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Carbon Sequestration in Protected Areas: A Case Study of an *Abies religiosa* (H.B.K.) Schlecht. et Cham Forest

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Abstract: The effects of global climate change have highlighted forest ecosystems as a key element in reducing the amount of atmospheric carbon through photosynthesis. The objective of this study was to estimate the amount of carbon content and its percentage capture in a protected *Abies religiosa* forest in which the study area was zoned with satellite image analysis. Dendrometric and epidometric variables were used to determine the volume and increase of aerial biomass, and stored carbon and its capture rate using equations. The results indicate that this forest contains an average of 105.72 MgC ha^{-1}, with an estimated sequestration rate of 1.03 MgC ha^{-1} yr^{-1}. The results show that carbon capture increasing depends on the increase in volume. Therefore, in order to achieve the maximum yield in a forest, it is necessary to implement sustainable forest management that favors the sustained use of soil productivity.

Keywords: climate change; protected forest; carbon sequestration; *Abies religiosa*

1. Introduction

The negative impacts of anthropogenic emissions of greenhouse gases such as irreversible damage to ecosystems, increased pressure on water resources, alterations in food production, and damage to human health, among others, have been reported in different studies [1–10]. The need to stabilize the carbon content of the atmosphere has been manifested in a series of international and local agreements and policies, such as the Kyoto Protocol and the Treaty of Paris. The purpose of these agreements and policies is to reduce emissions of greenhouse gases (GHG), with mechanisms to optimize carbon sinks.

Currently, forests store about 800 gigatons of carbon (GtC) [11] and it is estimated that by 2050 they could sequester up to an additional 87 GtC [12,13]. It was estimated that in the period between 2000 and 2007, the carbon sequestration rate of the world's forests averaged 4.1 $GtCyr^{-1}$ [14], corresponding to approximately 30% of fossil fuel emissions in 2010 [15].

Globally, protected forests have been proposed as a potentially cost-effective strategy to counter deforestation and degradation [16–18], favoring carbon permanence in the forest. Countries with the greatest threats from their forests due to degradation and devastation have increased their percentage of protected areas (Figure 1) in an attempt to conserve the environmental services of their forests [19,20]. Out of 3984 million hectares of forests in the world, 13.25% have a protected area status [21], and this percentage is mainly because of many of these protected sites partially fulfilling their conservation objectives [22], primarily derived from the budgetary constraints in which most of these areas operate. Financial resources managers for protected areas are increasingly emphasizing cost-effective aspects such as ecosystem services, including carbon sequestration [23].

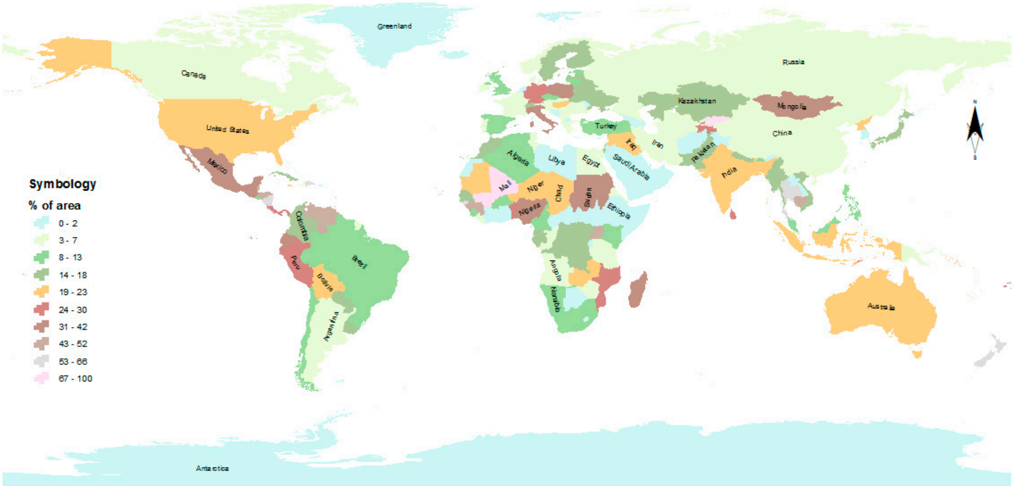

Figure 1. Percentage of protected area per country in 2015 in relation to its total forest area. Own elaboration with information of [24].

