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Chapter 2

Biomass Accumulation and Carbon Storage in *Pinus maximinoi*, *Quercus robur*, *Quercus rugosa*, and *Pinus patula* from Village-Forests of Chiapas, Mexico

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Abstract

The Frailesca region (Chiapas, Mexico) presents a lack of forest studies and its environmental contribution. This chapter displays a first case study with preliminary research information regarding the identification of main forest trees and rural villages with best potential for biomass production and carbon storage management. Twenty two plots of 500 m^2 were selected in 11 villages of the region, in order to identify the main and dominant forest trees species and then to estimate the biomass production and carbon storage in pine (*Pinus maximinoi*), oak (*Quercus robur*), holm oak (*Quercus rugosa*) and Mexican weeping pine (*Pinus patula*) species. This study shows that the largest accumulation of both biomass and carbon occurred in the pine forests and the lowest in the oak forests. Pine trees showed carbon storage of 516.75 Mg ha^{-1}, followed by holm oaks,

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with 297.21 Mg ha^{-1}; the species with the lowest value was oak, with 75.02 Mg ha^{-1}. The forests of the *24 de* Febrero villages had the highest potential for carbon storage. Deep studies are being conducted in relation to the aboveground biomass, carbon contents in trees stem, branches and leaves, and the relation to biomass dynamics and carbon stocks and other ecological aspects of village-forests.

Keywords: total biomass, carbon sequestration, allometric relationships, tropical forest

1. Introduction

The role and importance of forests in environmental issues like carbon sequestration has been evaluated by many researchers, e.g., Cook et al. [4]; de Jong et al. [10] and Dixon et al. [9]. These analyses suggest that forest conservation and their sustainable management can contribute to global carbon sequestration and conservation while providing goods and services for rural communities of many countries. De Jong et al. [10] stated that forestry and agroforestry can compensate for greenhouse gas emissions in two ways: (i) by the creation of new sinks for carbon dioxide by increasing the mass of woody material within growing trees; and (ii) through the safeguard of endangered natural forests and soils which are carbon stores.

In Mexico, conifer and broadleaf forests occupy 15.4% of the national territory; managed forests cover 7.3 million hectares, while protected forests cover 7.1 million hectares [32]. On the other hand, nearly 80% of the forest areas are communal property, and 95% of the forest exploitations originate mainly from the native temperate forests [22].

In the state of Chiapas, these forests cover 1,117,248 ha, and the rainforests occupy 2,175,948 ha [32]; therefore, the entity has the second place nationally for forest surface area and timber extraction from pine, cypress, sweetgum, holm oak, Rosy trumpet, amate ficus, cedar, and mahogany trees. In addition, its vast forest cover confers it a great potential for CO_2 sequestration.

Forest ecosystems can capture significant amounts of greenhouse gases (GHG), particularly CO_2. For this reason, in the recent decades, there is considerable interest in increasing the carbon content of the vegetation through the preservation of forests, reforestation, the creation of forest farms, and other land management methods. A great number of studies have demonstrated the ability of forest species to store carbon in their biomass [2, 26, 29, 31].

Each year, these forest areas store significant amounts of biomass that contribute to reduce carbon levels in the atmosphere [8, 23], which acquire greater significance if we consider that the CO_2 content in the atmosphere has augmented since the industrial revolution, and estimations indicate that in the twenty-first century this tendency will increase further [6, 28, 35]. All this indicates that anthropic activities have caused disturbances that contribute to the deterioration of the ecosystems [7].

Various studies performed in Mexico have proven the potential of forests to capture atmospheric carbon. Masera et al. [22] created a model simulating carbon capture during the 2000–2030 period, which divided land use into forests, rain forests, arid zones, and nonforest uses. These authors used two scenarios: the first, referred to as "baseline," and the second, as "policies." If the proposed options derived from their results were to be adopted, Mexico would

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be able to capture approximately 46 million tons of carbon during the 2000–2030 period. Part of this mitigation would be achieved as follows: (a) by preventing deforestation, (b) through sustainable management of the natural forests, and (c) by restoring the degraded forest areas.

CO_2 is one of the main components of GHGs and is produced by human activities when fossil fuels are utilized to generate energy and to meet other demands of the society. Deforestation processes, land-use changes, and methane concentrations resulting from agricultural and stockbreeding activities also promote climate change [35].

The increase in GHG concentrations in the atmosphere has caused the "greenhouse effect" phenomenon, which has resulted in changes in the climatic scales of the Earth [21]. The increase of CO_2 in the atmosphere produces extreme climatic events such as floods caused by hurricanes, which result in regrettable losses of human lives as well as economic losses [20].

According to Alberto and Elvir [2], carbon sequestration has been the object of study of forest research in various countries. Montero and Kaninnen [25] point out that, in southern Costa Rica, the production of aboveground biomass and carbon sequestration in managed *Terminalia amazonia* (J. F. Gmel.) plantations after 10 years was of 97.03 and 45.30 Mg ha^{-1}, respectively. In central Honduras, the production of aboveground biomass was of 80.53 Mg ha^{-1} in natural *Pinus oocarpa* forests. Carbon storage in the aboveground biomass of the pine forests of the *La Majada* village in Michoacán, Mexico, amounted to 28.85 Mg ha^{-1}, while in the conifer forests of *Tancítaro*, Michoacán, Mexico, the annual capture and storage of carbon in the aboveground biomass added up to 19.00 and 1.65 Mg ha^{-1}, respectively [13]. Based on the lack of forests studies and their potential contribution to the mitigation of climate change, the purposes of this case study were (a) the generation of basic and preliminary information about the main forest trees species and (b) the identification of rural villages with best potential regarding biomass production and carbon storage. Thus, to estimate the pine, holm oak, Mexican weeping pine, and oak forests in the forest areas from rural villages of the Frailesca region, as well as to determine the relationship between the age of trees and biomass production, allometric relationships were used.

