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Article

Contenido de carbono y estructura horizontal de un bosque templado en Guadalupe y Calvo, Chihuahua

Carbon stock and horizontal structure of a temperate forest in *Guadalupe y Calvo*, *Chihuahua*

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Resumen

Es importante conocer la estructura y la cantidad de carbono almacenado en los ecosistemas forestales, ya que representan uno de los principales sumideros de dióxido de carbono (CO_2) en los ecosistemas terrestres. Este estudio se llevó acabo en el ejido Chinatú, municipio Guadalupe y Calvo, Chihuahua, donde se realizó un muestreo aleatorio de ocho sitios circulares de 1 000 m^2 distribuidos en 80.46 ha de superficie. Se analizó la estructura horizontal con base en el Índice de Valor de Importancia (*IVI*) y clases diamétricas; además, se determinó el cociente de mezcla, la riqueza y diversidad de especies de acuerdo con los índices de *Margalef* (D_{Mg}) y de *Shannon-Weiner* ($H´$); el carbono almacenado en la biomasa aérea se estimó mediante ecuaciones alométricas, por medio del volumen para cada una de las especies. Se identificaron 10 taxones con una densidad de 460 individuos (N ha^{-1}), la especie de mayor valor ecológico (*IVI*) fue *Pseudotsuga menziesii* con 26.14 %, la riqueza y diversidad obtenida fue de D_{Mg} = 1.47 y H' = 1.96, respectivamente, la distribución diamétrica correspondió a una curva de *Liocourt* balanceada, y el contenido de carbono almacenado fue de 45.20 Mg C ha^{-1}. Estos análisis muestran que el bosque es homogéneo, sin dominancia amplia de alguna especie en particular y está en buen estado de conservación, ya que en las categorías diamétricas menores hay abundante presencia de individuos pequeños que, posteriormente, sustituirán a la masa madura.

Palabras clave: Biomasa, caracterización, CO_2, diversidad, *Pseudotsuga menziesii* (Mirb.) Franco, sumideros de carbono.

Abstract

The need to know the structure and amount of carbon stored in forest ecosystems is very important, as these are a major sink of carbon dioxide (CO_2). This study was developed in the *ejido Chinatú*, municipality of *Guadalupe y Calvo*, *Chihuahua*, where random samplings were carried out at eight circular sites of 1 000 m^2 distributed in 80.46 hectares of surface. The horizontal structure was analyzed based on the importance value index (*IVI*) and diametric classes; in addition, the mixing ratio, richness and diversity of species were determined according to the Margalef index (D_{Mg}) and Shannon-Weiner index ($H´$), the carbon stored in the aerial biomass was estimated by means of allometric equations, based on the volume for each of the species. Ten species with a density of 460 N ha^{-1} were identified. The species with the highest ecological value (*IVI*) was *Pseudotsuga menziesii*, with 26.14 %; the wealth and diversity obtained were D_{Mg} = 1.47 and H'= 1.96, respectively; the diametric distribution is balanced, in the form of a Liocourt curve, and the stored carbon content was 45.20 Mg C ha^{-1}. These analyses show that the forest is homogeneous, without broad dominance of any specific species, and is in a good state of conservation since the smaller diameter categories abound in small individuals that will later replace the mature mass.

Key words: Biomass, characterization, CO_2, diversity, *Pseudotsuga menziesii* (Mirb.) Franco, carbon sinks.

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Introduction

Forests cover around 31 % of the Earth's surface and store near 45 % of the terrestrial carbon (Bonan, 2008; FAO-PNUMA, 2020), and therefore play an important role in the global carbon cycle and the regulation of the global climate system.

In Mexico, temperate forests amount to nearly 20 % of the national territory (Challenger, 1998); of these, 14 % are pine and pine-oak forests, 5 % are oak and 1 % are other species (Rzedowski, 1991). *Pseudotsuga* forests do not exceed 25 000 ha (Rzedowski, 1978); they are located in the *Sierra Madre Occidental*, *Sierra Madre Oriental* and in the central-southern part of the country (Castruita-Esparza *et al.*, 2016; Ortega, 2017; García *et al.*, 2019); moreover, their populations are small and fragmented (Reyes-Hernández *et al*., 2006).