Currently, decision-makers can use a large number of methods to assess protected area management and prioritize investments, and there are over 70 methods that have been developed to provide standards for obtaining indicators, analyses, and interpretations [25,26]; however, none of these provide an estimation of carbon sequestration rates.

The present study aimed to estimate the carbon content in the above-ground biomass (baseline) of a forest of *Abies religiosa* (H.B.K.) Schlecht. et Cham., which is part of El Chico National Park, Hidalgo, Mexico. In addition, it attempted to ascertain the carbon capture rate from the annual volumetric increase of the species in the area. This information is necessary for designing the strategies that allow the environmental objectives that contribute to the reduction of the negative effects in climate change to be fulfilled.

2. Materials and Methods

2.1. Study Area

The study was carried out in the federal zone of the protected natural area called "El Chico National Park" located in the western area of the mountain range of Pachuca, in the state of Hidalgo, Mexico. Geographically, it is located between the extreme coordinates 20°11′57″ and 20°12′02″ north latitude and 98°43′08″and 98°43′06″ west longitude.

The area is owned by the Mexican nation and comprises 1,833,000 hectares [27]. The climate is C (m) (w) b (i′) gw, which is described as: a temperate-sub-humid climate with a fresh and long summer; the average annual temperature varies between 12 and 18 °C. The rainfall regime is in summer, and the percentage of winter rain in relation to the annual total is less than 5% [28].

The soil type is constituted by associations that group the following soil units: Humic cambisol-Androsol ocrico-Litosol, which has a volcanic origin association typical of mountainous zones, and humic Andosol-Humic cambisol, corresponding to forest soils associated with *Abies* and *Quercus* forests [29].

The predominant type of vegetation is *Abies religiosa* forest, which covers 67% of the park surface. The shrub stratum is dominated by the species *Archibaccharis hieracioides* Blake, *Baccharis conferta* H.B.K., *Eupatorium hidalgense* Rob., *Fuchsia thymifolia* H.B.K., *Ribes affine* H.B.K., *Salvia elegans* Vahl., *Senecio angulifolius* D.C., and *Stevia monardifolia* H.B.K. [30].

2.2. Description of the Species

The *Abies* forest is considered a component of the Leopold boreal forest [31] because of its similarity in terms flora, fauna, physiognomy, and ecological conditions to large forest masses covering northern parts of North America and Eurasia, and is also known as Taiga. This type of forest usually develops in an interval of altitude between 2400 and 3600 m, and its humidity requirement is high, registering precipitations superior to 1000 mm annually. They are dense forests, of heights that can reach up to 50 m, with canopies of a triangular contour; the high density conditions reduce the amount of light reaching the interior, which limits the development of shrubs and herbaceous species [32].

2.3. Forest Zoning

This process was performed to identify the areas where the species of interest is dominant. The stands were also identified where the species is mixed with other genera; however, these were excluded from the study. This concept is also known as stratification and consists of the division of the forest area into portions or spatial units called stands, with sections that possess similar physical and biological characteristics [33,34].

The identification of the stands was made through a RapidEye-4 satellite (provided by the Space Agency of the Mexican Government) image analysis dated 25 February 2015, with a spatial resolution of 5 m [35]. Initially, the image was corrected atmospherically and radiometrically [36]. Subsequently, it was estimated at the pixel level "Red Edge Normalized Difference Vegetation Index" ($RedEdge_{NDVI}$) [37–41].

$$RedEdge_{\ NDVI} = \frac{R710 - R705}{R710 + R705} \tag{1}$$

where R710 is the band 4 RedEdge or near red and R705 corresponds to the band 3 RedEdge. The NDVI has been used in the elaboration of the process of forest logging, and it is mentioned that it has shown acceptable results in the identification of vegetal associations.

The RedEdge NDVI results were analyzed along with altitude, latitude, and exposure values to determine the final logging through an overlay positioning process.

The obtained image analysis was validated with the records obtained through field trips. The existing vegetation types and the boundaries between them were determined by georeferenced points.

2.4. Field Information

Sampling Design and Characteristics of Sites

A random sampling design was used to define the location of 33 circular sampling sites of 1000 m^2, in which a total of 682 trees were measured. The shape and size of the sites were suitable for the purpose pursued since they have shown good results for the calculation of volumetric stocks or biomass content [42,43].