2. Methodology

2.1. Location

The Frailesca region is made up of valleys and plains dominated by monoculture maize fields with Green Revolution technologies, surrounded by vast mountainous zones. The region is composed of six municipalities: *Villaflores, El Parral, la Concordia, Angel Albino Corzo, Montecristo de Guerrero*, and *Villa Corzo*, where traditional farming systems are practiced in small villages located within the natural forests from two natural protected areas, *La Frailescana* and *La Sepultura* reserves.

Climate is warm and semiwarm; the most predominant subclassifications are warm subhumid with occasional summer rain, followed by semiwarm humid with abundant summer rain. From May to October, the minimum average temperature ranges from 12 to 21°C (18 to 21°C in 54.9% of the region and 15 to 18°C in 37.8% of the region), while the maximum average temperature ranges from 21 to 34.5°C (30 to 33°C in 35.2% of the region and 27 to 30°C in

29.34% of the region). Average annual precipitation from May to October varies from 1000 to 2600 mm. From November to April, minimum average temperature ranges from 9 to 15°C, with averages of 12 to 15°C in 92.96% of the region, while the maximum ranges from 21 to 33°C, with averages of 27 to 30°C in 49.3% of the region and 33°C in 27.2% of the region.

The research was carried out in Villa Corzo municipality, in forest areas of 11 rural villages of La Frailesca region (**Figure 1**, **Table 1**), located between the coordinates 16°11′05″ N and 93°16′03″ W, at a mean altitude of 584 m above the sea level [3]. This municipality has a subhumid warm climate with abundant summer rains that prevails in the study area. The minimum annual precipitation is 1200 mm, and the maximum is 3000 mm, distributed among 100 and 200 days a year. The soils are affected by silt erosion precipitated by the action of the wind and by river floods; its fertility is variable, with its agricultural use conditioned by its depth and stoniness [3]. The localities have a vegetal cover that consists mainly of conifer forest secondary vegetation; montane cloud and holm oak forests; and deciduous, subdeciduous, and evergreen rainforests.

2.2. Plot selection and estimation of total biomass production and carbon storage

Dasometric data were recorded for the twenty-two 500 m^2 sampling plots (two in each village). This information was entered into a database which included data of 358 individuals of the following species: *Pinus maximinoi* H. E. Moore (pine), *Quercus robur* L. (oak), *Quercus rugosa Neé* (holm oak), and *Pinus patula* Schiede ex Schltdl. & Cham. (Mexican weeping pine) (**Table 1**).

The age of the trees was determined using a Pressler drill, as well as based on information provided by the common land holders; the normalized diameter formerly known as diameter at breast height (ND) was measured with a diameter measuring tape and the height (H) of the main stem with a clinometer [15].

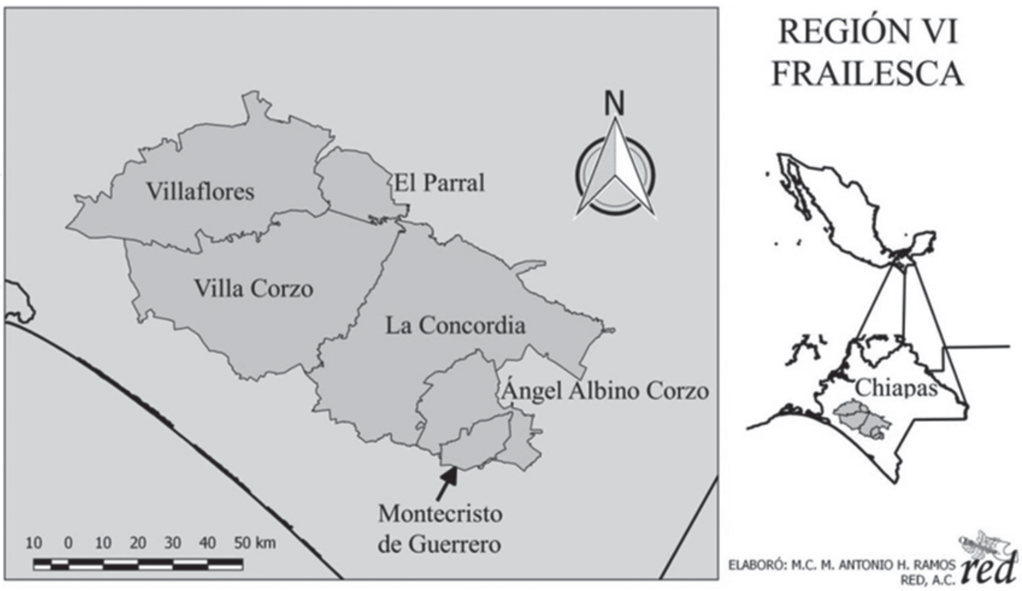

Figure 1. Location of Villa Corzo municipality in La Frailesca region (Chiapas, Mexico). Source: RED AC [36].

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Villages	500 m² plots			
	Pine	Holm oak	Oak	Mexican weeping pine
24 de Febrero	+	+		
Monterrey			+	
Patria Chica			+	
La Frailesca				+
Juan Sabines Gutiérrez	+			
Bonanza		+		
La Libertad			+	
Tierra Santa	+			
La Unión	+			
Nuevo Refugio				+
Unión del Carmen			+	

Table 1. Distribution of plots in the rural villages and by the identified main forest species.

The stem volume (*V*; m^3) was calculated using the following equation:

$$V = \frac{\pi}{4} \cdot H \cdot ND \cdot SC \quad (1)$$

where *H* = tree height (m); *SC* = shape coefficient (**Table 2**); *ND* = normalized diameter (m).

In order to estimate the stem biomass, the total volume was multiplied by the density of each of the species (**Table 2**) [16]. The carbon sequestration was estimated by multiplying the biomass by 0.50, a value that represents the mean concentration of carbon for conifers [18] and a value cited in the Green House Gas Inventories of the forestry sector for Mexico [20].

The value of the biomass production in the various parts of the tree was determined based on the biomass expansion factors (BEF) and shape coefficients (SC) published by González [16] (**Table 2**), using the following expressions:

Stem biomass (*SBM*)

$$SBM = V \cdot r \quad (2)$$

where *SBM* = stem biomass (kg); *V* = stem volume (m^3); *r* = wood density (kg m^{-3}) (**Table 2**).

