: Bogotá, Colombia, 2016.
3. WWF. *Aumento de la Deforestación en Colombia en 2022 Exige Acciones Urgentes*; WWF: Gland, Switzerland, 2022.
4. *MapBiomas Colombia*; Version 1.0; "Cobertura"; Instituto de Hidrología, Meteorología y Estudios Ambientales, IDEAM: Bogotá, Colombia, 2022.
5. Eloka-Eboka, A.C.; Bwapwa, J.K.; Maroa, S. Biomass for CO_2 Sequestration. *Encycl. Renew. Sustain. Mater.* **2020**, *3*, 277–290. [CrossRef]
6. Gemitzi, A.; Albarakat, R.; Kratouna, F.; Lakshmi, V. Land cover and vegetation carbon stock changes in Greece: A 29-year assessment based on CORINE and Landsat land cover data. *Sci. Total Environ.* **2021**, *786*, 147408. [CrossRef] [PubMed]
7. Muñoz-Rojas, M.; Jordán, A.; Zavala, L.M.; De la Rosa, D.; Abd-Elmabod, S.K.; Anaya-Romero, M. Impact of Land Use and Land Cover Changes on Organic Carbon Stocks in Mediterranean Soils (1956–2007). *Land Degrad. Dev.* **2012**, *26*, 168–179. [CrossRef]
8. Rusu, E.; Balan, M.-G.; Profir, O.; Bobric, D. Influence of recent land use change on total organic carbon stock in Humor River Basin. *Environ. Eng. Manag. J.* **2017**, *16*, 905–912.
9. Yepes, A.; Duque, A.; Navarrete, D.; Phillips-Bernal, J. Estimation of carbon stocks and loss by deforestation in the forests of Antioquia, Colombia. *Actual. Biol.* **2011**, *33*, 193–208. Available online: https://www.researchgate.net/publication/262517417 (accessed on 30 June 2023).
10. Yepes, A.; Navarrete, D.A.; Phillips, J.F.; Duque, A.J.; Cabrera, E.; Galindo, G.; Vargas, D.; García, M.C.; Ordoñez, M.F. *Estimación de Las Emisiones de Dióxido de Carbono Generadas Por Deforestación Durante el Periodo 2005–2010*; Instituto de Hidrología, Meteorología, y Estudios Ambientales-IDEAM: Bogotá, Colombia, 2011.
11. Phillips, J.F.; Duque, A.J.; Yepes, A.P.; Cabrera, K.R.; García, M.C.; Navarrete, D.A.; Álvarez, E.; Cárdenas, D. *Estimación de Las Reservas Actuales (2010) de Carbono Almacenadas en la Biomasa Aérea en Bosques Naturales de Colombia*; Instituto de Hidrología, Meteorología, y Estudios Ambientales-IDEAM: Bogotá, Colombia, 2011.
12. Asner, G.P.; Clark, J.K.; Mascaro, J.; García, G.A.G.; Chadwick, K.D.; Encinales, D.A.N.; Paez-Acosta, G.; Montenegro, E.C.; Kennedy-Bowdoin, T.; Duque, Á.; et al. High-resolution mapping of forest carbon stocks in the Colombian Amazon. *Biogeosciences* **2012**, *9*, 2683–2696. [CrossRef]
13. Alianza Quinchas. Plan de Ambiente, Desarrollo y Paz de la Serranía de las Quinchas en Otanche Boyacá. 2019. Available online: https://www.e3asesorias.com/wp-content/uploads/2019/07/Plan-de-ambiente-Paz-y-Desarrollo-Las-Quinchas-Boyac%C3%A1-final.pdf (accessed on 15 May 2023).
14. Paz, A.J. *Serranía de Las Quinchas: La Difícil Gestión de un Parque Colombiano Lleno de Conflictos Socioambientales*; Mongabay: Menlo Park, CA, USA, 2020.
15. Cunliffe, A.M.; Assmann, J.J.; Daskalova, G.N.; Kerby, J.T.; Myers-Smith, I.H. Aboveground biomass corresponds strongly with drone-derived canopy height but weakly with greenness (NDVI) in a shrub tundra landscape. *Environ. Res. Lett.* **2020**, *15*, 125004. [CrossRef]
16. Quintero, A.P.Y.; Navarrete, D.A.; Duque, A.J.; Phillips, J.F.; Cabrera, K.R.; Álvarez, E.; García, M.C.; Ordoñez, M.F. *Protocolo Para la Estimación Nacional y Subnacional de Biomasa-Carbono en Colombia*; Instituto de Hidrología, Meteorología, y Estudios Ambientales-IDEAM: Bogota, Colombia, 2011.
17. Puyravaud, J.-P. Standardizing the calculation of the annual rate of deforestation. *For. Ecol. Manag.* **2003**, *177*, 593–596. Available online: http://www.fao.org/ (accessed on 12 April 2023). [CrossRef]
18. Franco, R. Análisis Multitemporal Vectorial en ArcGIS. 2016. Available online: https://mixdyr.wordpress.com/ (accessed on 25 August 2023).
19. Instituto Geográfico "Agustín Codazzi", Subdirección Agrológica, and Universidad Pedagógica y Tecnológica de Colombia. *Estudio General de Suelos y Zonificación de Tierras del Departamento de Boyacá*; Instituto Geográfico Agustín Codazzi: Bogotá, Colombia, 2005.
20. Galindo, G.A.; Cabrera, E.; Vargas, D.M.; Pabón, H.R.; Cabrera, K.R.; Yepes, A.P.; Phillips, J.F.; Navarrete, D.A.; Duque, A.J.; García, M.C.; et al. *Estimación de la Biomasa Aérea Usando Datos de Campo e Información de Sensores Remotos, Versión 1.0*; Instituto de Hidrología, Meteorología y Estudios Ambientales-IDEAM: Bogotá, Colombia, 2011.
21. Alvarez, E.; Saldarriaga, J.G.; Cabrera, K.R.; Yepes, A.P.; Navarrete, D.A.; Phillips, J.F. *Selección y Validación de Modelos Para la Estimación de la Biomasa Aérea en Los Bosques Naturales de Colombia*; Instituto de Hidrología, Meteorología y Estudios Ambientales, IDEAM: Bogotá, Colombia, 2011.
22. Penman, J.; Kikan, C.K.S.K.; Intergovernmental Panel on Climate Change. National Greenhouse Gas Inventories Programme. In *Good Practice Guidance for Land Use, Land-Use Change and Forestry*; Institute for Global Environmental Strategies for the IPCC: Hayama, Japan, 2003.
23. Phillips, J.; Duque, Á.; Scott, C.; Wayson, C.; Galindo, G.; Cabrera, E.; Chave, J.; Peña, M.; Álvarez, E.; Cárdenas, D.; et al. Live aboveground carbon stocks in natural forests of Colombia. *For. Ecol. Manag.* **2016**, *374*, 119–128. [CrossRef]

24. Tang, X.; Hutyra, L.R.; Arévalo, P.; Baccini, A.; Woodcock, C.E.; Olofsson, P. Spatiotemporal tracking of carbon emissions and uptake using time series analysis of Landsat data: A spatially explicit carbon bookkeeping model. *Sci. Total Environ.* **2020**, *720*, 137409. [CrossRef] [PubMed]
25. Friedlingstein, P.; O'Sullivan, M.; Jones, M.W.; Andrew, R.M.; Gregor, L.; Hauck, J.; Le Quéré, C.; Luijkx, I.T.; Olsen, A.; Peters, G.P.; et al. Global Carbon Budget 2022. *Earth Syst. Sci. Data* **2022**, *14*, 4811–4900. [CrossRef]