A good forest management requires the characterization of its structure to understand its operation as a basis for decision making (Aguirre *et al*., 2003; Corral *et al*., 2005; Castellanos-Bolaños *et al*., 2008; Aguirre-Calderón, 2015).

Forest structure influences the rates and magnitudes of carbon accumulation in living and dead biomass, which is relevant to the climate regulation function of temperate forest ecosystems (Hardiman *et al*., 2011; Urbano and Keeton, 2017).

In this context, the objective of the present study was to know the horizontal structure, species richness and diversity as well as to estimate the carbon content of a temperate forest, with the presence of endangered species such as *Pseudotsuga menziesii* (Mirb.) Franco, in order to provide basic information for their conservation in *Guadalupe y Calvo, Chihuahua*.

Materials and Methods

The study was conducted in a mixed forest consisting mainly of *Pseudotsuga menziesii*, *Pinus arizonica* Engelm. and *Quercus tuberculata* Liebm., at the "*El Triste*" site, which is located in the *Chinatú ejido*, in *Guadalupe y Calvo* municipality, at the southwest of the state of *Chihuahua*, between the coordinates 26°24' N and 106°64'

W (Figure 1). It has an area of 80.46 ha and altitudes of 2 530 to 2 830 m. It belongs to the *Río Fuerte* hydrological region, which in turn corresponds to the physiographic province of *Sierra Tarahumara*, within the sub-province of *Gran Meseta* and the *Chihuahua* Canyons. The predominant soil types in the area are Litosol and, to a lesser extent, Regosol. The climate is classified as sub-humid temperate, and the average annual temperature of the region is 13.7 °C, with an average annual rainfall of 1 126.8 mm (Chávez, 2009).