Tree aboveground biomass (*AGBM*)

$$AGBM = SBM \cdot BEF \quad (3)$$

Species	SC	r (kg m⁻³)	BEF
Pinus maximinoi H. E. Moore	0.52	507	1.25
Quercus rugosa Neé	0.39	650	1.27
Quercus robur L.	0.39	650	1.27
Pinus patula Schiede ex Schltdl. & Cham	0.25	507	1.25

Table 2. Biomass expansion factors (BEF), shape coefficients (SC), and density (r) of the studied species.

where *AGBM* = tree aboveground biomass (Mg); *SBM* = stem biomass (Mg); *BEF* = biomass expansion factor.

Root biomass (*RBM*)

$$RBM = AGBM \cdot 0.30 \tag{4}$$

where *RBM* = root biomass (Mg); *AGBM* = tree aboveground biomass (Mg).

2.3. Statistical analyses

The differences in the total biomass produced among species and between tissues were determined by processing the data through an ANOVA. Frequency histograms were created for the age and the normalized diameter (ND), and nonlinear regression analyses were carried out between the tree height and normalized diameter (ND) variables, as well as between the total biomass (TBM) and the tree's age by species. The mean comparison was carried out using Tukey's test for $p \leq 0.05$ [33]. Previously to all the statistical analyses, the assumptions of normality and of variance homogeneity were also verified using the STATISTICA®, version 8.0 software [33].

3. Results and discussion

The histogram of tree age by species shows that the pine plots reflected a rather heterogeneous distribution, with 12% of the trees aged 40–50 years (**Figure 2**), followed by 10% of trees aged 90–100 years. The age of holm oaks ranged between 20 and 70 years, with 10% of the individuals in an age interval of 30–50 years. The oak forests had 95 trees aged 20–40 years, while 18% of the trees of Mexican weeping pine forests aged 30–60 years (**Figure 2**). The largest number of trees with ND values of 0.1–0.4 m were oaks, followed by pines and Mexican weeping pines (**Figure 3**). In every case, like for the tree age, the highest degree of heterogeneity was found in the pine plots, with ND values ranging between 0.13 and 1.02 m (**Figure 3**). The interval between maximums, minimums, and ND (**Table 3**) made it possible to determine that the species with the highest variability were pine, holm oak, oak, and Mexican weeping pine, in this order (**Table 3**).

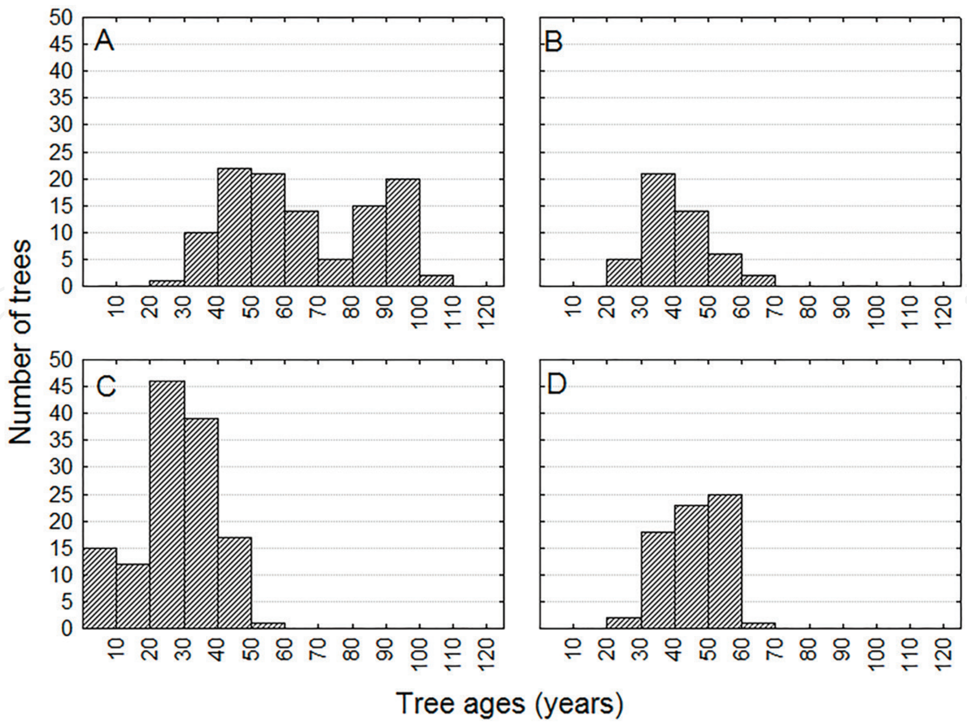

Figure 2. Frequency histograms of tree ages sampled by species in La Frailesca region (Chiapas, Mexico). A: Pine; B: Holm oak; C: Oak; D: Mexican weeping pine.

