Survival, growth and carbon content in a forest plantation established after a clear-cutting in Durango, Mexico

Jesús Alejandro Soto-Cervantes[1], Artemio Carrillo Parra[2], Rodrigo Rodríguez Laguna[3], José Javier Corral-Rivas[4], Marín Pompa-García[4], Pedro Antonio Domínguez Calleros[4]

[1] Programa Institucional de Doctorado en Ciencias Agropecuarias y Forestales, Universidad Juárez del Estado de Durango, Durango, México
[2] Instituto de Silvicultura e Industria de la Madera, Universidad Juárez del Estado de Durango, Durango, México
[3] Instituto de Ciencias Agropecuarias, Universidad Autónoma del Estado de Hidalgo, Tulancingo, Hidalgo, México.
[4] Facultad de Ciencias Forestales, Universidad Juárez del Estado de Durango, Durango, México

Corresponding Author:
Pedro Antonio Domínguez Calleros
Río Papaloapan y Blvd. Durango S/N Col. Valle del Sur, Durango, Durango, 34000, México
Email address: pdomingc@hotmail.com

Abstract

Background. Forest plantations play an important role in carbon sequestration, helping to mitigate climate change. In this study, survival, biomass, growth rings and annual carbon content storage were evaluated in a mixed *Pinus durangensis* and *P. cooperi* plantation that was established after a clear-cutting. The plantation is eight years old and covers an area of 21.40 ha.
Methods. Sixteen sites of 100 m^2 were distributed randomly. At each site, two trees distributed proportionally to the diametric categories were destructively sampled (one per tree species). Two cross-sections were cut from each tree: The first at the base of the stump and the second at 1.30 m. The width of tree rings of the first cross-section was measured using a stereoscopic microscope with precision in microns (µm). The year-by-year basal diameter of each tree was recorded and biomass and carbon content was estimated using allometric equations.
Results. The estimated survival was 75.2%. The results of the ANOVA showed significant differences between the year-by-year width records of tree rings, the highest value corresponding to the fifth year. The average carbon sequestration per year is 0.30 kg for both studied tree species.
Conclusions. *P. durangensis* and *P. cooperi* plantations adapt and develop well in Durango forests when they are established in areas that are subjected to clear-cutting.

Key words: Growth rings, biomass, basal diameter.

Introduction

In addition to the multiple benefits that forest ecosystems provide to society, forests can capture significant amounts of greenhouse gases (GHG), particularly carbon dioxide *(Benjamín & Masera, 2001; Aguirre-Calderón & Jiménez-Pérez, 2011; Martínez et al., 2016; González-Cásares et al., 2019)*. However, the vegetation cover is not always adequate due to inappropriate forest management, and so the establishment of trees is necessary. Whatever the purpose of this action, reforestation (forest plantations) is an excellent alternative to mitigate high atmospheric concentrations of CO_2 and, at the same time, reducing global warming *(van Minnen et al., 2008; López-Reyes et al., 2016; Patiño et al., 2018; Ramírez-López & Chagna-Avila, 2019)*. Proper soil management also contributes significantly to the expansion of the carbon sink in the terrestrial biosphere *(Zambrano, Franquis & Infante, 2004; Caviglia, Wingeyer & Novelli, 2016; Halifa-Marín et al., 2019)*.

The Mexican forests have been considered as diverse in terms of tree species *(Medrano et al., 2017)* and have great potential as a carbon sink, and therefore are considered essential to assess carbon content in programs designed to mitigate global warming *(Pompa-García & Sígala-Rodríguez, 2017; Domínguez-Calleros et al., 2017)*. Forest plantations stand out as the most efficient way to consolidate carbon capture capacity, because they are easy to set up and operate *(Reyes, León & Herrero, 2019)*.

Frequently 50% carbon concentration of total biomass has been assumed, however, this methodology leads to inaccurate results, so recent research indicates that there are variations between tree species, trees and tissues (*Pompa-García & Yerena-Yamalliel, 2014; Wang et al., 2015; Hernández-Vera et al., 2017*).

Pinus durangensis and *P. cooperi* are species frequently used in forest reforestations in the Mexican state of Durango *(Prieto et al., 2016)*. However, the main success of forest plantations is the use of quality plants with high survival capacity *(Grossnickle, 2012; Pérez-Luna et al., 2019, 2020)*. The use of quality plants favors success in plantations under climate change conditions *(Vallejo et al., 2012)*. In Mexico 57% of mortality is caused by the poor quality of the plant *(Prieto et al., 2016)*, also another important factor are the deficiencies that occur during the planting process *(Burney et al., 2015)*.