At each sampling site, the diameter information at the breast height (dap) of all trees with a diameter equal to or greater than 7.5 cm and the total height of each tree [44] was recorded. For the determination of the number of annual growth rings in 2.5 cm, known as passage time, an average tree per diameter category was selected at each sampling site by means of a 250-mm Haglöf® Presser (Haglöf, Langsele, Sweden) drill and the results were calculated as the annual volumetric increase per hectare [45], which was subsequently used for estimating carbon sequestration.

2.5. Information Processing

2.5.1. Calculation of Volumetric Stocks

With the records of each stand, we proceeded to estimate the value of the variables basal area and timber volume [36,46]. The basal area for each tree was obtained by the following equation:

$$B_A = \frac{\pi}{4} * D_{bh}^2 \tag{2}$$

where B_A is the basal area (m^2) and D_{bh} corresponds to the diameter at breast height (m), which were grouped in diametric categories of 5 cm.

The volume per hectare per stand was determined through a procedure known in the forest as the average hectare [47] by employing the following equation:

$$\overline{V}s = \sum_{i=1}^{DC} \left(B_{Ai} * \overline{H} * M_{Ci} * E_{Fi} * N_{Ti} \right) \tag{3}$$

where $\overline{V}s$ corresponds to the total volume (trunk + branches + leaves + roots) of the woodland per hectare (m^3); DC is the number of diametric categories in the stand; i is the diameter category; B_A is the basal area of the average tree by diameter category (m^2); $\overline{H}$ corresponds to the average height of the trees in the stands for each diameter category (meters); M_C is the morphic coefficient for gender Abies; E_F is the expansion factor of stem to total volume (branches, leaves, and roots) [48]; and N_{Ti} is the number of trees per hectare per diameter category.

2.5.2. Volumetric Increment

The calculation of the increment of the forest mass for each of the stands was obtained by means of the "Klepac Fast" method, which relates the number of trees per diameter category per hectare, the volume of the tree type for each diameter category, and the step time for each case [45,49]. This method considers a series of calculations between these three variables to obtain the percentage of the increase by the following equation:

$$P = \frac{1000}{Dbh} * \frac{1}{T} \tag{4}$$

where P corresponds to the percentage of increase, Dbh is the diameter at breast height, and T is the step time. It is worth mentioning that this parameter was used to obtain the carbon sequestration rate.

2.5.3. Aerial Biomass Content

This information was obtained by the equation developed by Avendaño et al. [50], for the calculation of biomass for *Abies religiosa* based on the diameter at breast height.

$$B = 0.0713\ D_{bh}^{2.5104} \tag{5}$$

where B is the total biomass of the tree (Mg) and Dbh is the diameter at breast height (m).

2.5.4. Carbon Content

The estimated carbon content for each tree was calculated using the equation developed for this species, which is based on the diameter at breast height [50].

$$A_{CC} = 0.0332\ D_{bh}^{2.5104} \tag{6}$$

where A_{CC} is the carbon content for *Abies religiosa* (Mg) and D_{bh} is the diameter at breast height (m).

The carbon content for each diameter category was obtained by the following equation:

$$Dc_{cc} = A_{cc} * N_T \quad (7)$$

where Dc_{cc} is the carbon content by diameter category (Mg), A_{cc} is the carbon content per tree (Mg), and N_T is the number of trees of the corresponding diametric category.

The carbon content per hectare was obtained by adding the carbon content from all the diametric categories.

2.5.5. Carbon Sequestration Rate

After calculating the carbon content per hectare and after having determined the volumetric increments, the carbon capture rate for each stand was determined, considering that the increment parameter refers to the volume increase per unit time. Once the amount of biomass that this forest can generate in a certain time period was obtained, the carbon stored was calculated using the following equation:

$$\overline{C}_{SR} = (\overline{C}_C / \overline{V}s) * C_{AI} \quad (8)$$

where $\overline{C}_{SR}$ is the rate of carbon sequestration per hectare per year (Mg), $\overline{C}_C$ is the carbon content (MgC ha^{-1}), $\overline{V}s$ corresponds to the volumetric stocks (m^3 ha^{-1}), and C_{AI} is the current annual increase (m^3).

3. Results

3.1. Forest Zoning and Field Information

Of the total area studied, eight stands were identified, with *Abies religiosa* covering an area of 1229.65 hectares. The rest of the area (603.35 hectares) corresponds to rock formations and other types of vegetation such as *Quercus*, *Juniperus*, and grassland. The study was addressed to *Abies religiosa* since it is the conservation species of interest in this protected area (Figure 2).