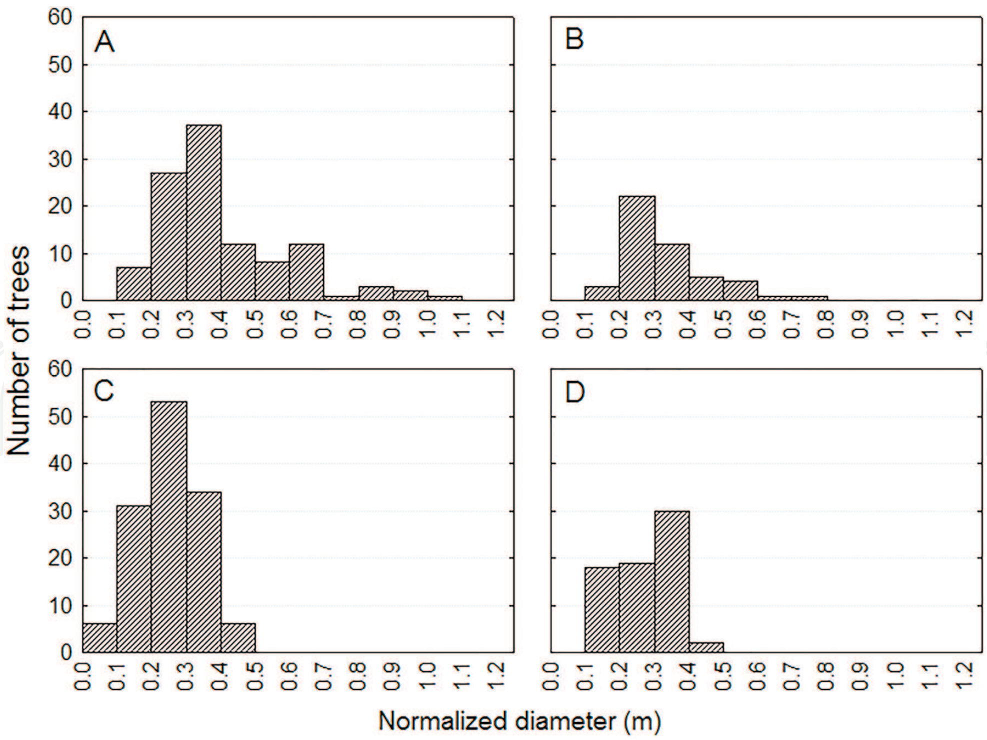

Figure 3. Frequency histograms of the ND of the sampled trees by species in La Frailesca region (Chiapas, Mexico). A: Pine; B: Holm oak; C: Oak; D: Mexican weeping pine.

Species	Mean	Maximum	Minimum	Range
	m			
Pinus maximinoi H. E. Moore	0.40	1.02	0.13	0.89
Quercus rugosa Neé	0.33	0.75	0.15	0.60
Quercus robur L.	0.26	0.46	0.05	0.41
Pinus patula Schiede ex Schltdl. & Cham	0.27	0.40	0.10	0.30

Table 3. Intervals between the maximums, the minimums, and the normalized diameters (NDs) of the studied species.

Given the close relationship observed between the ND, the age of the trees, and biomass production and carbon sequestration in various forest species [11, 12, 15], it is possible to understand the capacity of these village-forests to capture carbon from the atmosphere, particularly if it can be proven that the total biomass produced and the captured carbon increase with the age of the trees. The relationship between the height and the ND of the species was adjusted to an exponential model (**Figure 4**) called allometric, previously cited by Acosta et al. [1] and Gómez-Castro et al. [15].

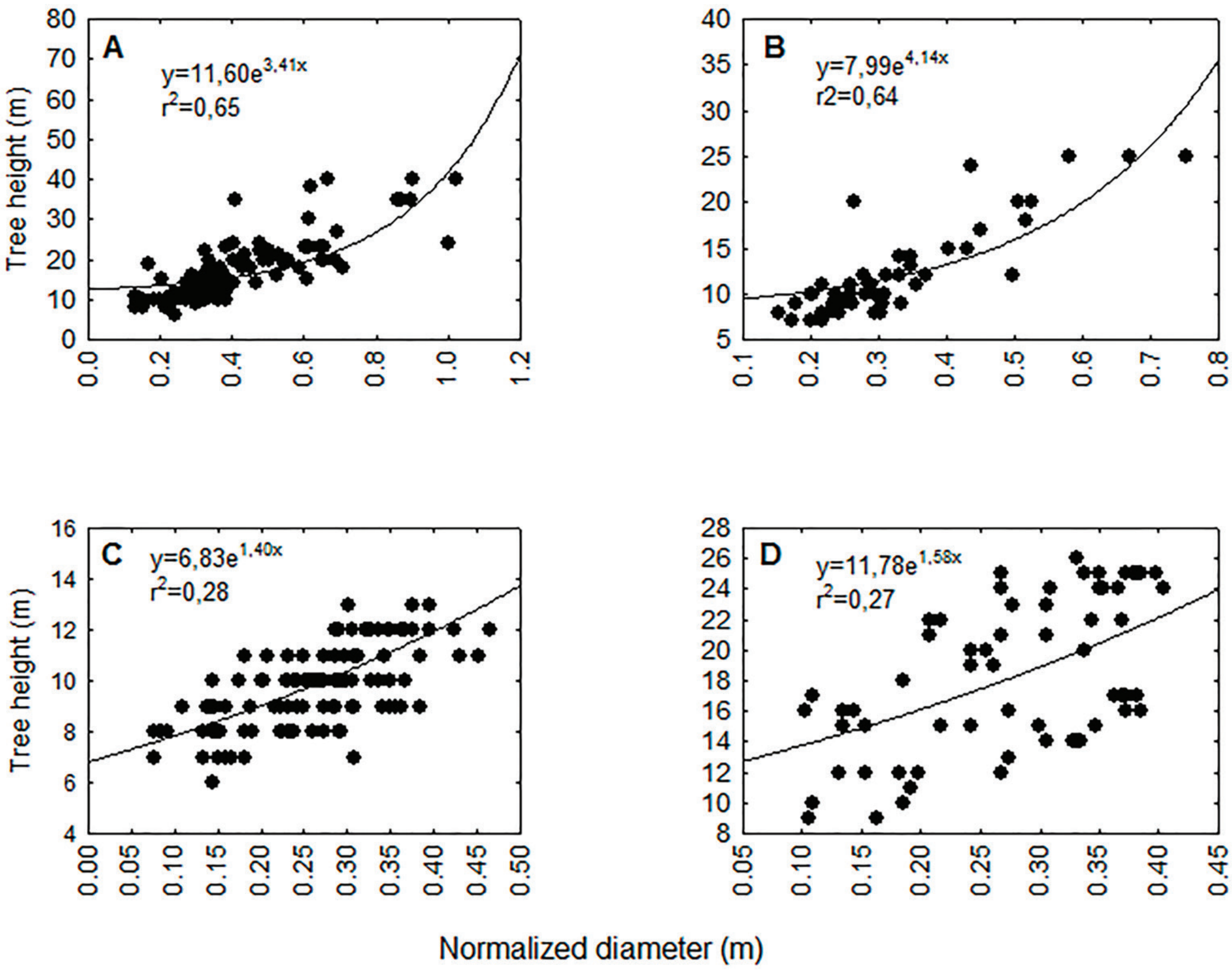

Figure 4. Exponential regression models of adjustment between the height and the ND of the studied species of La Frailesca region (Chiapas, Mexico). A: Pine; B: Holm oak; C: Oak; D: Mexican weeping pine.

