Comparison of carbon content between plantation and natural regeneration seedlings in Durango, Mexico

Jesús Alejandro Soto-Cervantes[1], José Javier Corral-Rivas[2], Pedro Antonio Domínguez-Calleros[2], Pablito Marcelo López-Serrano[2], Eusebio Montiel-Antuna[2], Emily García-Montiel[2] and Alberto Pérez-Luna[3,4]

[1] Programa Institucional de Doctorado en Ciencias Agropecuarias y Forestales, Universidad Juárez del Estado de Durango, Durango, Durango, México
[2] Facultad de Ciencias Forestales y Ambientales, Universidad Juárez del Estado de Durango, Durango, Durango, México
[3] Centro de Bachillerato Tecnológico Industrial y de Servicios Número 89, Dirección General de Educación Tecnológica Industrial, Durango, Durango, México
[4] Postgrado en Ciencias Forestales, Colegio de Postgraduados, Texcoco, México, México

Submitted 11 April 2022
Accepted 3 January 2023
Published 9 February 2023

Corresponding author
Alberto Pérez-Luna, aperez@ujed.mx

Academic editor
Maria Luisa Fernandez-Marcos

Additional Information and Declarations can be found on page 12

DOI **10.7717/peerj.14774**

ABSTRACT

Forest plantations and natural forests perform a relevant role in capturing CO_2 and reducing greenhouse gas concentrations. The objective of this study was to compare the diameter increment, biomass and carbon accumulation in a plantation of *Pinus durangensis* and a naturally regenerated stand. The data were collected from 32 circular plots of 100 m^2 (16 plots in the planted site and 16 in naturally regenerated area). At each plot, the diameter at the base (cm) and height (m) of all seedlings were measured using a Vernier and tape measure, and a seedling was destructively sampled collecting one cross-section at the base of the stump. The annual ring-width increment of each sampled seedling was recorded to obtain its diameter at the base and estimate annual aboveground biomass and carbon accumulation through allometric equations. The response variables were evaluated using mixed-effects ANOVA models. Results indicated that there were significant differences ($P \leq 0.05$) on annual tree-ring width growth, biomass and carbon accumulation. The plantation seedlings showed significantly higher growth rates, biomass and carbon accumulation at most evaluated years. After 7 years of growth the lines of current annual increment (CAI) and mean annual increment (MAI) in basal diameter for both the plantation and the natural regeneration have not yet intersected. Both forest plantations and naturally regenerated stands of the studied tree species may be suitable alternatives to promote CO_2 capture and increase timber production.

Subjects Agricultural Science, Conservation Biology, Plant Science, Environmental Contamination and Remediation, Forestry
Keywords *Pinus durangensis* Martínez, Biomass, Carbon sequestration, Seed-tree cutting, Clear-cutting

How to cite this article Soto-Cervantes JA, Corral-Rivas JJ, Domínguez-Calleros PA, López-Serrano PM, Montiel-Antuna E, García-Montiel E, Pérez-Luna A. 2023. Comparison of carbon content between plantation and natural regeneration seedlings in Durango, Mexico. **PeerJ 11:e14774 DOI 10.7717/peerj.14774**

INTRODUCTION

Plantations and natural forests are an excellent alternative for CO_2 capture and to reduce greenhouse gas concentrations and to mitigate the effects of global warming (*Patiño Forero et al., 2018*; *González-Cásares et al., 2019*).

Mexico is one of the highest emitters of greenhouse gases, which include 407,695 megatons of CO_2 annually (*INECC-SEMARNAT, 2015*). Therefore, it is important to know the stocks and flows of carbon in its forest areas. Biomass estimation can be calculated using indirect methods such as the use allometric equations (*Návar et al., 2004*; *Montes de Oca-Cano et al., 2008*; *Vargas-Larreta et al., 2017*), and remote sensing techniques (*López-Serrano et al., 2015*).

Pinus durangensis Martínez is one of the most commercially important tree species in northern Mexico. It is also one of the forest species with the greatest potential to accumulate carbon (*Graciano-Ávila et al., 2019*). Its performance and adaptability allow it to be used frequently in commercial forest plantations in the state of Durango (*Prieto Ruíz et al., 2016*). *Flores, Pineda Ojeda & Flores Ayala (2019)* estimate that in Mexico, 1,400 hectares of *Pinus durangensis* are planted annually. The success of the forest plantations depends to a large degree on the use of high-genetic-quality plants (*Stewart et al., 2016*) with good adaptability to the plantation site (*Grossnickle, 2012*; *Vallejo et al., 2012*). In Mexico, 57% of mortality in plantations is caused by poor-plant quality (*Prieto Ruíz et al., 2016*), in addition to bad practices that occur during the plantation process (*Burney et al., 2015*).

With the establishment of commercial forest plantations in Mexico, the aim is to increase the country's timber production (*Hernández-Zaragoza et al., 2019*). They also constitute an important element in carbon sequestration and the generation of other environmental services. However, there are few studies related to the evaluation of their timber yield and their potential for carbon sequestration (*Soto-Cervantes et al., 2020*).

The natural regeneration of pine species by means of the use of seed-tree cuttings or selective fellings are the most used methods to achieve the establishment of the new seedlings in the areas under forest management in the Mexican temperate forests (*Ramírez Santiago et al., 2015*). In addition, they are appropriate options for the ecological rehabilitation of forests (*Pensado-Fernández et al., 2014*), since they have the advantage to retain the germplasm's genetic memory (genotype) to guarantee a higher percentage of survival and development than plantations (*Landis, 2011*). However, few studies have compared tree growth and carbon sequestration between forest plantations and natural regeneration of *Pinus durangensis* (*Fernández-Pérez, Ramírez-Marcial & González-Espinosa, 2013*).