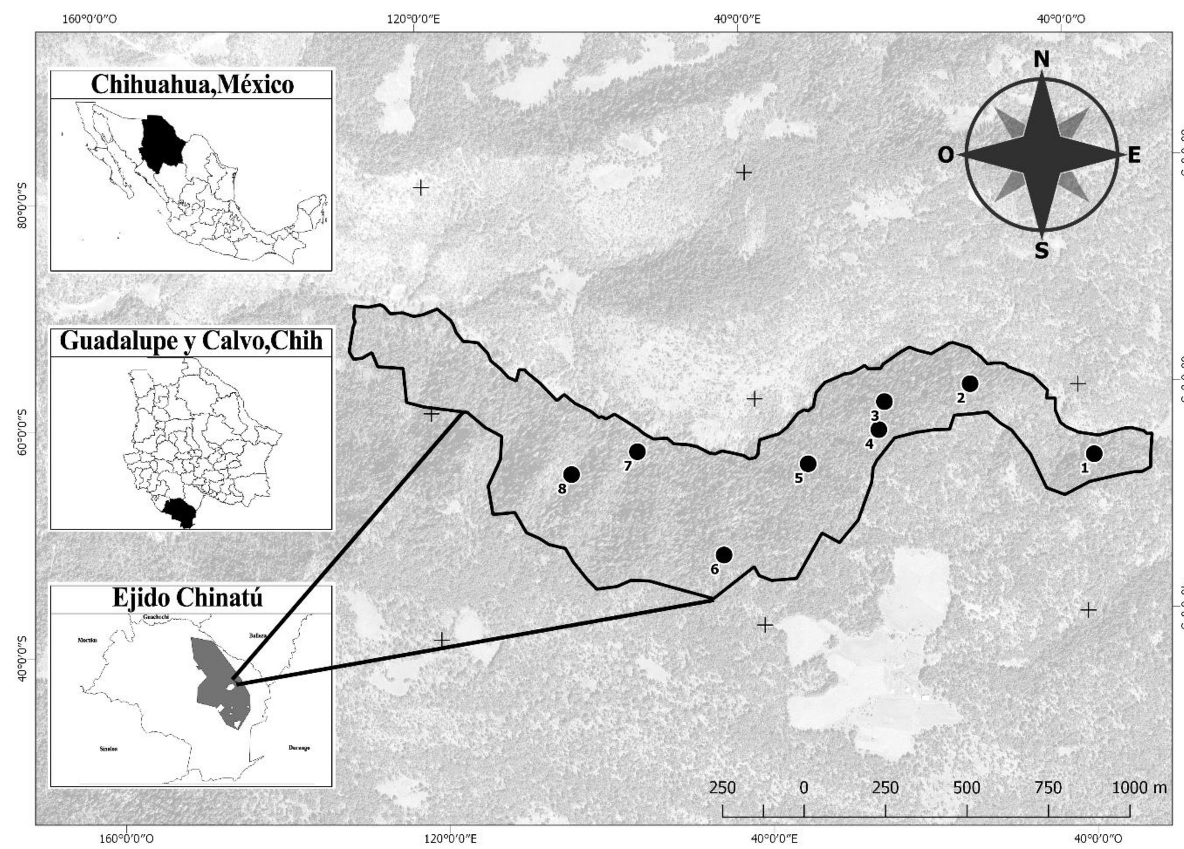

Figure 1. Location of the study area and sampling sites.

On-site evaluation

In order to evaluate the vegetal community, eight 1 000 m^2 circular sampling sites were established; this sampling site was determined according to the following formula:

$$n = \frac{t^2 * CV^2}{E_{\%}^2}$$

Where:

n = Number of points required for the desired accuracy, E, with the probability level implied by the value of t.

t = Student's t

CV = Coefficient of Variation (expressed in percent) of the forest to be sampled

E = Allowable error or desired accuracy (expressed in percent) for the average volume (or basimetric area)

The random distribution was generated based on the coordinates of the vertices of the area previously covered, thus obtaining random coordinates using the "RANDOM.BETWEEN" formula of the Excel program; subsequently, the first eight pairs of resulting coordinates were georeferenced in QGIS 2.18.28, with which the location and sampling map were made (Figure 1).

Trees with a normal diameter ($d_{1.30}$) ≥ 7.5 cm for adult trees were considered at the sampling sites. The total height (h) was recorded with a Suunto Pm-5 hypsometer; the normal diameter (DBH), with a Forestry Suppliers diameter tape; the crown diameter, with a 100 m Truper® crossover fiberglass tape (north-south and east-west) per individual (Alanís-Rodríguez *et al.,* 2020), and the species of each individual was recorded.

Species richness, diversity and horizontal structure

Absolute and relative values of abundance, dominance and frequency were measured; then, the average value for each taxon was obtained, and the Importance Value Index (IVI) of the tree stratum was calculated; in addition, the mixing ratio (MR), which gives a general idea of the intensity of the mixture, was determined (Alvis, 2009). The diversity of the plant community was evaluated using the Shannon-Weiner (H') index (Shannon, 1948) and the Margalef (D_{Mg}) index (Magurran, 2004) (Table 1).

Table 1. Importance Value Index (*IVI*), mixing ratio (*MR*), wealth index (D_{Mg}) and diversity index (*H'*).

Indexes		Description
Importance value index (*IVI*)	$IVI = A_r + F_r + D_r$	Where: *IVI* = Importance value index A_r = Relative abundance D_r = Relative dominance F_r = Relative frequency
Mixing ratio (*MR*)	$CM = \frac{S}{N}\frac{\frac{S}{S}}{\frac{N}{S}}$	Where: *S* = Total number of species sampled *N* = Total number of individuals in the sample
Margalef (D_{Mg})	$D_{Mg} = \frac{S-1}{ln(N)}$	Where: *S*= number of species *N*= total number of individuals
Shannon-Weiner (*H'*)	$H' = -\sum_{i=1}^{S} P_i \times ln(P_i)$ $P_i = {}^{n_i}/_{N}$	Where: *S*= number of species P_i= proportion of individuals of the species *i*

Volume, biomass and carbon stock estimation

The volume calculation was determined according to the formula of total tree volume with bark (Ttv_{wb}) and the proposed parameters (Table 2).

$$Ttv_{wb} = b_0 * D^{b1} * h^{b2} + b_3 * D^2$$

Where:

D = Normal tree diameter i (cm)

h = Total height of the tree i (m)

b_i = Proposed coefficients

Table 2. Model parameters for volume estimation of evaluated species.