The highest determination coefficients (r^2) were observed in pines and holm oaks, which also had the broadest interval between tree ages and NDs. For all the species, the mathematical adjustment produced a statistical significance of the model parameters, according to the Student's t-test (**Table 4**), a fact that corroborates the selection of the exponential model to estimate tree heights through the normalized diameter, although it suggests the need to delve into the effect of the normalized diameter interval, for which the best estimates were obtained.

For all species, the ratio of the total biomass of the tree (BMt) and the age was significantly fitted according to an exponential model (**Figure 5**, **Table 5**), with determination coefficients ranging between 0.56 and 0.85. Similar results were obtained by Rodríguez et al. [30] for the allometric relationships between the biomass production and the age of the pine trees. This result corroborates the biomass and carbon estimation studies based on the ND and ratifies the relationship between tree age and the photosynthetic processes that trigger biomass and carbon storage [27].

According to Fonseca et al. [12], both the aboveground biomass and the root biomass increase with the age in secondary forests and forest plantations. Hughes et al. [19] register an average biomass of 272.1 Mg ha^{-1} at 16 years of age. Corrales [5] registers a biomass of 162.1 Mg ha^{-1} in secondary forests aged 15 years and of 324.1 Mg ha^{-1} in primary forests in humid and very humid climates in Costa Rica.

The trees that produced the largest amount of biomass in the stem and other aboveground parts and in the roots were pines, with values above 506.92, 882.05, and 264.61 Mg ha^{-1}, respectively (**Figure 6**). Oak trees produced the least biomass. Monroy and Navar [24] cite similar results for *Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg., with values of 73.9% stem biomass and 27.1% branch biomass, both of which increased with the age of trees.

As for the relationship between the carbon content and the total biomass production in the various components of the plant, the results suggest that the high rates registered in pine forests for both growth and aboveground carbon fixation, may be due, as Pacheco et al. [27]

Species	Model parameters	Estimate	Standard error	t	p	Confidence limits 95%	
						Min.	Max
Pinus maximinoi H. E. Moore	a	8.71	0.524	16.701	0.01	7.707	9.792
	b	1.51	0.099	15.193	0.01	1.313	1.706
Quercus rugosa Neé	a	6.64	0.314	21.146	0.01	6.018	7.261
	b	4.27	0.270	15.779	0.01	3.732	4.802
Quercus robur L.	a	6.83	0.414	16.475	0.01	6.008	7.647
	b	1.40	0.206	6.785	0.01	0.992	1.808
Pinus patula Schiede ex Schltdl. & Cham	a	11.78	1.251	9.417	0.01	9.283	14.277
	b	1.58	0.344	4.598	0.01	0.894	2.265

t = Student's t; p = probability of error.

Table 4. Parameters and statistical significance of the model of mathematical fit between the height and the normalized diameter.

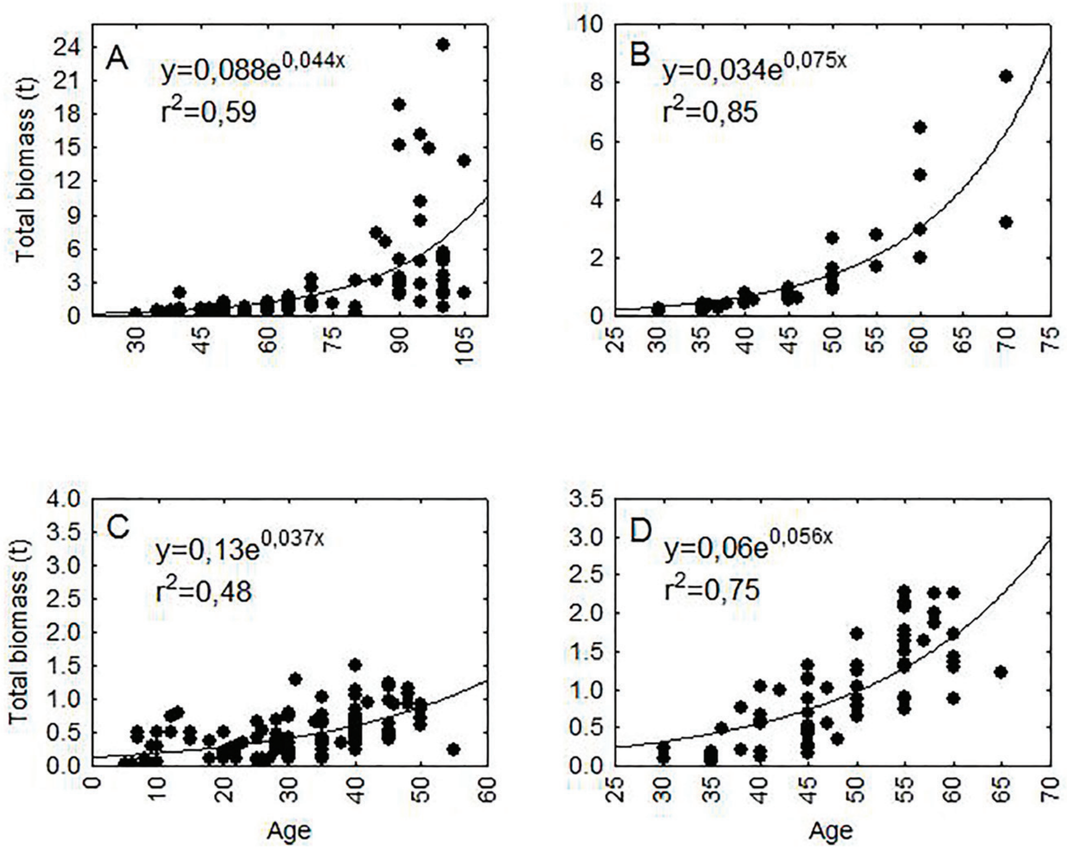

Figure 5. Regression curves of fit between the total biomass (BMt) and age of trees of (A) pine, (B) holm oak, (C) oak, and (D) Mexican weeping pine.