For the proper management of forests in Mexico, including areas planted with the main commercial tree species, different silvicultural systems are employed in order to ensure the regeneration of the site. The Mexican Irregular Forest Management Method (MMOBI) and the Silvicultural Development Method (MDS) *(Solís et al., 2006; Pérez-Verdín et al., 2009; Pérez-Rodríguez et al., 2013)*. The former is used in forest stands with a high tree species richness, and the latter in stands dominated by one or two tree species of pine *(Hernández-Díaz et al., 2008)*. Moreover, in areas covered with little or no slope, the use of a clear-cutting as a regeneration method can be also used. It is characterized by having periodic crops, determined by commercial rotations (*Gadow, Sánchez & Aguirre, 2004)*, and their regeneration can be natural or artificial. If the regeneration is artificial, then the use of fast-growing species is preferable.

Although clear-cutting can be used successfully in Mexican forests, this silvicultural method is still considered inappropriate, considering that complete tree removal of an area is the main cause of degradation, at least at the beginning of the forestry process *(Keenan & Kimmins, 1993; Hernández, Jaeger & Samperio, 2017; Monárrez-González et al., 2018)*. However, its use has economic advantages. On the one hand, an intermediate economic income is possible, through silvicultural interventions (thinnings); on the other, the reduction of competition improves the dimensions of the trees that remain standing and the CO_2 sequestration increases *(Rodríguez-Larramendi et al., 2016; Rodríguez-Ortiz et al., 2019)*. As a hypothesis of this study, we consider that plantations of *Pinus cooperi* and *P. durangensis* established after clear-cuttings, show high

Commented [KM1]: It would be helpful to explain this further…

Commented [KM2]: It would be helpful to explain this further, and to incorporate it smoothly into either the preceding paragraph or the following paragraph…

Commented [KM3]: It would be useful to explain these ideas further… are you making statements about plantsions generally, or plantations in Mexico, or plantations in Durango, or only Pinus plantations in Mexico or Durango? In what ways is plant quality often low, in practice? Are the plants too small or young? Or diseased due to poor nursery management? Or…? Similarly, what kind of common mistakes are made during planting?

Then, in the Materials and Methods section, be sure you describe the plant propagation, plant selection, and planting process in such a way that the reader can see how this plantation was established compared to common mistakes or problems with establishing a plantation.

Commented [KM4]: Are these examples of common, but alternative silvicultural systems? Either use a colon after the preceding sentence, or add wording to this sentence to make it clear how this sentence relates to the previous sentence.

Commented [KM5]: It would be helpful to explain this 'degradation' further, and other potential problems or issues with clear-cutting.

levels of survival and growth, and contribute efficiently to carbon sequestration. Thus, the objectives of this work were to evaluate survival, the width of tree rings and carbon content in a plantation of *Pinus durangensis* and *P. cooperi* at a site exposed to clear-cutting in the State of Durango, Mexico.

Commented [KM6]: Before getting to this point, the Introduction should make it a little clear what scientists and foresters do, and do not, already know about P. durangensis and P. cooperi plantations in Mexico and Durango. What is most 'new' about this study? Is it the altered planting practices that led to higher survival? Is it the measurements of biomass and carbon?

Materials & Methods

Study area

This study was conducted in the private property "Las Veredas", municipality of San Dimas, Durango, Mexico, belonging to the Compañía Silvícola Chapultepec, S. DE R. L. DE C. V., in the coordinates of the site are: 24° 20' 40" N and 105° 51' 20" W (Fig. 1). The climate is temperate with a brief rainy season during the summer months (C_W), and the temperature ranges between -3 and 18 °C *(García, 2004)*. The topography is characterized by hills, with slopes ranging from soft to medium (0 to 50%). The area occupied by the clear-cutting has a slope of 9% and an altitude of 2803 m asl. The average annual rainfall recorded during the period 2010 to 2018 was 1,034.5 mm (this value was recorded by the weather station in the town of Vencedores, located 15 km away from the study area). Rainfall occurs in the months of June, July, August and September; The first frost occurs in October and the last frost occurs in June; snowfall occurs most frequently in the months of December and January *(FSC & SmartWood, 2002)*.
The vegetation is characterized by mixed coniferous and broadleaved forests. The dominant pine species are: *Pinus durangensis* Martínez, *P. cooperi* Blanco, *P. teocote* Schl. and *P. strobiformis* Engelm. The main oak species are: *Quercus rugosa* Née and *Q. sideroxyla Bonpl*, in addition some species of the genera *Juniperus, Arbutus*, and *Alnus* are also part of the forest composition *(González-Elizondo et al., 2012)*.