Species	b_0	b_1	b_2	b_3
Pinus durangensis Martínez	0.000085	1.995095	0.764492	0.000050
Pinus arizonica Engelm.	0.000067	1.783568	1.098266	0.000063
Pinus ayacahuite C. Ehrenb. ex Schltdl.	0.000082	2.102772	0.606456	0.000054
Abies durangensis Martínez	0.000066	1.788316	1.055175	0.000013
Arbutus xalapensis Kunth	0.000142	1.483474	1.121788	0.000116
Juniperus deppeana Steud.	0.000591	1.338876	0.707074	0.000029
Picea chihuahuana Martínez	0.000061	1.992235	0.869354	0.000057
Pseudotsuga menziesii (Mirb.) Franco	0.000062	1.882421	0.946587	0.000010
Quercus sideroxyla Bonpl.	0.000188	1.851694	0.572656	0.000044
Quercus tuberculata Liebm.	0.000188	1.851694	0.572656	0.000044

Source: Corral-Rivas and Vargas-Larreta (2013).

Biomass was calculated by multiplying the volume by the density of the wood of each of the species (Table 3) and the number of recorded individuals (N ha^{-1}). Subsequently, carbon stock was estimated by multiplying the value of the biomass by the carbon concentration 0.5 (Change, 2006; Ordóñez *et al*., 2008).

Table 3. Forest density of the species evaluated for the "*El Triste*" property of the *Chinatú ejido* in *Guadalupe y Calvo, Chihuahua*.

Species	Density (g cm^{-3})	Source
Pinus durangensis Martínez	0.47	Silva-Arredondo and Návar-Cháidez, 2012
Pinus arizonica Engelm.	0.43	Sotomayor, 2008
Pinus ayacahuite C. Ehrenb. ex Schltdl.	0.37	Vázquez-Cuecuecha *et al*., 2015
Abies durangensis Martínez	0.38	Sotomayor, 2008
Arbutus xalepensis Kunth	0.75	Ordóñez *et al*., 2015
Juniperus deppeana Steud.	0.46	Nájera and García, 2009
Picea chihuahuana Martínez	0.42	Sotomayor-Castellanos and Hernández-Maldonado, 2012
Pseudotsuga menziesii (Mirb.) Franco	0.45	Zanne *et al*., 2009
Quercus sideroxyla Bonpl	0.61	De la Paz and Dávalos-Sotelo, 2008
Quercus tuberculata Liebm.	0.77	Silva-Arredondo and Návar-Cháidez, 2012

Results and Discussion

The assessed plant community consisted of 10 species, with a total density of 460 N ha^{-1}, distributed in seven genera of four families. The most representative families were Pinaceae, with six taxa, and Fagaceae with two. The number of registered taxa (10) is similar to that documented by Álvarez *et al.* (2004) for a forest of *Pseudotsuga menziesii* in the *La Barranca ejido*, in *Pinal de Amoles* municipality, state of *Querétaro,* but lower than that cited by Encina-Domínguez *et al.* (2008) in a fir forest located in the *Sierra de Zapalinamé,* state of *Coahuila*.

The diameter distribution of the forest showed a negative exponential trend in the form of a Liocourt curve or "inverted J" (Figure 2), which reveals a community in the process of regeneration, with development towards greater stages of growth. The mature plant community, made up of trees, probably in a long-lived phase and belonging to the upper diameter classes, will be replaced by a large number of young individuals (Arruda *et al*., 2011; Hernández-Stefanoni *et al.,* 2011).