As a hypothesis of this study, we suppose that there are significant differences ($P < 0.05$) in terms of the increase in the diameter at the base and carbon capture between plantation and natural regeneration seedlings. Therefore, the objectives of this work were (i) to compare the basic bioclimatic conditions (precipitation and temperature) of the study areas in the years of growth of the seedlings evaluated, (ii) to compare the diameter increment at the base, (iii) estimate and compare the accumulated content of biomass and

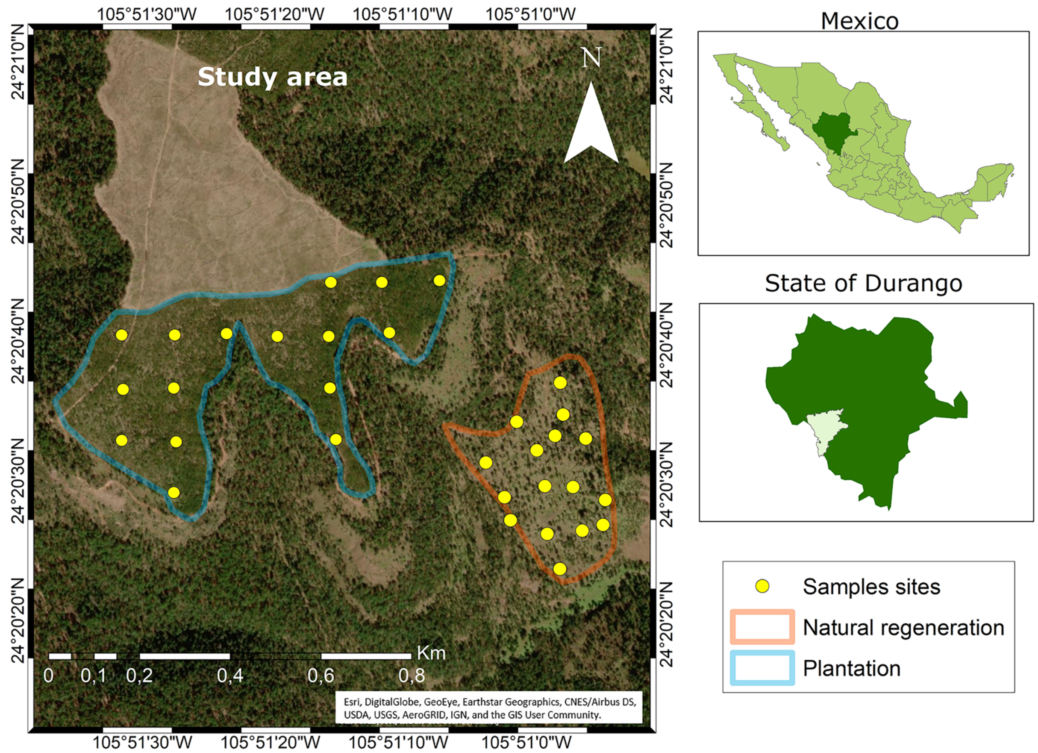

Figure 1 Location of the study area. Source: ARCGIS Software (at Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community). Maps were created using ArcGIS® software by Esri. Copyright ©Esri. All rights reserved. Available at https://www.arcgis.com/index.html#. Full-size DOI: 10.7717/peerj.14774/fig-1

carbon and (iv) estimate the current annual increment (CAI) and mean annual increment (MAI) in basal diameter of *Pinus durangensis* seedlings in a plantation and a stand of natural regeneration.

MATERIALS AND METHODS

Characteristics of the study area

The study area is located on the private property "Las Veredas" in the municipality of San Dimas, in Durango, Mexico (Fig. 1). Data collection was carried out in two sub-stands: (1) clear-cutting with immediate plantation of 21.4 ha located at coordinates 24°20′40″ N and 105°51′20″ W with an elevation of 2,600 m, and (2) seed-tree cutting of 10.2 ha located at 24°20′30″ N and 105°50′58″ W at 2,800 m altitude.

The climate in the study area is temperate with summer rains (CW) and the temperature ranges between −3 and 18 °C (*García, 2004*). The average slope in the clearcut is 9%, while in the seed-tree cutting is 27%. The most frequent rains occur between July and September, which provide an average annual rainfall of 1,000 mm. The soil of both stands is similar and may be classified as Umbrisol (*INEGI, 2007*). The characteristic vegetation is mixed coniferous and broadleaf forests. The first type is dominated by pines, of which the following stand out: *Pinus durangensis*, *P. cooperi* C.E. Blanco, *P. teocote* Schl. et Cham. and *P. strobiformis* Engelm. Of the broadleaves, the oaks stand out, among these:

Table 1 Descriptive statistics of the study sites and sampled seedlings.

Study sites	Area (ha)	Stand variable				Sampled seedlings					
		N		BA (m^2)		Age (years)		DB (cm)		Height (m)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Plantation	21.40	1,881	389	7.41	2.85	8	0.00	8.20	1.06	3.70	0.50
Natural Regeneration	10.20	725	420	10.58	10.01	11	1.45	8.36	2.11	4.50	1.20

Note:
N, Number of trees per hectare; BA, Basal area per hectare (m^2); DB, diameter at the base; SD, Standard deviation.

Quercus rugosa Née and *Q. sideroxyla* Bonpl. There are also trees of some ecologically important species of the genera *Juniperus*, *Arbutus* and *Alnus*, among others (*González-Elizondo et al., 2012*).

Forestry background

The clearcut was carried out in February 2010, and during the rainy season (July and August) of the same year the plantation of *Pinus durangensis* was established.
The seedlings were 12 months old at the time the plantation, which was carried out with a density of 2,500 plants/ha. The plantation was produced with germplasm from trees with superior genetic characteristics that grow in seed tree stands near the study area. Land preparation consisted of clearing, scattering and doing a controlled burn of forest waste. To improve soil conditions, the soil was plowed using a D-6 track-type tractor equipped with a ripper. On the other hand, the seed-tree cutting was carried out in 2007 with a cut intensity of standing trees of 58% for the genus Pinus, 100% for Quercus, 100% for Juniperus and 100% for Arbutus, leaving approximately 25 fifty-year-old mother trees per hectare of *Pinus durangensis* to promote the natural regeneration.

The monthly climatic data of total precipitation, as well as the maximum, minimum and mean temperatures for the grid centered on the study area (24–24.5°N, 105–105.5°W) were obtained through the KNMI-Climate database (*Van Oldenborgh & Burgers, 2005*) as plantation growth and natural regeneration in the early years occurred at different times.

Field evaluation

To collect the data, 32 circular plots of 100 m^2 were established (16 in the plantation and 16 in the seed-tree cutting). These were distributed through a completely randomized design according to the methodology established by *CONAFOR (2013)*. Between the plantation and the natural regeneration, there is a distance of approximately 350 m. At each plot, variables such as diameter at the base (cm) and height (m) were measured using a Vernier and a 5 m tape measure, respectively. A reference tree was selected according to the plot´s mode diameter and destructively sampled from each plot. The sampling of the felled seedlings involved the collection of one cross-section at the base of the stump. In total, 32 *Pinus durangensis* seedlings were felled (16 in the plantation and 16 in the stand with seed-tree cutting). Table 1 presents the descriptive statistics of the studied sites and sampled seedlings.