Figure 1

Forestry background

Before the clear-cutting, the stand had a stocking of 220.4 m^3 ha^{-1} of trees of the following genera: *Pinus, Quercus, Juniperus* and *Arbutus (PMF, 2010)*. The trees were harvested at the beginning of 2010 on an area of 21.40 ha. Months later, during the rainy season, the plantation was established with seedlings of *P. durangensis* and *P. cooperi* (it was not possible to know the proportion, but *P. durangensis* was planted in greater quantity). The plantation was produced with germplasm collected from trees growing in natural stands next to the study area. Land preparation consisted of clearing, scattering and applying the controlled burning of forest waste. To improve soil conditions, the ground was plowed using a D-6 track-type tractor, equipped with a ripper, breaking equidistant lines (2 m) at a depth of 60 cm, in the perpendicular direction to the slope. The seedlings were 12 months old with a height of between 15 and 20 cm and a diameter at the base of the stem of 5 mm. They were planted using the common strain method in a "real frame" at a spacing of 2 × 2 m to generate a density of 2,500 seedlings ha^{-1}.

Field Evaluation

Sixteen (16) circular sites of 100 m^2 were established, distributed completely randomly to evaluate survival according to the recommendations of *CONAFOR (2013)*. In addition to survival, variables such as diameter (cm) and height (m), were measured using a Vernier and hypsometer (Vertex V®), respectively. The sample implied the demolition of 32 trees, distributed proportionally to the diametric categories (16 of each tree species). Two cross-sections were obtained from each tree (over-bark and under-bark): one was cut at the base of the tree and the second one at 1.3 m above ground.

The cross-sections were labeled, dried and polished, and the measurement of each growth ring was subsequently performed using a stereomicroscope with precision in µm. This process was carried out in the dendroecology laboratory at the Facultad de Ciencias Forestales of the Universidad Juárez del Estado de Durango. The year-by-year width of each tree ring was estimated by the average of four-way measurements. The measurements were performed by starting from the year 2017, looking back to previous years.

Estimation of biomass and carbon content.

In order to obtain the total aerial biomass, the equation developed by *Návar et al. (2004)* was used for the species in question, which takes the basal diameter as a predictive variable (Equation 1).

$$y_i = a(DB)^b \qquad [1]$$

Where

y_i = *Total aerial biomass*

a = *0.0199 y b = 2.5488*

DB = *Basal tree diameter (cm)*

The carbon content for *Pinus cooperi* was calculated according to the percentage reported by *Pompa-García et al. (2017)*, who indicate that, the carbon concentration for this species is 49.64% of the total aerial biomass. For *Pinus durangensis* the carbon concentration reported for Hernández-Vera *et al. (*2017) was used (50.36% of the total aerial biomass).

Considering that the terrain is relatively flat and homogeneous, an analysis of variance (ANOVA) was performed under a completely randomized experimental design for the statistical analysis of the data. The classification variables were the two studied tree species and the tree age. The response variables were the year-by-year width of the tree ring, the biomass and the carbon content. The Shapiro-Wilk Normality Test was used to evaluate data normality and equality of variances for all response variables. Significant differences ($p \leq 0.05$) for the year-by-year width of the tree rings were evaluated with the Tukey Means Comparison Test, while the Kruskal-Wallis Non-Parametric Test was used to evaluate significant differences among the median values of biomass and carbon content because these two variables did not meet the normality data assumption. These analyzes were performed using R® statistical software *(R Core Team, 2019)*.

Results

Table 1 shows the descriptive statistics of the sampled trees. Similarity is observed in the parameters evaluated (diameter at the base and total height), which means that, at the age of eight years, the studied tree species show similar growth patterns.

Table 1.

Eight years after the establishment of the plantation, an average survival of 75.2% was observed for the two species, which corresponds to a density of 1,881 trees per ha (Table 2). From studied sites stand out 10 and 2 which showed the highest and lowest survival rates, respectively. No survival comparisons were made, because it was not possible to know the proportion in which both species were planted, however, *Pinus durangensis* was found to be planted in a greater quantity (almost double according to the observed average of the number of trees of the sampling sites), and assuming that survival had been the same for the two studied trees species, an initial density of 2,500 trees ha^{-1} was planted (25 trees in 1000 m^2).