Species	Model parameters	Estimate	Standard error	t	p	Confidence limits 95%	
						Min.	Max
Pinus maximinoi H. E. Moore	a	0.09	0.07	1.22	0.23	−0.055	0.23
	b	0.04	0.009	5.06	0.01	0.027	0.06
Quercus rugosa Neé	a	0.034	0.016	2.18	0.05	0.002	0.07
	b	0.075	0.007	10.28	0.01	0.059	0.09
Quercus robur L.	a	0.13	0.036	3.72	0.01	0.063	0.21
	b	0.4	0.007	5.55	0.01	0.024	0.05
Pinus patula Schiede ex Schltdl. & Cham	a	0.006	0.024	2.48	0.01	0.012	0.1
	b	0.06	0.007	7.59	0.01	0.041	0.07

t = Student's t; p = probability of error.

Table 5. Parameters and statistical significance of the model of mathematical fit between the biomass and the age of the trees.

proved, to a good combination between the production of wood and cellulose compared to other species; this is helpful for the implementation of reforestation and CO_2 sequestration projects [14]. However, other factors, such as the site and the tree mass, also determine biomass

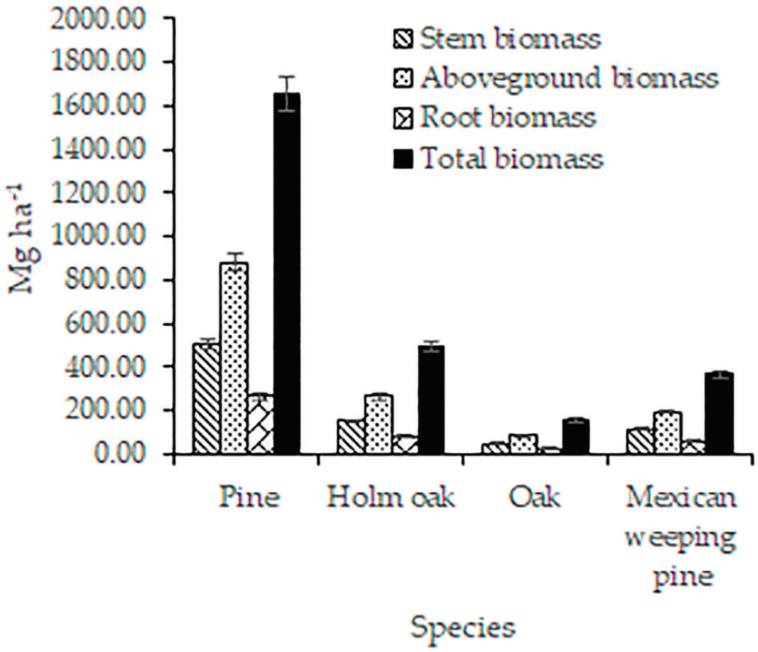

Figure 6. Total biomass production in the stem, branches, and roots of pine, oak, holm oak, and Mexican weeping pine trees in villages of La Frailesca region (Chiapas, Mexico). Note: Vertical lines in the columns represent the mean standard error.

production and carbon storage. Furthermore, this author cites a direct relationship between the sequestered carbon and growth, in both the normal diameter (ND) and the total height of the trees [34]. Analysis of the information from the various villages proved that the total biomass produced in pine trees was highest at *24 de Febrero* and *Juan Sabines* villages (**Figure 7**), with values above 2606.67 and 1045.61 Mg ha^{-1}, respectively. Therefore, these villages also had the highest values for carbon capture.

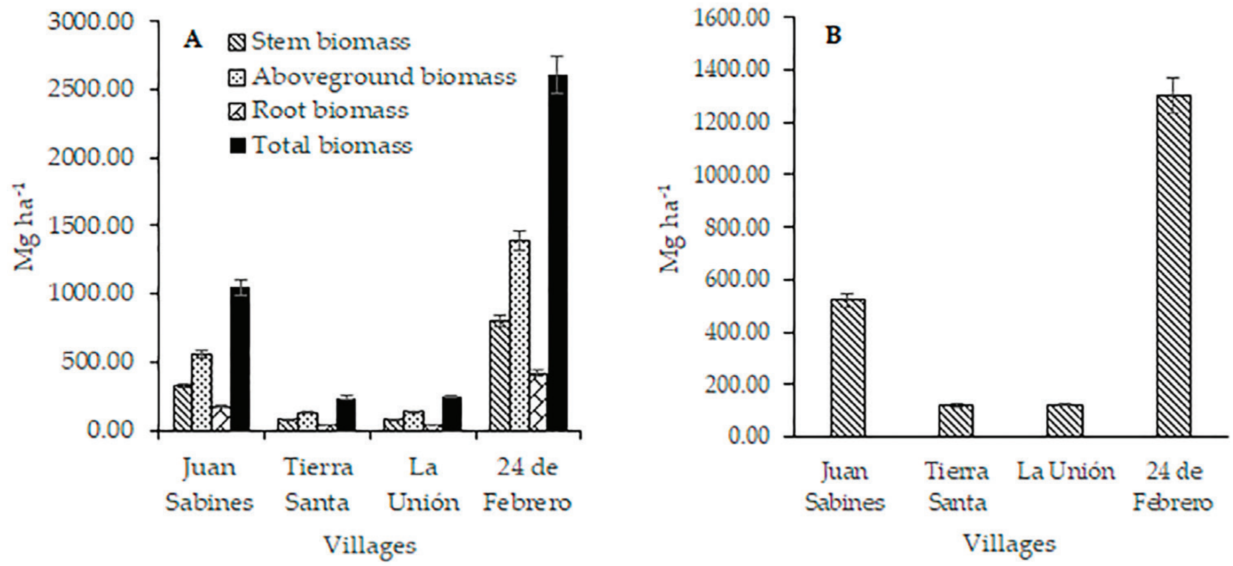

Figure 7. Total biomass (A) and carbon (B) storage in *Pinus maximinoi* H. E. Moore forests of the *Juan Sabines, Tierra Santa, La Unión* and *24 de Febrero* villages of La Frailesca region (Chiapas, México). Note: Vertical lines in the columns represent the mean standard error.