The cross-sections were labeled, dried and polished, and each growth ring was subsequently measured using a stereomicroscope with micrometer precision in the dendroecology laboratory at the Facultad de Ciencias Forestales y Ambientales, Universidad Juárez del Estado de Durango. The average ring width was estimated by the average of the measurement in four directions. For the comparison of ring width, only the first 7 years of growth were taken into account since the age of the seedlings in both studied sites was different. The data was obtained in July 2018; therefore, the measurement of ring widths was done retrospectively from the year 2017 because the last ring of the plantation was still under development.

Annual biomass estimation and carbon content

The aboveground seedlings biomass was estimated with the equation developed and recommended by *Návar et al. (2004)* for *Pinus durangensis* for trees with basal diameters ranging from 5 to 15 cm. It uses the basal diameter as the predictive variable (Eq. (1), R^2 = 0.86).

$$Y_i = a(DB)^b \tag{1}$$

where:

Y_i = Total dry biomass

a = 0.0199 y b = 2.5488

DB = Diameter at the base of the tree (cm)

Annual values of aboveground tree were derived from the difference of total biomass values between two consecutive years. The carbon content was calculated according to the percentage indicated by *Hernández-Vera et al. (2017)*, who reported a concentration of 50.36% of the total biomass *Pinus durangensis*.

Tree increment estimation

The increment for both studied kind of seedlings was assessed on the cross-sections collected at the base of the sampled trees. The individual tree-ring width growth, individual tree current annual diameter increment (CAI), and mean annual diameter increment (MAI) were accounted for years 1 to 7. The tree-ring width growth corresponded with the individual tree annual ring width average (mm), CAI represented the individual tree basal diameter increment observed for each of the studied years (cm/year), while the MAI was the total individual tree diameter increment up to a given age divided by that age (cm/year) (*Cardalliaguet et al., 2019*).

Statistical analysis

Due to the use of hierarchical data obtained from the same trees, differences in tree-ring width growth, biomass and the carbon accumulation among seedlings of studied sites were evaluated with a two-way mixed-effects analysis of variance model (*Snedecor & Cochran, 1989*; *Oberfeld & Franke, 2013*). In our data, the mixed-effects models attempt to generalize results beyond both the sampled sites and seedlings. Thus, to take into account the possible temporal correlation between data from the same individual, the studied sites (*i.e.*,

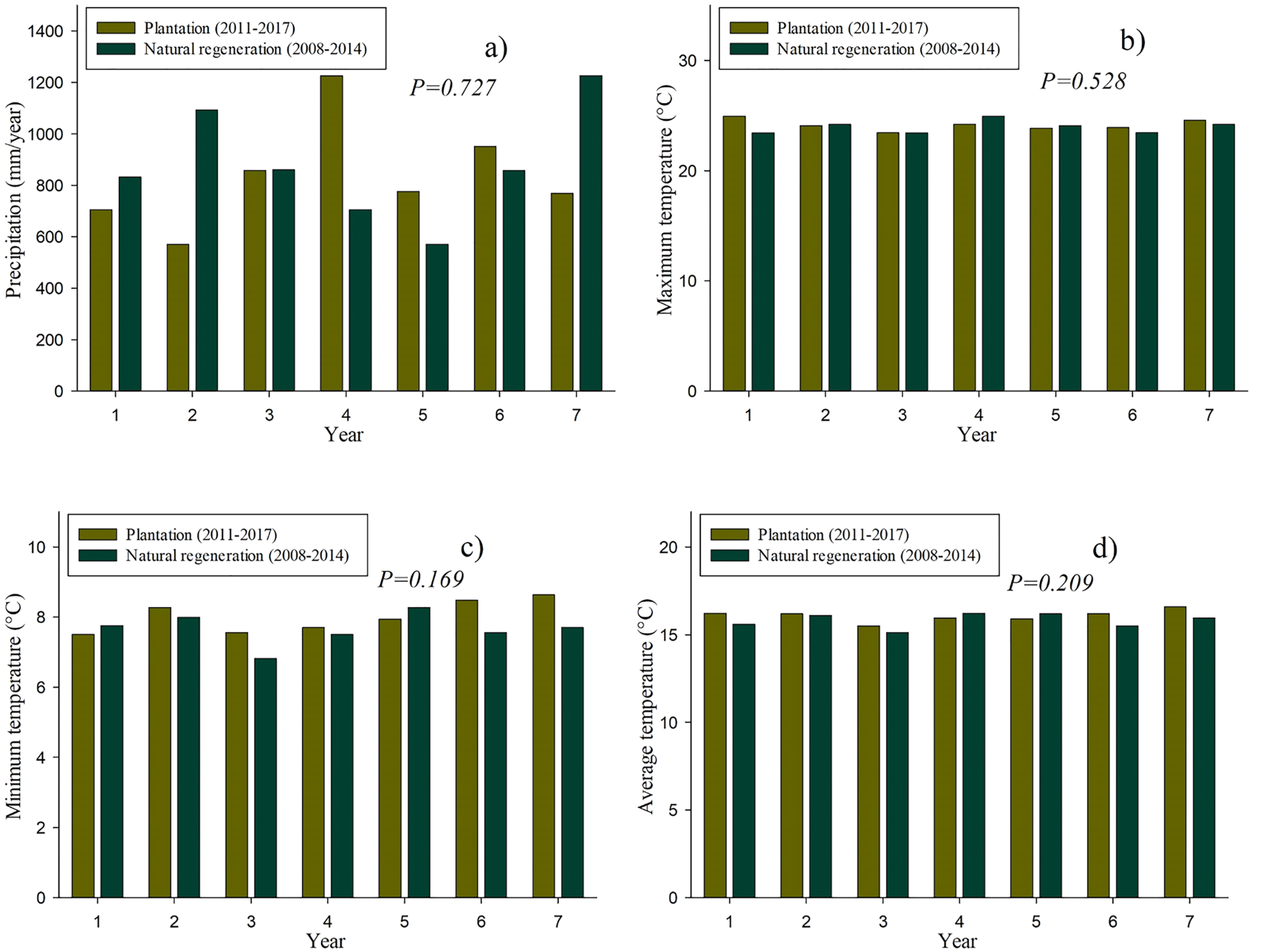

Figure 2 Historical climate data on the plantation (2011–2017) and natural regeneration (2008–2014): Precipitation (A), maximum of monthly average temperature (B), minimum of monthly average temperature (C) and average temperature (D).
Full-size DOI: 10.7717/peerj.14774/fig-2

plantation or natural regeneration) and evaluated years (1 to 7) were classified as the fixed factors, while the basal diameter of trees at age *i* was used as a random factor. Multiple comparisons were conducted when there were significant differences among means of plantation and natural regeneration seedlings with the Tukey Means Comparison Test ($P < 0.05$). All statistical analyses were performed in the statistical software R® version 3.5.3 (*R Core Team, 2019*).