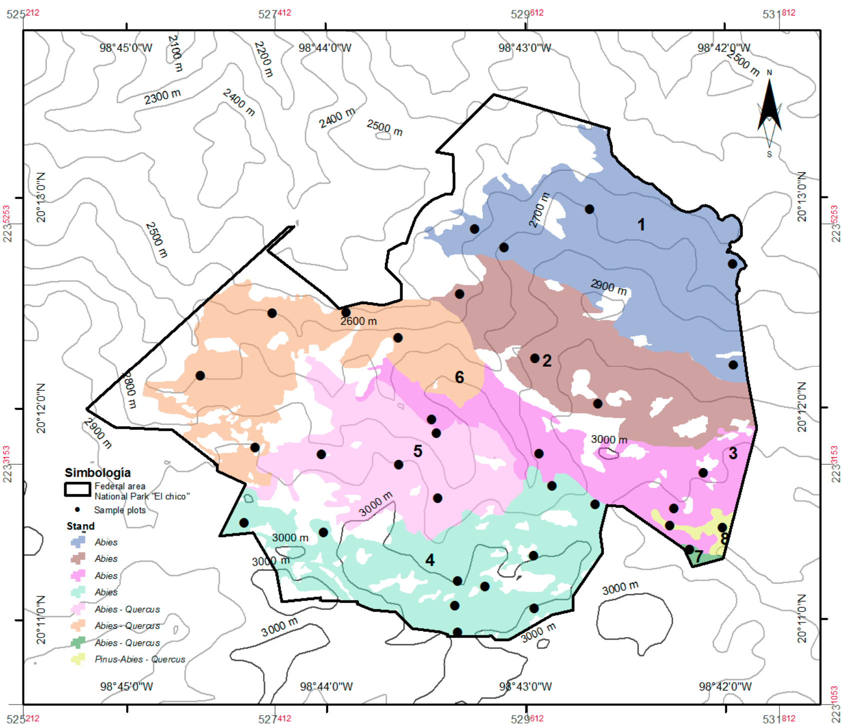

Figure 2. Forest zoning obtained through the analysis of satellite images in combination with altitude information, orientation, and slope.

The Table 1 show the values of the NDVI together with the land orientation, as well as the slope range that exists in each one of the stands, for which the criteria for the realization of the forest zoning were the values of NDVI, orientation, and species composition.

Table 1. Criteria and values used for forest zoning.

Stand	NDVI			Orientation	Slope	Species Composition
	Mean	Min	Max			
1	0.3495	0.1764	0.4350	North	10–25°	*Abies*
2	0.3709	0.2043	0.4681	North	10–25°	*Abies*
3	0.3678	0.3016	0.4806	Southeast	10–25°	*Abies*
4	0.3900	0.2004	0.4613	Northwest	10–25°	*Abies*
5	0.3849	0.2773	0.4510	Northwest	10–25°	*Abies-Quercus*
6	0.3603	0.2751	0.4360	North	10–25°	*Abies-Quercus*
7	0.3849	0.3228	0.4228	East	10–25°	*Abies-Quercus*
8	0.3441	0.2841	0.4064	Northwest	4–9°	*Abies-Pinus-Quercus*
Other *	0.2753	0.0228	0.3990	-	-	-

* Refers to other uses or plant formations, "-" refers to not obtained.

3.2. Volumetric Stocks

The total volume is 757,681.69 m^3, and the average volumetric stock per hectare is 616.18 m^3. Table 2 details the *Abies religiosa* volumes for each stand.

Table 2. Volume in m^3 per stand.

Stand	Surface (Hectares)	Number of Trees ha^{-1}	Basal Area m^2 ha^{-1}	Volumetric Stocks m^3 ha^{-1}	Volumetric Stocks m^3 $Stndl^{-1}$
1	263.43	220	47.37	771.57	203,252.50
2	194.20	210	35.18	716.46	139,139.25
3	153.63	210	32.63	672.41	103,299.63
4	223.27	282	40.44	789.37	176,238.35
5	178.26	140	22.02	462.22	82,392.82
6	203.92	70	11.86	239.33	48,805.67
7	3.29	270	36.84	727.16	2524.82
8	9.66	140	12.37	223.86	1770.21

Stands 1, 2, 3, 4, and 7 have a density of more than 200 trees per hectare, a basal area greater than 30 m^2, and a volume that exceeds 670 m^3 ha^{-1}. Stands 5, 6, and 8 have densities of less than 150 trees per hectare and volumes below 470 m^3 ha^{-1}, which is due to the presence of disturbances such as forest fires and pests that have affected the density per unit area.