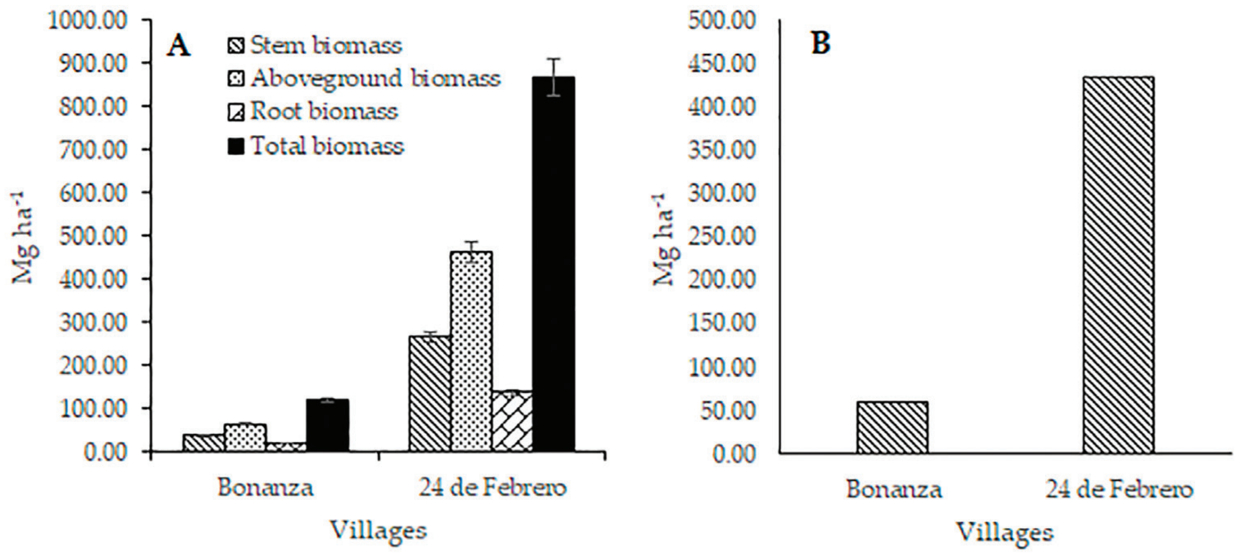

Figure 8. Total biomass (A) and carbon (B) storage in *Quercus rugosa* Neé forests in the *Juan Sabines, Tierra Santa, La Unión*, and *24 de Febrero* villages of La Frailesca region (Chiapas, Mexico). Note: Vertical lines in the columns represent the mean standard error.

Holm oak forests, which are prevalent in the *Bonanza* and *24 de Febrero* villages, produced up to 120.87 and 988.82 ha^{-1} Mg of total biomass, respectively (**Figure 8**), whereas the carbon sequestered was higher at *24 de Febrero*, with 433.98 Mg of C ha^{-1}, which proves the potential of this village for CO_2 capture and its contribution to the abatement of GHGs.

The total biomass production in oak trees was 154.03–176.21 Mg ha^{-1}, the highest record in the forest areas of the *La Libertad* village, followed by *Monterrey* (**Figure 9**). The lowest value was found at *Patria Chica*. As for carbon storage, in all the villages, it was above 50 Mg ha^{-1}; the highest was obtained in the forests of the *La Libertad* village, with 88.11 Mg of C ha^{-1} (**Figure 9**).

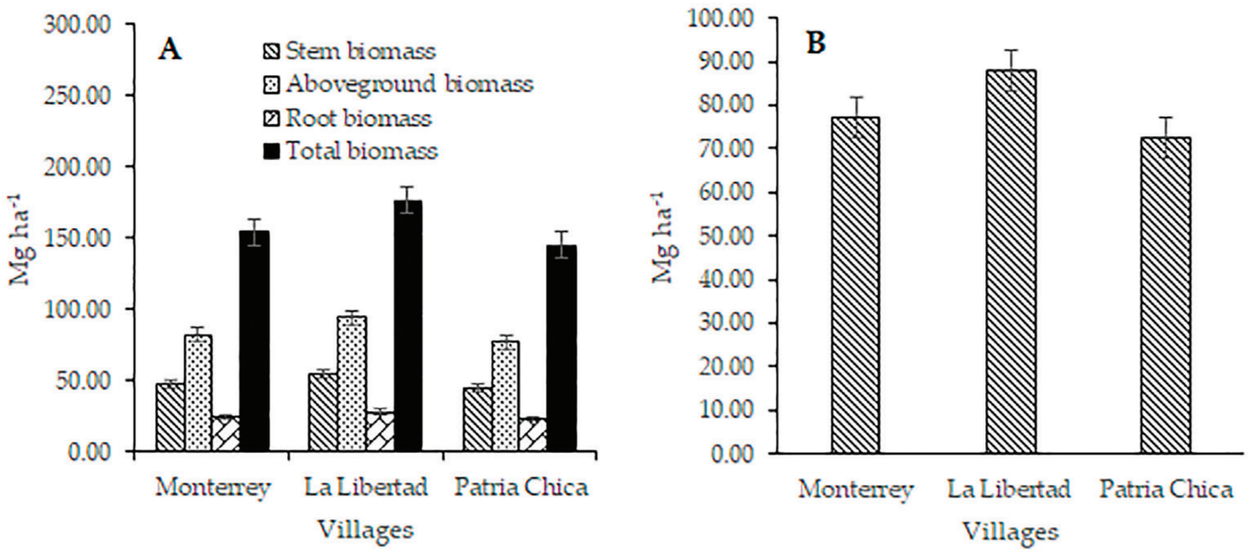

Figure 9. Total biomass (A) and carbon (B) storage in *Quercus robur* L. forests of the *Juan Sabines, Tierra Santa, La Unión*, and *24 de Febrero* villages of La Frailesca region (Chiapas, Mexico). Note: Vertical lines in the columns represent the mean standard error.