RESULTS

Figure 2 shows the historical data of the precipitation and temperature that occurred both in the plantation and natural regeneration sites in their first 7 years. It should be noted that

Table 2 Pairwise comparisons for annual tree-ring width growth of seedlings in plantation and natural regeneration.

Comparison	Year	*t* ratio	*P* value
Plantation—Natural regeneration	1	−0.689	0.4915^{ns}
Plantation—Natural regeneration	2	2.172	0.0312*
Plantation—Natural regeneration	3	4.133	0.0001***
Plantation—Natural regeneration	4	4.175	<0.0001***
Plantation—Natural regeneration	5	5.946	<0.0001***
Plantation—Natural regeneration	6	3.722	0.0003***
Plantation—Natural regeneration	7	1.381	0.1688^{ns}

Notes:
* ($P < 0.05$).
*** ($P < 0.001$).
ns, not significant.

no significant differences ($P > 0.05$) were found neither in precipitation nor in temperature among the studied sites.

Tree-ring width growth

Results of mixed-effects analysis of variance model indicated that both fixed and random factors show significant effects on annual tree-ring width growth ($P < 0.01$), which means that there are significant differences among studied sites and years when they are kept constant. Table 2 shows the pairwise comparisons for annual tree-ring width growth. There were significant differences on tree-ring width growth for most evaluated years, except at ages 1 and 7 ($P > 0.01$). Figure 3 shows that annual tree-ring width growth is significantly greater in seedlings from plantation than in trees naturally regenerated at 2–6 years. It is interesting to observe that annual tree-ring width growth of seedlings in the natural regeneration shows an upward growth tendency from the beginning to the end of the evaluation period, whereas, the annual tree-ring width growth of trees in plantation shows a decrease in growth at 6 and 7 years.

Biomass and carbon accumulation

Results of mixed-effects analysis of variance model indicated that both fixed and random factors show significant effects on individual biomass and carbon accumulation ($P < 0.01$), which means that both biomass and carbon accumulation differ among sites and annual rates when they are kept constant. Table 3 shows the pairwise comparisons for annual biomass and carbon accumulation of seedlings in plantation and natural regeneration sites. The significant differences on biomass and carbon accumulation were observed at ages of 5, 6 and 7 ($P > 0.01$). Figure 4 shows that important values of biomass accumulation are observed at 4–7 years, especially in the plantation as a product of a greater tree-ring width growth in comparison to the naturally regenerated site. The estimates of biomass and carbon accumulation by tree age both for plantation and natural regeneration are shown in Table 4. After 7 years of evaluation, the seedlings in the plantation contain twice the biomass and carbon allocation than those evaluated in the natural regeneration. In the plantation, a 7-year-old tree has on average 4.38 and 2.21 kg of biomass and carbon

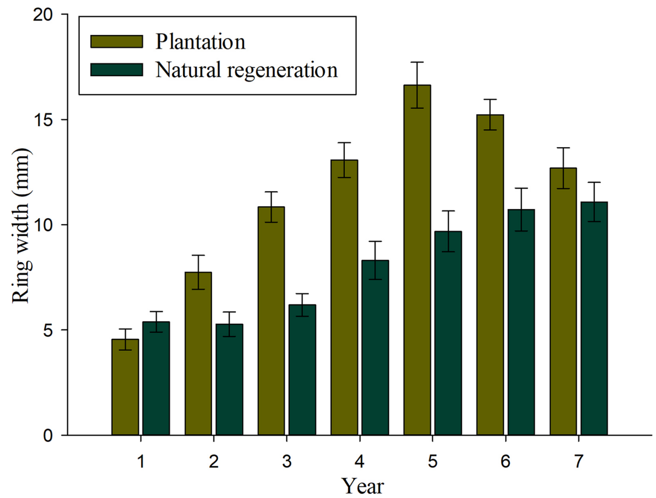

Figure 3 **Average values (bars) and standard error (whiskers) of the ring width per year recorded in *Pinus durangensis* seedlings from plantations and natural regeneration.**
Full-size DOI: 10.7717/peerj.14774/fig-3

Table 3 **Pairwise comparisons for the annual accumulation of biomass and carbon of seedlings in plantation and natural regeneration sites.**

Comparison	Year	Biomass		Carbon	
		t ratio	*P* value	*t* ratio	*P* value
Plantation—Natural regeneration	1	−0.062	0.9506ns	−0.062	0.9506ns
Plantation—Natural regeneration	2	0.057	0.9548ns	0.057	0.9548ns
Plantation—Natural regeneration	3	1.026	0.3064ns	1.026	0.3064ns
Plantation—Natural regeneration	4	1.766	0.0794ns	1.766	0.0794ns
Plantation—Natural regeneration	5	4.057	0.0001***	4.057	0.0001***
Plantation—Natural regeneration	6	5.307	0.0001***	5.307	0.0001***
Plantation—Natural regeneration	7	5.001	0.0001***	5.001	0.0001***

Notes:
*** ($P < 0.001$).
ns, not significant.

content, respectively, whereas a naturally-regenerated seedling at the same age has on average 2.16 and 1.09 kg of biomass and carbon content, respectively (Table 4).

CAI and MAI

The evolution of the CAI and the MAI with respect to the age of the seedlings in the plantation and the natural regeneration is shown in Fig. 5. Individual tree basal diameter increments both CAI and MAI were higher in the plantation at all analyzed ages in comparison to the naturally regenerated site. Trees from plantation exhibit an increasing linear trend on CAI at 1–5 years, and a decrease at 6 and 7 years (Fig. 5A), whereas seedlings from natural regeneration show a positive linear trend at all evaluated years (Fig. 5B). The maximum value of CAI in plantation seedlings was observed at 5 years, whereas this value in naturally regenerated seedlings is probably still not reached.