Table 2.

The analysis of variance indicated that there are highly significant statistical differences ($p < 0.001$) in the year-by-year width of the tree rings of the studied tree species. The Tukey test (Fig. 2), forms 6 groups for both tree species, among these, the values of the first and fifth year stand out, which were, respectively, the minor and major width rings. Starting from fifth year, the width of the tree rings shows a decline, and allows their values to be grouped with the values of the third and fourth years. Although the width of the tree rings was slightly larger in *P. cooperi*, no significant statistical differences ($p = 0.9336$) were found among the two studied tree species. The upper and lower horizontal lines crossing the vertical bars (standard deviation) indicate that the year-by-year width growth of the tree rings has been similar among the tree species until the period of time evaluated in this study.

Figure 2.

The Kruskal-Wallis Test indicated that there are significant differences in the estimates of year-by-year biomass and carbon content ($p \leq 0.05$). The comparison of medians using the Bonferroni method does not show significant differences in those years whose observations were consecutive. In contrast, comparisons between discontinuous years showed significant differences ($p < 0.01$) (Table 3).

Table 3.

Estimates of year-by-year biomass and carbon content among tree species did not show significant statistical differences ($p \geq 0.05$).

The accumulation of biomass showed higher values after the fifth year in the studied species, which is a product of the increase in the dimensions of the BD of the trees (Fig. 3).

Figure 3.

Estimates of biomass and carbon content year-by-year of the studied species are shown in Table 4. It is observed that the accumulation of biomass and carbon content increases with increasing age. However, *Pinus cooperi* shows a decrease in the seventh year with respect to the previous year. Considering that a tree has in average an estimate of 4.42 and 2.21 kg of biomass and carbon content, respectively, at the age of 7 years, the studied plantation accounts for 8,315.12 and 4,157.56 kg ha^{-1} of aerial biomass and carbon, respectively.

Table 4.

Discussion

Commented [KM7]: After revising the Introduction, be sure to make any necessary changes in the Discussion that would make it complementary to, and consistent with, the revised Introduction

The results of survival reported in this work (75.2%) are superior than the findings reported by *Prieto et al. (2016)*, who found out an average of 43% in a forest plantation studied in Durango

State. These survival results are also superior to those showed by *Bojórquez, Rodríguez & Flores (2015)* in 25-year-old plantations of *P. durangensis*, *P. engelmannii*, *P. cooperi* and *P. arizonica* var. in Durango State. Although different species were dealt with in a similar study, our results are also better than those reported by *Vásquez-García et al. (2016)*, who informed an average survival of 69% in four-year old plantations of *P. greggii* Englem and *P. oaxacana* Mirov - in three communities in the High Oaxacan Mixtec region in Southern Mexico. However, our survival results were inferior than those reported by *Prieto-Ruiz et al. (2007)* in an 18-month *Pinus cooperi* plantation established on a site in the municipality of Durango, reaching a survival rate of 85.6%. They are also inferior than those informed by Prieto-Ruiz et al. (2018), who reported a 93% of survival in a *Pinus cooperi* plantation after 13 months of its establishment at a site in Agua Zarca, Otinapa, Durango.

Prieto et al. (2018), argue that successful plantations and reforestations depend on the quality of the plant, as it is decisive for its adaptation and development after planting *(Fontana, Pérez & Luna, 2018)*. In our study, it is observed that both species show uniform growth from their establishment to the fifth year of planting. However, from the sixth year onwards, plant growth tends to decline, remaining low until the end of the study, being more noticeable in *P. cooperi*. *Crecente-Campo et al. (2007)* documented that the decrease in plant growth is influenced among other factor by the competition that trees experience from other trees, and that competition increases with increasing age of the plantation *(Soto-Cervantes et al., 2016)*.

Although this work does not include an analysis that correlates ecological factors with tree growth, studies performed by *Anchukaitis et al. (2013), Gutiérrez-García & Ricker (2019),* documented that maximum temperature negatively influences radial growth of the trees. However, the growth, and consequently, the CO_2 sequestration may vary with environmental conditions of the site and the tree species evaluated *(Haghshenas et al., 2016; Pompa-García & Sígala-Rodríguez, 2017; Lanza, Chartier & Marcora, 2018)*. These growth patterns can be attributed to the fact that, at the beginning of the plantation, the genotype-environment interaction and the plasticity of the species influence the adaptability of the plants to a specific sites *(Miranda, 2006; Thomas et al., 2015)*.