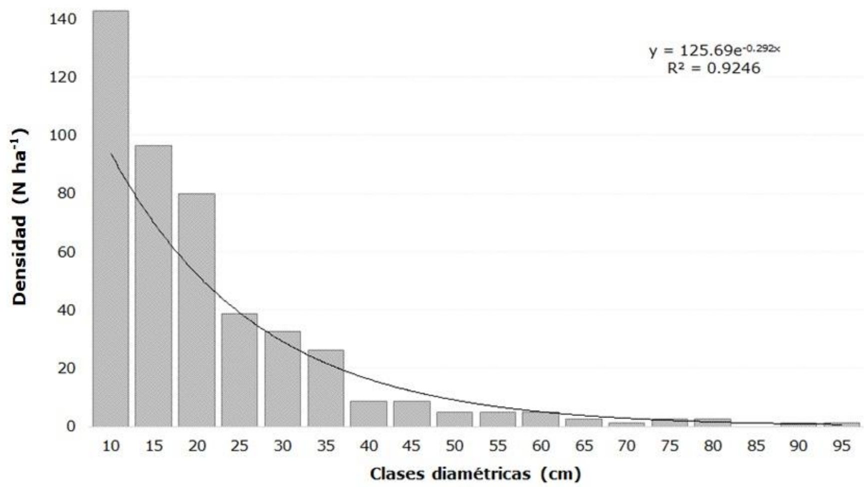

Figure 2. Tree species density by diameter class.

A research carried out in Mexico reported similar results, for example, to those of López-Hernández *et al.* (2017) in a temperate forest in the state of *Puebla*, and of Encina-Domínguez *et al.* (2008) in one of a fir forest in *Coahuila*. Irregular and unbalanced structures have been registered in other locations, as it happens with some populations of *Pseudotsuga menziesii* in the states of *Tlaxcala* and *Puebla* (Guerra *et al.,* 2012).

The species with the highest density were *Pseudotsuga menziesii,* with 154 N ha^{-1}; *Pinus arizonica*, with 83 N ha^{-1}, and *Quercus tuberculata*, with 48 N ha^{-1}; while *Pinus durangensis* had the lowest density, with only 5 N ha^{-1} (Table 4). The superiority of *Pseudotsuga menziesii* over pine or oak species is also indicated by Domínguez-Calleros *et al.* (2014) in an area of *Chalchihuites*, in the state of *Zacatecas*, with 324 N ha^{-1}, and Aguirre-Calderón *et al.* (2003) indicate a density of 240 N ha^{-1} for the *El Potosí* mountain in *Galeana, Nuevo León*.

Table 4. Density, dominance, frequency, and *IVI* values of a mixed forest in *Guadalupe y Calvo* municipality.

Species	**Density**		**Dominance**		**Frequency**		***IVI***
	N ha^{-1}	**(%)**	**G (m^2 ha^{-1})**	**(%)**	**N/Site**	**(%)**	**(%)**
Pseudotsuga menziesii (Mirb.) Franco	154	33.42	5.23	27.92	7	17.07	26.14
Quercus tuberculata Liebm.	48	10.33	4.50	24.02	6	14.63	16.33
Pinus arizonica Engelm.	83	17.93	2.47	13.17	6	14.63	15.25
Arbutus xalepensis Kunth	43	9.24	2.34	12.52	2	4.88	8.88
Juniperus deppeana Steud.	38	8.15	0.78	4.18	5	12.20	8.17
Pinus ayacahuite C. Ehrenb. ex Schltdl.	21	4.62	0.71	3.79	6	14.63	7.68
Abies durangensis Martínez	40	8.70	1.19	6.36	3	7.32	7.46
Quercus sideroxyla Bonpl.	16	3.53	0.41	2.17	3	7.32	4.34
Pinus durangensis Martínez	5	1.09	0.64	3.40	2	4.88	3.12
Picea chihuahuana Martínez	14	2.99	0.46	2.47	1	2.44	2.63
Total general	460	100.00	18.72	100.00	41	100.00	100.00

IVI = Importance Value Index.

The basimetric area (dominance) turned out to be 18.72 G m^2 ha^{-1}, similar to that cited by Hernández-Salas *et al.* (2013), who obtained 19.58 G m^2 ha^{-1} to 23. 70 G m^2 ha^{-1} in temperate forests of the *El Largo ejido,* in *Madera* municipality, *Chihuahua*; however, the value is low in contrast to that detailed by Encina-Domínguez *et al.* (2008) and Domínguez-Calleros *et al.* (2014), authors who estimated 29.69 G m^2 ha^{-1} and 34.43 G m^2 ha^{-1}, respectively.