3.3. Volumetric Increment

Table 3 presents the results of the calculation of volumetric increase, for which we considered the records of 165 trees. It can be observed that stands 4, 5, and 6 present smaller times of passage in relation to the rest of the stands, probably due to the age and density of the forest mass. The highest productivity is found in stands 1, 4, and 5, where the area of these stands also influences the result.

Table 3. Result of calculating volumetric increments.

Stand	Sampling Plot	Step Time Average	Drilled Trees	Current Annual Increase	
				m^3	%
1	4	19	20	6.616	3.007
2	3	22	15	4.440	2.114
3	4	24	20	4.870	2.319
4	9	17	45	7.077	2.508
5	5	16	25	5.261	3.758
6	4	15	20	2.605	3.722
7	2	23	10	4.662	1.554
8	2	26	10	1.164	0.831

3.4. Carbon Content

The estimate of the total carbon content is 130,004.02 Mg, with an average per hectare of 105.72 MgC. The results for each stand are shown in Table 4.

Table 4. Carbon content per hectare and per stand in megagrams.

Stand	Surface ha^{-1}	Content of C ha^{-1} (MgC)	Content of C $Stand^{-1}$ (MgC)
1	263.43	164.25	43,268.71
2	194.20	110.92	21,540.97
3	153.63	100.44	15,430.38
4	223.27	129.55	28,925.22
5	178.26	70.95	12,646.44
6	203.92	36.25	7392.48
7	3.29	120.68	396.63
8	9.66	41.72	403.18

3.5. Carbon Sequestration

The result for the carbon capture rate in the *Abies religiosa* aerial biomass is 1267.66 MgC yr^{-1}, considering the studied area, with an average of 1.03 MgC yr^{-1} per hectare.

Stands 1 and 4 have higher volumetric increments. Consequently, the sequestered carbon is higher in relation to the rest of the stands (Figure 3), and this can be attributed to the north orientation of the surface where the insolation is less and more moisture is available. Stand 6 is located in a transition zone with the presence of other tree genres that were not counted but that compete with the *Abies*, decreasing its density, due to the fact that the volume and increase of biomass is reduced. Stand 8 presents a situation similar to the previous stand, only in this case the mixture of genera is due to anthropic activities (reforestation).

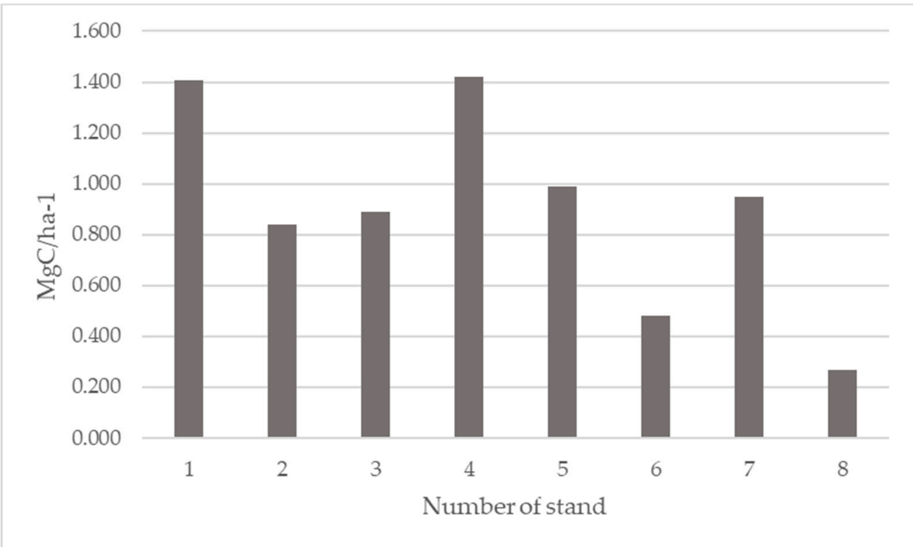

Figure 3. Annual carbon sequestration per hectare in megagrams.

Carbon sequestration in stand 1 is the one with the highest catch mainly due to the surface area and annual increment, followed by stand 4. The strata with the least carbon sequestration are the ones with the lowest surface area and the lowest density of trees (Figure 4).