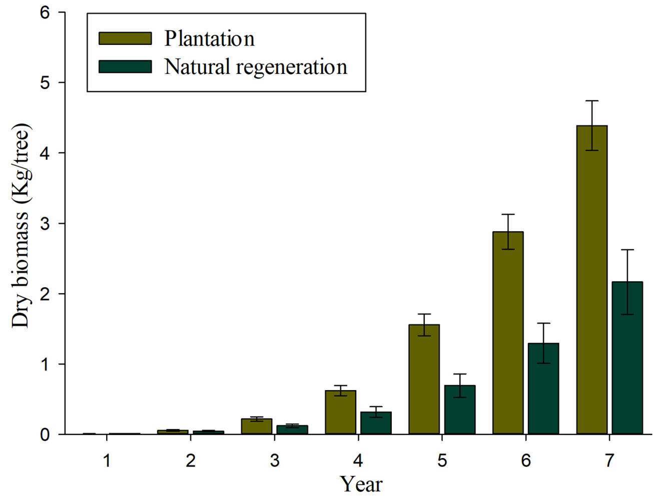

Figure 4 Average values (bars) and standard error (whiskers) of the total aerial biomass accumulated in *Pinus durangensis* seedlings from plantation and natural regeneration.
Full-size DOI: 10.7717/peerj.14774/fig-4

Table 4 Annual average biomass and carbon accumulation in seedlings of *Pinus durangensis* in plantation and natural regeneration sites.

Year	Biomass (kg/tree)				Carbon (kg/tree)			
	Plantation		Natural regeneration		Plantation		Natural regeneration	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	0.006	0.005	0.011	0.008	0.003	0.003	0.006	0.004
2	0.047	0.045	0.034	0.029	0.024	0.023	0.017	0.015
3	0.164	0.086	0.077	0.066	0.082	0.043	0.039	0.033
4	0.404	0.183	0.195	0.203	0.203	0.092	0.098	0.102
5	0.934	0.397	0.376	0.369	0.470	0.200	0.189	0.186
6	1.324	0.451	0.599	0.509	0.667	0.227	0.302	0.256
7	1.509	0.608	0.874	0.728	0.760	0.306	0.440	0.366
Total	4.388	1.776	2.165	1.912	2.210	0.894	1.090	0.963

Note:
SD, Standard deviation.

DISCUSSION

In this article, we did not find significant effects in precipitation and temperature among the two studied sites, which make results on individual tree growth, biomass and carbon content comparable regarding these two environmental variables. However, even though precipitation and temperature are similar at both sites, it is well-known that these factors have a significant influence on the radial growth of tree species in Mexican forests (*Rodríguez Flores et al., 2014*; *Chávez-Gándara et al., 2017*).

The tree-ring width growth is the most used parameter to evaluate tree growing of forests (*Dobner, Huss & Tomazello Filho, 2018*). Both the kind and age of seedlings showed significant effects on annual tree-ring width growth. The planted seedlings showed a

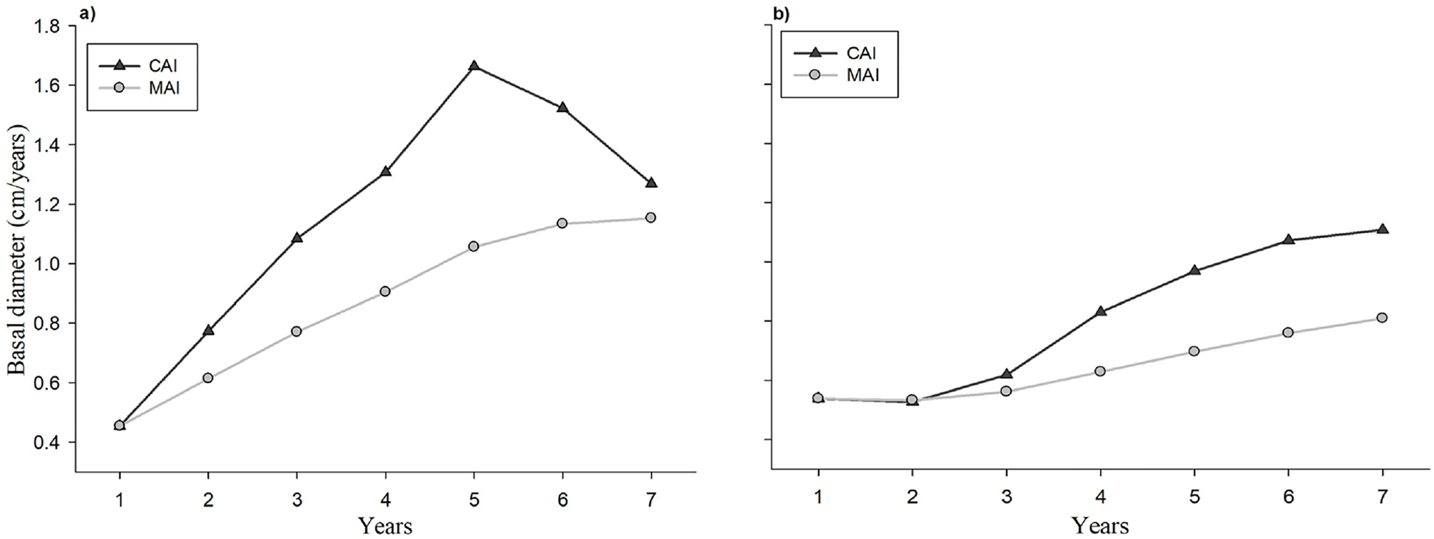

Figure 5 **Evolution of the current annual increment (CAI) and average annual increment (AAI) in basal diameter of the plantation (A) and natural regeneration (B).**
Full-size DOI: 10.7717/peerj.14774/fig-5

constant increase from their establishment until age 5, while in the natural regeneration, this behaviour was maintained during all the evaluation periods. The decrease in tree-ring width growth observed in the plantation at 6–7 years may be due to the effect of competition that increases with stand age (*Soto-Cervantes et al., 2016*), especially in areas established with a high density like the one used in this work. On the other hand, the significantly lower tree density recorded in natural regeneration explains the constant increase on annual tree-ring width growth observed during the 7 years. Results on annual tree-ring width growth observed in the plantation of *Pinus durangensis* suggest that when a density of 2,500 plants ha^{-1} is used, a pre-commercial thinning is needed at age 5 (1 year before tree growth reduction) to reduce tree competition and promote basal diameter growth. Studies have shown that a greater spacing between trees of pine species generates high availability of light and nutrients, which benefits growth both in diameter and height (*Baldwin et al., 2000*; *Arias, 2005*). The significantly higher tree-ring width growth recorded in the plantation at most evaluated ages may be also explained by the fact that in this site, seedlings have more light availability due to the absence of seed-trees in this site, and therefore, light is better assimilated to develop their maximum growth capacity and variations soil preparation activities during planting (*Plateros-Gastélum et al., 2018*; *Moretti et al., 2019*; *Landis, 2011*; *Pérez-Luna et al., 2020*). However, significant differences in width growth may also be partly due to variations in soil properties, slope, genetic differences, aspects that have not been evaluated in this study due to data limitations. According to *Måren et al. (2015)* tree growth is affected also by factors like climate, topography, aspect, inclination of slope and soil type. For example, tree growth is expected to be lower on steeply sloping sites than on flat or gently sloping sites because slope is one of the factors controlling the processes of infiltration of surface water into the subsurface (*Morbidelli et al., 2019*).