The width of the tree rings is the most used parameter to evaluate the growth rate of the trees *(Dobner, Huss & Tomazello, 2018)*. In this study, the lowest width ring growth value was presented during the first year, this can be attributed to plant adaptation to environmental stresses (e.g., drought, salinity, and temperature extremes) *(Pérez-Luna et al., 2020)*. On the other hand, the tree development during the fifth year was higher and after that it showed some reduction in growth caused by tree competition (*Crecente-Campo et al., 2007)*. The average width growth of the rings observed for both tree species was 11.51 mm yr^{-1}. *Pompa-García et al. (2018)*, evaluated the width growth rings in *P. arizonica* y *P. cembroides* Zucc in northern Mexico and found that their average increase was 1.84 mm yr^{-1} and 1.73 mm yr^{-1}, respectively.

A study in *Pinus taeda* L. developed by *Dobner, Huss & Tomazello (2018)*, found out that the width growth of tree rings varied between 6 to 9 mm during the first three to six years before performing silvicultural activities. On the other hand, *Melandri, Dezzeo & Espinoza de Pernía (2007)* in a study with *Pinus caribaea* var. hondurensis in Venezuela indicated that the width growth of tree rings is dependent on various site factors, as well as atmospheric, in this case they pointed out that different rainfall regimes yielded significantly differences in with growth rings.

Several studies related the radial growth rate and the characteristics of the rings with environmental variables such as temperature, precipitation and light intensity *(García-Suárez, Butler & Baillie, 2009; Chacón-de la Cruz & Pompa-García, 2015)*. However, due to the

Commented [KM8]: And/or to 'transplant' stress…

dynamics of the exchange activity during the formation of the wood, the relationship of growth with climatic conditions is very complex and inconstant *(Żywiec et al., 2017).*

Studies indicate that tree spacing influences total tree volume, width growth of rings, and length and diameter of branches *(Hart, 2010).* Also, with increasing thinning intensity the effect on the thickness of the width of tree rings is greater *(Zhang et al., 2006)*. *Baldwin et al. (2000)*, studied the effects of spacing and thinning on stand and tree characteristics of a 38-year-old *Pinus taeda* L plantation and found out that, at higher initial spacing, trees develop greater diameter and crown length. This favors the formation of wider tree rings and more early wood *(Rossi, Morin & Deslauriers, 2012)*. *Rodríguez-Ortiz (2010),* recommended an initial spacing of 2.40 to 2.75 m for *Pinus patula* Schl, because it is a tree species sensitive to competition during its first years of development.

In this study, estimates of year-by-year biomass and carbon content were analyzed for individual trees, however, estimates per hectare were not performed because survival in previous years was unknown and results extrapolation based on survival at the time of assessment could be considered erroneous. In this study the average carbon content per tree was estimated in 0.30 kg yr^{-1} for both studied tree species. *Pompa-García et al. (2018)* estimated that adult trees of *Pinus arizonica* and *P. cembroides* accumulate 4.80 kg C yr^{-1} and 4.84 kg C yr^{-1}, respectively. *Pacheco et al. (2007)* evaluated the accumulated biomass content in a six-year-old *Pinus greggii* plantation, and found out that the average aerial dry biomass was 8.0 kg per tree. These results are above those observed in this study with an average per tree of 4.39 kg for *Pinus durangensis* and 4.46 kg for *P. cooperi*.

Intensive forestry is key to maintaining or increasing stand productivity in the future, wood biomass from plantations of fast-growing trees is an alternative because it is produced in short periods of time *(Thiers, Gerdinga & Schlatter, 2007)*. However, intensive forest management may impact the conservation of plant diversity and the regulation of water flows *(Monárrez-González et al., 2018)*. The results of this research suggest that clear-cuttings are suitable logging practices for the studied tree species in the study area, especially because they create optimal growing conditions for pine trees. However, after opening the gaps it is recommended to replant the area with certain additional complementary practices to protect and guarantee its good development (e.g. fencing, firebreaks, pest prevention, etc.), and avoid risk of soil erosion and loss of biodiversity. The estimates of carbon content made in this study coincide with the results reported by *Pacheco et al. (2007)*, in the sense that young plantations have high growth rates and therefore they also have a greater potential for carbon sequestration.