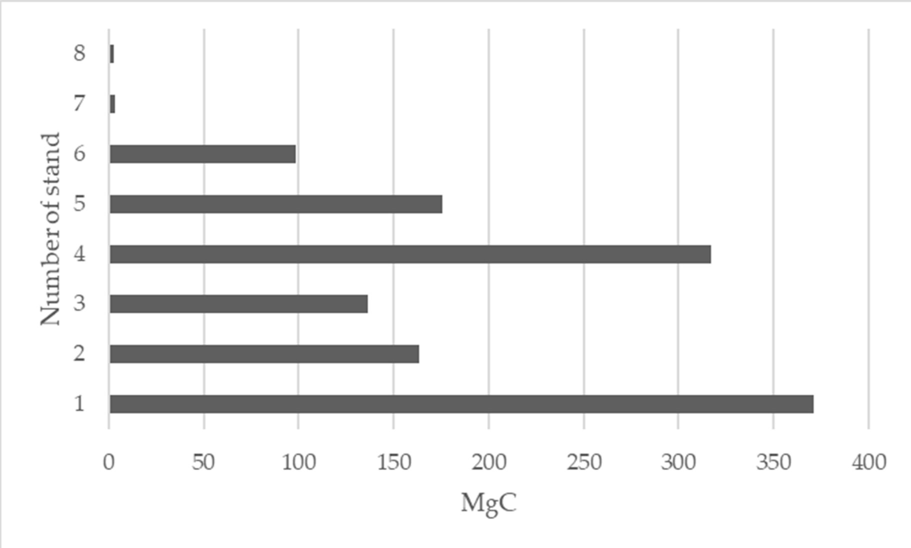

Figure 4. Annual carbon capture above-ground per stand.

4. Discussion

4.1. Carbon Content

The area of study corresponds to a protected area decreed in 1898, in which the conservation policies that prevent the modification of the forest structure have caused the longevity of this mass, placing it in the last stage of development (old fustal), and this is derived from the age and diameters present. Diameters greater than 1.10 m were recorded, while the smallest diameter registered was 7.5 cm. On average, the number of trees per hectare is 193, with a volume of 616.18 m^3. Table 5 presents comparative information of estimated carbon in protected areas with the presence of *Abies religiosa*.

Table 5. Comparison of studies in protected forests where they have calculated the carbon content in aerial biomass in *Abies religiosa*.

Author	Place of Study	Status of the Area	Species	Carbonor Estimated Mg ha^{-1}	Observations
Present study	Hidalgo, Mexico	Protected	*Abies religiosa*	105.72	Long-lived forest mass and scarce natural regeneration.
[51]	Mexico City, Mexico	Protected	*Abies religiosa*	117.00	The author makes reference to 3 associations *Abies religiosa* with shrub and/or herbaceous species. It is not mentioned the method to determine the carbon content.
[52]	Mexico City, Mexico	Protected	*Abies religiosa*	136.41	A conserved forest was studied.
[53]	Hidalgo, Mexico	Protected	*Abies religiosa*	138.62	The author details 3 carbon scenarios for this type of forest, in which include disturbed areas, the area studied was 212.95 hectares.
[54]	Veracruz, Mexico	Protected	Various conifers	146.30	It is a protected forest, the authors detail scenarios where the species of *Abies religiosa* is combined with other conifers.
[55]	Mexico State, Mexico	Protected	*Abies religiosa*	163.62	A similar methodology was used to calculate the carbon content.

There are several hypotheses about the carbon content in forest ecosystems. This storage is dependent on the amount of existing biomass, which depends on the age, diameter, and height of the trees. When woodland density is affected or altered for some cause such as: pests, diseases, forest fires, clandestination, or harvesting, the carbon content per unit area is also altered [56]. The silviculously managed forests have young stands as a result of the application of silvicultural treatments [57], where the stands with a higher density and basal area are those containing more volume of above-ground biomass, and consequently, more carbon content.

The records consulted about carbon contents in protected temperate forest are $\geq$115 MgC ha^{-1} [51–55], whereas this study estimated more than 105.72 MgC ha^{-1}. These differences can be attributed to several factors such as the quality of the site studied, and the density and age of the trees, among others. Unlike the preserved forests, disturbed forests contain less carbon, due to the affected forest mass. Aguirre et al. [57] mentions that for a managed forest of *Pinus patula* with an orientation that is contemporary, the content is 63.98 MgC ha^{-1}.