Biomass and carbon allocation in forests are important elements for timber production, carbon sequestration and the generation of other environmental services (*Graciano-Ávila et al., 2019*). In this article both the studied sites and seedlings age show significant differences in annual biomass and carbon accumulation ($P < 0.01$). The significantly higher annual biomass and carbon accumulation observed in the plantation trees may be due to the existence of a higher light environment which produces a high photosynthetic ability and favor growth in seedlings in comparison to the natural regeneration that has still seed-trees producing shadow (*Poorter et al., 2012*). However, the observed significant differences in biomass and carbon may be also caused by varying site conditions which greatly depend on soil quality, unfortunately such a soil data was not available for the present study. Results show that a 7-year-old seedling growing in the plantation produces an average of two times more biomass and carbon (*i.e.*, 4.38 and 2.21 kg, respectively) than a seedling of the same age growing in the natural regeneration (2.16 and 1.09 kg). Considering that the current stand density is of 1,881 trees ha^{-1}, the potential for carbon sequestration of the studied 7-year-old plantation of *Pinus durangensis* is of 4.15 tons ha^{-1}. These estimates of biomass and carbon content are lower than the estimations reported by *Pacheco-Escalona et al. (2007)* for a 6-year-old plantation of *Pinus greggii* Englem. With averages of 8.0 and 4.08 kg per tree, respectively. Higher biomass and carbon content in the *Pinus greggii* plantation may be a reflection of the use of higher number of seedlings per hectare during planting (4425), a better growth rate, and site conditions (*Rodríguez-Vásquez et al., 2021*).

The study of the current annual increment (CAI) and the mean annual increment (MAI) allow to define the optimum harvest age if the management objective is to maximize long-term yield (*Santiago-García et al., 2015*; *Cardalliaguet et al., 2019*). In this study, the maximum CAI point in basal diameter of seedlings in the evaluation period occurred at year 5 in the plantation, whereas in the natural regeneration it had not occurred yet. Moreover, it was observed that the curves of the CAI and MAI in basal diameter increment had not meet during the evaluation period, which indicate that is not yet possible to know the stand's optimal harvest age (age at which CAI = MAI), and therefore, new studies at older ages both in plantation and natural regeneration for the studied tree species are required. This result agrees with the study of *Mejía-Bojórquez, García Rodríguez & Muñoz Flores (2015)* who mention that for forest plantations of *Pinus durangensis*, younger than (15-years old), the intersection between the CAI and MAI curves has been not reported.

CONCLUSIONS

The plantation and natural regeneration seedlings studied in this work showed significant differences on annual tree-ring width growth and annual biomass and carbon accumulation, the plantation exhibiting higher rates at most evaluated ages. Better tree growth rates observed in plantation seedlings are attributed mainly to silvicultural practices but can be also caused by variations in soil properties, slope and genetic differences, aspects that have not been evaluated in this study due to data limitations. Both kind of seedlings still do not show their maximum growth because the lines of CAI and MAI in basal diameter still do not intersect. The study reveals that forest plantations of

Pinus durangensis can be successfully established in the forests of Durango, Mexico, favoring both CO_2 capture among other ecosystem services.

ACKNOWLEDGEMENTS

The authors are grateful to Andrea Losoya Simental for help with English language editing.

ADDITIONAL INFORMATION AND DECLARATIONS

Funding

This work was supported by Consejo Nacional de Ciencia y Tecnología (CONACYT-No. 297160). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Grant Disclosures

The following grant information was disclosed by the authors:
Consejo Nacional de Ciencia y Tecnología (CONACYT): 297160.

Competing Interests

The authors declare that they have no competing interests.

Author Contributions

- Jesús Alejandro Soto-Cervantes conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.
- José Javier Corral-Rivas conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.
- Pedro Antonio Domínguez-Calleros conceived and designed the experiments, performed the experiments, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.
- Pablito Marcelo López-Serrano performed the experiments, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.
- Eusebio Montiel-Antuna analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.
- Emily García-Montiel analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.
- Alberto Pérez-Luna conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.

Data Availability

The following information was supplied regarding data availability:

The raw data are available in the Supplemental File.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.14774#supplemental-information.

REFERENCES

Arias D. 2005. Morfometría del árbol en plantaciones forestales tropicales. *Revista Forestal Kurú* **2(5)**:2–11. *Available at http://www.scielo.org.mx/scielo.php?script=sci_nlinks&ref=4447938&pid=S1405-0471201200020000400006&lng=es* (accessed 26 July 2022).

Baldwin VC, Peterson KD, Clark IIIA, Ferguson RB, Strub MR, Bower DR. 2000. The effects of spacing and thinning on stand and tree characteristics of 38-year-old loblolly pine. *Forest Ecology and Management* **137(1–3)**:91–102 DOI 10.1016/S0378-1127(99)00340-0 (accessed 26 July 2022).

Burney O, Aldrete A, Álvarez Reyes R, Prieto Ruíz JÁ, Sánchez Velázquez JR, Mexal JG. 2015. México—Addressing challenges to reforestation. *Journal of forestry* **113(4)**:404–413 DOI 10.5849/jof.14-007.

Cardalliaguet L, Muñoz AA, Humanes V, Aguilera-Betti I, Génova M, LeQuesne C, Rojas-Badilla M, Veas C. 2019. Crecimiento radial de *Abies pinsapo* en el sur de Chile: relaciones con el clima local y su comparación con poblaciones naturales en España. *Bosque (Valdivia)* **40(2)**:141–152 DOI 10.4067/s0717-92002019000200141.

Chávez-Gándara MP, Cerano-Paredes J, Nájera-Luna JA, Pereda-Breceda V, Esquivel-Arriaga G, Cervantes-Martínez R, Cambrón-Sandoval VH, Cruz-Cobos F, Corral-Rivas S. 2017. Reconstrucción de la precipitación invierno-primavera con base en anillos de crecimiento de árboles para la región de San Dimas, Durango, México. *Bosque (Valdivia)* **38(2)**:387–399 DOI 10.4067/S0717-92002017000200016.

CONAFOR. 2013. Metodología para realizar y presentar los informes de sobrevivencia inicial (ISI) de las plantaciones forestales comerciales (aspectos técnicos). *Available at http://www.conafor.gob.mx/apoyos/index.php/inicio/download/1422* (accessed 3 February 2022).