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The total biomass produced by Mexican weeping pines (*Pinus oocarpa* Schiede) ranged between 281.78 and 450.52 Mg ha^{-1} (**Figure 10**). This species occurred only in the *La Frailesca* and *Nuevo Refugio* villages; the forests of the latter contributed a larger amount to this production. The highest value for carbon storage (225.26 Mg of C ha^{-1}) was found in the forests of *Nuevo Refugio*, while the *La Frailesca* village stored only 140.89 Mg ha^{-1}. As for the production of biomass per tree components (**Figures 6–10**), in all the taxa and localities, the highest accumulation occurred in the aboveground biomass, as indicated by Gower et al. [17], who proved that approximately 75% of the biomass of a tree is produced in the aboveground parts, while only 25% is accumulated in the roots.

Comparison between biomass production and carbon storage by species showed that *Pinus* spp. and *Quercus* spp. had the highest values, while *Quercus robur* had the lowest (**Table 6**). This agrees with the findings of González [16], who, after comparing three tree species, determined that *P. maximinoi* had the highest biomass accumulation, followed by *Quercus* spp. In regard to carbon, pine and holm oak had a storage potential of 516.75–247.02 Mg of C ha^{-1} (**Table 6**).

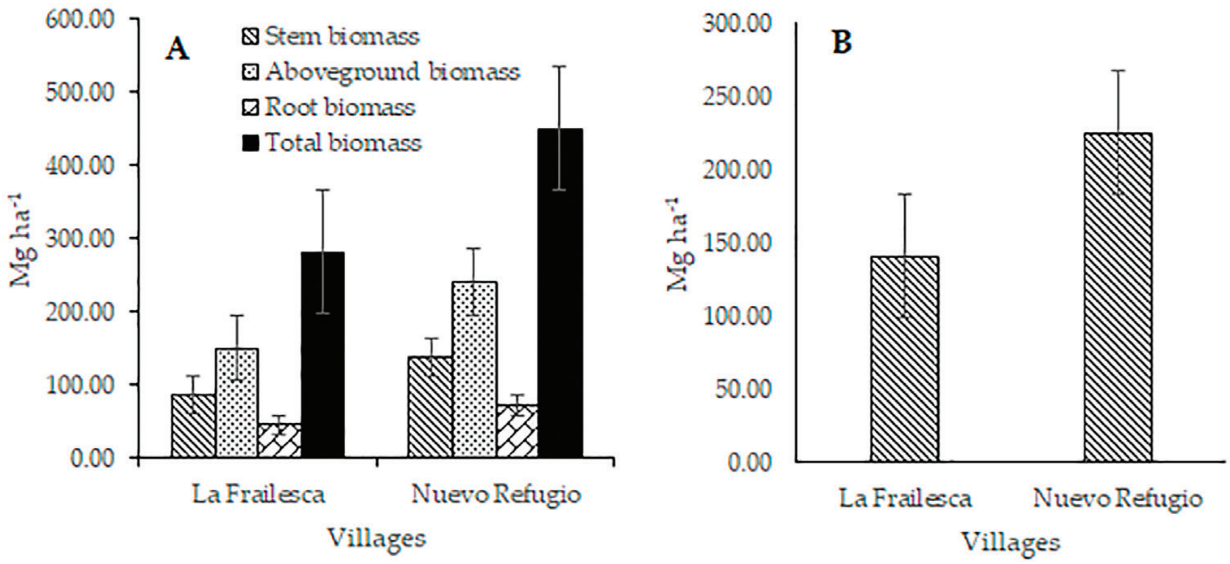

Figure 10. Biomass (A) and carbon (B) storage in *Pinus oocarpa* Schiede forests of the *La Frailesca* and *Nuevo Refugio* villages in La Frailesca region (Chiapas, Mexico). Note: Vertical lines in the columns represent the mean standard error.

Species	Total biomass (Mg ha^{-1})		Carbon storage (Mg ha^{-1})	
	Mean	Standard error	Mean	Standard error
Pinus maximinoi H. E. Moore	1033.49	557.65	516.75	278.82
Quercus rugosa Neé	494.41	373.54	247.21	186.77
Quercus robur L.	150.03	10.60	75.02	5.30
Pinus patula Schiede ex Schltdl. & Cham	366.15	84.37	183.08	42.19
General	537.94	207.32	268.97	103.66

Table 6. Total biomass and carbon storage in pine, holm oak, oak, and Mexican weeping pine forests of La Frailesca region, Chiapas.

4. Conclusions

The forests of the *24 de Febrero* villages registered the highest growth, based on their height and stem diameter, as well as on the total biomass, rendering this village one of the localities with the highest potential for carbon storage of all the studied sites. Pine, holm oak, oak, and Mexican weeping pine trees in villages of *Frailesca* region in *Chiapas*, Mexico, accumulate between 150.03 and 1033.49 Mg ha^{-1} of vegetal biomass; therefore, they are considered to have a high potential for carbon sequestration. Pine trees reached a value of 516.75 Mg ha^{-1} of C; due to its high degree of development, this species has the highest capture potential of all.

Since the present study was an initial effort to begin with data collection for preliminary insights and understandings about the village-forests in la Frailesca region, it is important to keep in the research track with deeper and longer term investigations on forest dynamics in this geographical area, especially due to its importance for biodiversity conservation, sustainable management of natural resources, and the environmental services provision for the rural and urban areas of the Chiapas state.

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