In the case of protected forests or silvically managed forests, the ecosystem service of carbon storage is fulfilled, whereas in the case of harvested forests, the carbon content is lower and mainly depends on applied silvicultural treatments. For the production of coetaneous masses, the content is variable and dependent on the age, diameter, height, and density of the trees in a given stand. The present study considers there to be 48% more carbon content in El Chico than the data provided by Aguirre et al. [57]. Masera et al. [58] mentions that managed forests with a temperate climate contain 118 MgC ha^{-1} or 10% more than the estimated data in this study. The differences between Aguirre and Masera information can be mainly attributed to the applied silvicultural system (intensive or conservative).

4.2. Carbon Sequestration

Forest ecosystems sequester carbon and are considered as an option for the mitigation of the effects of an increasing atmospheric CO_2 load [59–62]. The potential for carbon of any forest species depends on the maximum amount of biomass it can produce per unit of time. In species of accelerated growth, this parameter is relatively fast reached, whereas in species with a slow growth, the period of time required to reach the maximum biomass content is longer, and consequently, carbon sequestration is higher [63].

The volumetric increases represent the parameter which is able to determine the rate of carbon sequestration, and for the case presented in this study, the *Abies religiosa* forest captures 1.03 MgC ha^{-1} yr^{-1}, which is equivalent to 3.78 $MgCO_2$ ha^{-1} [64], with an annual average increase of 2.92%. Because it is located within a protected area, the forest mass has not been altered, which has caused the increment curve to decline. As the age of the mass increases, the increments decrease [45], and as a consequence, the potential for carbon capture is also affected.

Compared with protected forests, sustainably harvested forest areas capture more carbon [65], which is mainly due to the management of the age factor within the masses. Similarly, the use of harvested biomass for the production of long-lasting products retains carbon for long periods of time [66,67]. There are records of carbon capture in managed forests that exceed the results obtained in this study. Liu et al. [68] estimated net biomass productivity for forests in the Appalachian region where the forest harvest exists, and reported data ranging from 1.8 to 6.2 MgC ha^{-1}. Zhang et al. [69] estimated a value of 2.4 MgC ha^{-1} captured for a Massonian *Pinus* forest in China. For the specific case of *Abies religiosa* with the information of Manzanilla et al. [70], we can estimate 3.1 MgC ha^{-1}. The differences between these investigations and the estimated rate in this study can be attributed to factors such as: forest management, location of the studied area, and species, among others. Navarro et al. [65] mentioned that these results cannot be cofrontable since they correspond to different ecosystems, each with their own particularities.

Unlike carbon content, the rate of sequestration is influenced by forest management techniques; in protected forests, the amount of stored carbon is higher, but the catch rate is reduced. With sustainable forest management practices, this difference can be balanced.

Forest management should be included in protected forests, and it is desirable to consider aspects that relate the conservation of species and their habitats with the carbon storage outside forest areas. The extraction of biomass for the elaboration of long-lasting products such as furniture or infrastructure is a way to reduce the risk of leakage within this type of ecosystem, reducing the carbon content inside a warehouse, so that emissions risks are reduced and capture is encouraged by stimulating increases in forest mass in order reach the maximum biomass production potential.

5. Conclusions

The methodology used for the evaluation of a protected forest of *Abies religiosa* as aerial carbon storage and its capture capacity is adequate and reproducible in areas with similar conditions where it is not possible to use destructive methods. The use of high resolution satellite images combined with the analysis of physical aspects of the terrain allowed for detailed zoning directly related to the density of the forest mass, and its amount of biomass and carbon.

The results presented denote that the amount of carbon stored above-ground is directly related to the density and degree of disturbance. In this case, because it is a protected forest where the silvicultural activities are restricted, the productivity of the mass is lower, and consequently, the rate of carbon sequestration decreases.

The quantified carbon additionality is a parameter that depends on several factors, for which the age of the forest mass is considered one of the most important, and in the young and vigorous forests, the rate of sequestration is higher than in forests of advanced stages of development. In this study, *Abies religiosa* caught 1.03 MgC ha^{-1} yr^{-1}, with an annual average increase of 2.92%.

The implementation of silvicultural techniques governed by forest management with correct principles, foundations, and objectives greatly contributes to the reduction of atmospheric carbon. Within protected forests, the application of forest management techniques makes it possible to obtain sustainable forests and maximize the potential of forest soils to increase this important ecosystem service.

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