Dobner M, Huss J, Tomazello Filho M. 2018. Wood density of loblolly pine trees as affected by crown thinnings and harvest age in southern Brazil. *Wood Science and Technology* **52(2)**:465–485 DOI 10.1007/s00226-017-0983-9.

Fernández-Pérez L, Ramírez-Marcial N, González-Espinosa M. 2013. Reforestación con *Cupressus lusitanica* y su influencia en la diversidad del bosque de pino-encino en Los Altos de Chiapas, México. *Botanical Sciences* **91(2)**:207–216 DOI 10.17129/botsci.415.

Flores A, Pineda Ojeda T, Flores Ayala E. 2019. Potencial de reforestación de seis especies de pino para la restauración de zonas degradadas. *Revista Mexicana de Ciencias Forestales* **10(55)**:171–179 DOI 10.29298/rmcf.v10i55.604.

García ME. 2004. *Modificaciones al sistema de clasificación climática de Köppen*. 6 Ed. Instituto de Geografía, Universidad Nacional Autónoma de México. *Available at http://www.publicaciones.igg.unam.mx/index.php/ig/catalog/book/83* (accessed 3 February 2022).

González-Cásares M, Pompa-García M, Venegas-González A, Domínguez-Calleros P, Hernández-Díaz J, Carrillo-Parra A, González-Tagle M. 2019. Hydroclimatic variations reveal differences in carbon capture in two sympatric conifers in northern Mexico. *PeerJ* **7(5)**:e7085 DOI 10.7717/peerj.7085.

González-Elizondo MS, González-Elizondo M, Tena-Flores JA, Ruacho-González L, López-Enríquez IL. 2012. Vegetación de la sierra madre occidental, México: una síntesis. *Acta Botánica Mexicana* **100**:351–403 DOI 10.21829/abm100.2012.40.

Graciano-Ávila G, Alanís-Rodríguez E, Aguirre-Calderón OA, González-Tagle MA, Treviño-Garza EJ, Mora-Olivo A, Buendía-Rodríguez E. 2019. Estimation of volume, biomass and carbon content in a forest of temperate-cold climate of Durango. *Mexico Revista Fitotecnia Mexicana* **42(2)**:119–127 DOI 10.35196/rfm.2019.2.119-127.

Grossnickle SC. 2012. Why seedlings survive: influence of plant attributes. *New Forests* **43(5)**:711–738 DOI 10.1007/s11056-012-9336-6.

Hernández-Vera D, Pompa-García M, Yerena-Yamallel JI, Alanís-Rodríguez E. 2017. Variación de la concentración de carbono en tres especies mexicanas de pino. *Bosque (Valdivia)* **38(2)**:381–386 DOI 10.4067/S0717-92002017000200015.

Hernández-Zaragoza P, Valdez-Lazalde JR, Aldrete A, Martínez-Trinidad T. 2019. Evaluación multicriterio y multiobjetivo para optimizar la selección de áreas para establecer plantaciones forestales. *Madera y Bosques* **25(2)**:1–17 DOI 10.21829/myb.2019.2521819.

INECC-SEMARNAT. 2015. Primer Informe Bienal de Actualización ante la Convención Marco de las Naciones Unidas sobre el Cambio Climático. Ciudad de México, México. *Available at https://www.gob.mx/cms/uploads/attachment/file/40746/2015_bur_mexico.pdf* (accessed 3 February 2022).

INEGI. 2007. Conjunto de datos vectorial edafológico. Escala 1:250,000 Serie II. Continuo Nacional Durango. *Available at https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=702825236007* (accessed 11 October 2022).

Landis TD. 2011. The target plant concepts-a history and brief overview. In: Riley LE, Haase DL, Pinto JR, eds. *National Proceedings: Forest and Conservation Nursery Associations-2010*. Washington, D. C.: Fort Collins.

López-Serrano PM, Corral-Rivas JJ, López-Sánchez CA, Paz Pellat F, Wong González J, Torres Alamilla R. 2015. Programa Mexicano del Carbono. Serie: síntesis nacional. Estado actual del conocimiento del ciclo del carbono y sus interacciones en México. In: Paz Pellat F, Wong González J, Torres Alamilla R, eds. *Capítulo 1. Mapeo espacial de almacenes de carbono en el bosque templado del estado de Durango*. Tabasco, México: Centro del Cambio Global y Sustentabilidad en el Sureste, A.C., Universidad Juárez Autónoma de Tabasco, 158–163. *Available at https://www.researchgate.net/profile/Fernando-Ayala-5/publication/331686242_Secuestro_de_carbono_en_suelos_con_deficit_hidrico_en_la_cuenca_de_la_Paz_Baja_California_Sur_noroeste_de_Mexico/links/5c87e8eba6fdcc38174f8630/Secuestro-de-carbono-en-suelos-con-deficit-hidrico-en-la-cuenca-de-la-Paz-Baja-California-Sur-noroeste-de-Mexico.pdf#page=158* (accessed 26 July 2022).

Mejía-Bojórquez M, García Rodríguez JL, Muñoz Flores HJ. 2015. Evaluación de plantaciones de cuatro especies forestales en el estado de Durango. REAXION: ciencia y Tecnología Universitaria (Versión imprimible). *Available at http://reaxion.utleon.edu.mx/Art_Impr_Evaluacion_plantaciones_cuatro_especies_forestales_Durango.html* (accessed 3 February 2022).

Montes de Oca-Cano E, Ramírez-García P, Nájera Luna JA, Méndez-Gonzáles J, Graciano Luna JDJ. 2008. Flujos y asimilación de CO_2 de *Pinus durangensis* (Martínez M.) en la Región de El Salto, Durango, México. *InterSedes* **9(17)**:181–192.

Morbidelli R, Corradini C, Saltalippi C, Flammini A, Dari J, Govindaraju RS. 2019. A new conceptual model for slope-infiltration. *Water* **11(4)**:678 DOI 10.3390/w11040678.

Moretti AP, Olguín FY, Pinazo M, Gortari F, Vera Bahima J, Graciano C. 2019. Supervivencia y crecimiento de un árbol nativo maderable bajo diferentes coberturas de dosel en el Bosque Atlántico, Misiones, Argentina. *Ecología Austral* **29(1)**:099–111 DOI 10.25260/ea.19.29.1.0.779.

Måren IE, Karki S, Prajapati C, Yadav RK, Shrestha BB. 2015. Facing north or south: does slope aspect impact forest stand characteristics and soil properties in a semiarid trans-Himalayan valley? *Journal of Arid Environments* **121(5)**:112–123 DOI 10.1016/j.jaridenv.2015.06.004.