In the present study, the species that stood out were *Pseudotsuga menziesii*, with 5.23 G m^2 ha^{-1}; *Quercus tuberculata*, with 4.50 G m^2 ha^{-1}; *Pinus arizonica*, with 2.47 G m^2 ha^{-1}, and *Arbutus xalepensis*, with 2.34 G m^2 ha^{-1}. Together these taxa represented 77.63 % of the total. *Picea chihuahuana* Martínez registered the lowest value: 0.46 G m^2 ha^{-1} (2.47 %).

Pseudotsuga menziesii had the highest sampling frequency, with 17.07 % and presence in seven sites, followed by *Quercus tuberculata*, *Pinus arizonica* and *Arbutus xalepensis* with 14.62 %, observed in six sites. *Picea chihuahuana* was the least frequent species, as it was registered in one site only. Gordon (1968) and García and González (1998) point out that there are very few small populations of *P. chihuahuana* in the *Sierra Madre Occidental*, which are considered an endemic relict.

The Index of Value of Importance (*IVI*) was determined according to the relative values of density, dominance and frequency; the results showed *Pseudotsuga menziesii* as the species with the highest ecological value, of 26.14 %; followed by *Quercus tuberculata*, with a value of 16.33 %; and *Pinus arizonica*, with 15.25 %. These three species represented 57.71 % of the *IVI*, while to *Picea chihuahuana* corresponded the smaller value (2.63 %). Guerra *et al.* (2012) indicate that *Pseudotsuga menziesii* coexists with tolerant oak and conifer species such as the oyamel fir.

The mixing ratio (*MR*) had a value of 1:46; that is, for every 46 individuals it is possible to register the presence of a different species. Therefore, this type of forest is considered homogeneous; others, such as the Sub-Andean riparian forest, exhibit greater heterogeneity, as is the case of the one evaluated by Chaves and Rodríguez (2012) in the Western *Cordillera* of the *Andes, Colombia*, where they calculated a *MR* of 1:8. Melo (2019) documents *MR*s of 1:04 to 1:34 for tropical dry forest fragments in *Tolima, Colombia*.

According to the Margalef index (D_{Mg}), the species richness in the forest under study, was 1.47, higher than that recorded by López-Hernández *et al.* (2017) who obtained a D_{Mg} = 1.35 in temperate forests of *Puebla*, Mexico. It was also higher than that cited by Návar-Cháidez and González-Elizondo (2009) in a temperate forest of the state of *Durango* (D_{Mg} = 1.04), and by Hernández-Salas *et al.* (2013), who obtained values of D_{Mg} = 0.81, 0.91 and 0.90 in three evaluations conducted in different periods.

Diversity based on the Shannon Index (*H'*) had a value of *H'* =1.96, which indicates low diversity, since, according to Margalef (1972) the index has an interval of 1 to 5, in which values below 2 indicate a low diversity. The results from this research are similar to the value of *H'* =1.82 recorded by García-Aranda *et al.* (2011) in a temperate forest with presence of *Pseudotsuga menziesii* in *Zaragoza*, state of *Nuevo León*. However, it is higher than that described in other studies, as that carried out by Návar-Cháidez and González-Elizondo (2009), who recorded values of *H'* =0.53 to

1.33 for the *Cielito Azul* stand in *Durango*; González *et al*. (2018) calculated *H'* =1.76 for a forest of *Abies vejarii* Martínez in *Nuevo León*, and Delgado *et al.* (2016) estimated values of *H'* =0.77 to 1.58 in *Pueblo Nuevo, Durango*. According to these values, the evaluated plant community exhibits a greater diversity than other temperate forests in Mexico.

In regard to the species volume, a total of 168.58 m^3 ha^{-1} was obtained. *Quercus tuberculata*, *Pseudotsuga menziesii* and *Pinus arizonica* had the largest volume with 49.24, 37.64 and 26.14 m^3 ha^{-1}, respectively. With respect to its biomass, figures between 1.85 Mg ha^{-1} and 28.98 Mg ha^{-1} were registered; with a behavior similar to the one described before; in this item *Arbutus xalepensis* was integrated as one of the species that contributed more biomass.