Návar JDJ, González N, Graciano Luna JDJ, Dale V, Parresol B. 2004. Additive biomass equations for pine species of forest plantations of Durango. *Mexico Madera y Bosques* **10(2)**:17–28 DOI 10.21829/myb.2004.1021272.

Oberfeld D, Franke T. 2013. Evaluating the robustness of repeated measures analysis: the case of small sample sizes and nonnormal data. *Behavior Research Methods* **45(3)**:792–812 DOI 10.3758/s13428-012-0281-2.

Pacheco-Escalona FC, Aldrete A, Gómez Guerrero A, Fierros González AM, Cetina Alcalá VM, Vaquera Huerta H. 2007. Almacenamiento de carbono en la biomasa aérea de una plantación joven de *Pinus greggii* Engelm. *Revista Fitotecnia Mexicana* **30(3)**:251–254 DOI 10.35196/rfm.2007.3.251.

Patiño Forero S, Suárez Santos LN, Andrade Castañeda HJ, Segura Madrigal MA. 2018. Captura de carbono en biomasa en plantaciones forestales y sistemas agroforestales en Armero-Guayabal, Tolima, Colombia. *Revista de Investigación Agraria y Ambiental* **9(2)**:121–134 DOI 10.22490/21456453.2312.

Pensado-Fernández JA, Sánchez-Velásquez LR, Pineda-López M, Díaz-Fleischer F. 2014. Plantaciones forestales vs. regeneración natural in situ: el caso de los pinos y la rehabilitación en el Parque Nacional Cofre de Perote. *Botanical Sciences* **92(4)**:617–622 DOI 10.17129/botsci.109.

Plateros-Gastélum PA, Reyes-Hernández VJ, Velázquez-Martínez A, Hernández-de la Rosa P, Campos-Ángeles GV. 2018. Disponibilidad de luz bajo dosel en rodales de *Abies* religiosa. *Madera y Bosques* **24(3)**:1–15 DOI 10.21829/myb.2018.2431711.

Poorter H, Niklas KJ, Reich PB, Oleksyn J, Poot P, Mommer L. 2012. Biomass allocation to leaves, stems and roots: metaanalyses of interspecific variation and environmental control. *New Phytologist* **193(1)**:30–50 DOI 10.1111/j.1469-8137.2011.03952.x.

Prieto Ruíz JÁ, Aldrete A, Sánchez Velázquez JR, Hernández Díaz JC. 2016. Antecedentes sobre las reforestaciones en México. In: Prieto Ruíz JA, Goche Télles JR, eds. *Las Reforestaciones en México, Problemática y Alternativas de Solución*. Durango, México: Universidad Juárez del Estado de Durango.

Pérez-Luna A, Wehenkel C, Prieto-Ruíz JÁ, López-Upton J, Hernández-Díaz JC. 2020. Survival of side grafts with scions from pure species *Pinus engelmannii* Carr. and the *P. engelmannii*× *P. arizonica* Engelm. var. arizonica hybrid. *PeerJ* **8(6)**:e8468 DOI 10.7717/peerj.8468.

R Core Team. 2019. *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing. *Available at https://www.R-project.org/* (accessed 3 February 2022).

Ramírez Santiago R, Ángeles Pérez G, Clark Tapia R, Cetina Alcalá VM, Plascencia Escalante O, Hernández de La Rosa P. 2015. Efectos del manejo forestal en la repoblación de *Pinus* spp. en la Sierra Norte de Oaxaca, México. *Revista Mexicana de Ciencias Forestales* **6(32)**:49–62 DOI 10.29298/rmcf.v6i32.98.

Rodríguez Flores FJ, Pompa-García M, Mallén Rivera C, Goche Télles R. 2014. Modelos dendroclimáticos para crecimiento radial forestal. *Revista Mexicana de Ciencias Forestales* **5(26)**:30–37 DOI 10.29298/rmcf.v5i26.288.

Rodríguez-Vásquez ME, Rodríguez-Ortiz G, Enríquez-Del Valle JR, Campos-Ángeles GV, Velasco-Velasco VA, Hernández-Hernández A. 2021. Ensayos de progenies y huertos semilleros de especies forestales en México. *Revista Mexicana de Agroecosistemas* **8(1)**:79–88.

Santiago-García W, de los Santos-Posadas HM, Ángeles-Pérez G, Valdez-Lazalde JR, Corral-Rivas JJ, Rodríguez-Ortiz G, Santiago-García E. 2015. Modelos de crecimiento y rendimiento de totalidad del rodal para *Pinus patula*. *Madera y Bosques* **21(3)**:95–110 DOI 10.21829/myb.2015.213459.

Snedecor GW, Cochran WG. 1989. *Statistical Methods*. Ames, Iowa: Iowa State Univ Press.

Soto-Cervantes JA, Carrillo-Parra A, Rodríguez-Laguna R, Corral-Rivas JJ, Pompa-García M, Domínguez-Calleros PA. 2020. Survival, growth and carbon content in a forest plantation established after a clear-cutting in Durango. *Mexico PeerJ* **8(2)**:e9506 DOI 10.7717/peerj.9506.

Soto-Cervantes JA, López-Sánchez CA, Corral-Rivas JJ, Wehenkel C, Álvarez-González JG, Crecente-Campo F. 2016. Desarrollo de un modelo de perfil de copa para *Pinus cooperi* Blanco en la UMAFOR 1008, Durango, México. *Revista Chapingo Serie Ciencias Forestales y del Ambiente* **22(2)**:179–192 DOI 10.5154/r.rchscfa.2015.09.040.

Stewart JF, Will R, Crane BS, Nelson CD. 2016. Occurrence of shortleaf×loblolly pine hybrids in shortleaf pine orchards: implications for ecosystem restoration. *Forest Science* **63(2)**:225–231 DOI 10.5849/forsci.15-167.

Vallejo VR, Smanis A, Chirino E, Fuentes D, Valdecantos A, Vilagrosa A. 2012. Perspectives in dryland restoration: approaches for climate change adaptation. *New Forests* **43(5)**:561–579 DOI 10.1007/s11056-012-9325-9.

Van Oldenborgh GJ, Burgers G. 2005. Searching for decadal variations in ENSO precipitation teleconnections. *Geophysical Research Letters* **32(15)**:L15701 DOI 10.1029/2005GL023110.

Vargas-Larreta B, López-Sánchez CA, Corral-Rivas JJ, López-Martínez JO, Aguirre-Calderón CG, Álvarez-González JG. 2017. Allometric equations for estimating biomass and carbon stocks in the temperate forests of North-Western Mexico. *Forests* **8(8)**:269 DOI 10.3390/f8080269.