As for the stock of stored carbon, it was determined that the forest contains a total of 45.29 Mg C ha^{-1}. *Quercus tuberculata* and *Pseudotsuga menziesii*, which had the highest value of importance, also exhibited the highest carbon content, with 14.49 Mg C ha^{-1} and 11.08 Mg C ha^{-1}, respectively, followed by *Pinus arizonica* (5.62 Mg C ha^{-1}) and *Arbutus xalepensis* (5.16 Mg C ha^{-1}), both of which occupied the first places in *IVI*. The species with the lowest volume, biomass and carbon content was *Picea chihuahuana*; this is attributable to its low value of importance (Table 5).

Table 5. Volume, biomass and carbon stock values of a mixed forest in Guadalupe y Calvo municipality.

Species	Volume (m^3 ha^{-1})	Biomass (t ha^{-1})	Carbon (Mg C ha^{-1})
Quercus tuberculata Liebm.	37.64	28.98	14.49
Pseudotsuga menziesii (Mirb.) Franco	49.24	22.16	11.08
Pinus arizonica Engelm.	26.14	11.24	5.62
Arbutus xalepensis Kunth	13.77	10.33	5.16
Abies durangensis Martínez	13.68	5.20	2.60
Pinus durangensis Martínez	8.44	3.97	1.98
Pinus ayacahuite C. Ehrenb. ex Schltdl.	7.49	2.77	1.38
Quercus sideroxyla Bonpl.	3.36	2.05	1.02
Juniperus deppeana Steud.	4.41	2.03	1.02
Picea chihuahuana Martínez	4.42	1.85	0.93
Total	168.58	90.57	45.29

In a similar study conducted in a forest of *Abies religiosa* in Mexico City, Avila-Akerberg (2010) registered an average of 108 Mg C ha^{-1}; Razo-Zárate *et al.* (2013) estimated 138.69 Mg C ha^{-1} in a fir forest in the state of *Hidalgo*; Ordóñez *et al.* (2015) estimated 103. 1 Mg C ha^{-1} in managed forests in *San Pedro Jácuaro*, state of *Michoacán*; González (2008) estimated an average of 80.98 Mg C ha^{-1} for *Pinus maximinoi* H.E.Moore -dominant forests and 71 Mg C ha^{-1} in *Pinus oocarpa* Schiede ex Schltdl. -dominant stands in northern *Chiapas* State, Mexico, and Martínez *et al.* (2016) calculated that temperate forests in *Durango*, Mexico, store 26.87 Mg C ha^{-1}.

Conclusions

The most relevant families in the studied temperate forest are Pinaceae and Fagaceae. The distribution of the diameters indicates that the tree vegetation is in the process of regeneration, since most of its individuals belong to the classes of smaller diameter that will later replace the mature mass. *Pseudotsuga menziesii*, *Quercus tuberculata* and *Pinus arizonica* exhibit the highest importance value index. These species have the highest values of volume, biomass and carbon content. According to the mixing ratio, the forest shows a tendency towards homogeneity. Species richness and diversity is slightly higher than other studies in similar forests. This research can serve as a reference for future conservation or restoration plans in forests that are not subject to logging and that have vulnerable species such as *P.menziesii* (Under Special Protection), *P. Chihuahuana* (Endangered) according to NOM-059-SEMARNAT-2010 (Semarnat, 2002), and *A. durangensis*, which is an endemic species.

Conflict of interests

The authors declare no conflict of interest.

Contribution by author

Samuel Alberto García García and Eduardo Alanís Rodríguez: research design, data analysis and drafting of the manuscript; Óscar Alberto Aguirre Calderón: preparation and review of the manuscript, coordination and implementation of field activities; Eduardo Javier Treviño Garza: data capture and analysis, and review of the manuscript; Gabriel Graciano Ávila: species identification, drafting and revision of the manuscript.

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