Conclusions

According to the results of the present study, the observed survival percentage (75.2 %) is considered high in comparison with other similar studies. It indicates that both *Pinus durangensis* and *P. cooperi* adapt and develop well in areas harvested with clear-cutting in the forests of Durango. The width growth of the tree rings was similar in the two species but different among the years evaluated. No significant differences were found in terms of biomass and carbon content among the studied tree species. The accumulation of biomass and carbon content observed in the studied forest plantation is considered to be high, accounting for 8,315.12 and 4,157.56 kg ha^{-1}, respectively, at the age of 7 years. The study reveals that clear-cuttings can be successfully used as logging practices in the study area to create even aged pine stands and increase the productivity of these forests in terms of timber and CO_2 sequestration, among other ecosystems services.

Acknowledgements

To CONACYT for the financial support provided to the first author who carried out his training in the Programa Institucional de Doctorado en Ciencias Agropecuarias y Forestales (PIDCAF-UJED). Our thanks to C.P. Alfonso Gerardo Fernández de Castro Toulet, legal representative of the Compañía Silvícola Chapultepec S. DE R.L. de C.V., for providing access to the study area for data collection. To UCODEFO No. 4 (Unidad de Conservación y Desarrollo Forestal No. 4 La Victoria Miravalles SC), for providing information related to the study area.

References

Aguirre-Calderón ÓA, Jiménez-Pérez J. 2011. Evaluación del contenido de carbono en bosques del sur de Nuevo León. *Revista Mexicana de Ciencias Forestales* 2:73–84 DOI: 10.29298/rmcf.v2i6.575.

Anchukaitis KJ, Taylor MJ, Martin-Fernandez J, Pons D, Dell M, Chopp C, Castellanos EJ. 2013. Cronología anual y respuesta climática en Abies guatemalensis Rehder (*Pinaceae*) en Centroamérica. *The Holocene* 23:270–277 DOI: 10.1177/0959683612455548.

Baldwin VC, Peterson KD, Clark III A, 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: 91–102 DOI: 10.1016/S0378-1127(99)00340-0.

Benjamín JA, Masera O. 2001. Captura de carbono ante el cambio climático. *Madera y Bosques* 7:3–12.

Bojórquez MM, Rodríguez LG, Flores JM. 2015. Evaluación de plantaciones de cuatro especies forestales en el estado de Durango. *Ciencia y Tecnología Universitaria* (Versión imprimible). *Available at http://reaxion.utleon.edu.mx/Art_Impr_Evaluacion_plantaciones_cuatro_especies_forestales_Durango.html*.

Burney O, Aldrete A, Alvarez R, Prieto JA, Sánchez JR, Mexal JG. 2015. México—Addressing challenges to reforestation. *Journal of Forestry* 113:404–413 DOI: 10.5849/jof.14-007.

Caviglia OP, Wingeyer AB, Novelli LE. 2016. El rol de los suelos agrícolas frente al cambio climático. *Serie de Extensión INTA Paraná* 78:27–32.

Chacón-de la Cruz JE, Pompa-García M. 2015. Response of tree radial growth to evaporation, as indicated by earlywood and latewood. *Revista Chapingo Serie Ciencias Forestales y del Ambiente* 21: 57–65 DOI: 10.5154/r.rchscfa.2014.10.050.

Comisión nacional forestal (CONAFOR). 2013. Metodología para realizar y presentar los informes de sobrevivencia inicial (ISI) de las plantaciones forestales comerciales (aspectos técnicos):1–21. *Available at www.conafor.gob.mx/apoyos/index.php/inicio/download/1422*.

Crecente-Campo F, Amigo-López F, Álvarez-González J, Diéguez-Aranda U. 2007. Elaboración de un modelo de perfil de copa para *Pinus radiata* D. Don en Galicia. *Cuadernos de la Sociedad Española de Ciencias Forestales* 23:159–165.

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

Domínguez-Calleros PA, Rodríguez-Laguna R, Capulín-Grande J, Razo-Zárate R, Díaz-Vásquez MA. 2017. Influencia de factores edáficos en el crecimiento de una plantación de *Pinus greggii* Engelm. en Santiago de Anaya, Hidalgo, México. *Madera y Bosques* 23:145-154 DOI: 10.21829/myb.2017.2321522.

Fontana M, Pérez V, Luna C. 2018. Efecto del origen geográfico en la calidad morfológica de plantas de *Prosopis alba* (Fabaceae). *Revista de Biología Tropical* 66:593–604 DOI: 10.15517/rbt.v66i2.33383.

FSC (Forest Stewardship Council), SmartWood. 2002. Resumen Público de Certificación de Compañía Silvícola Chapultepec S. de R.L. de C.V. 1–40. *Available at* https://docplayer.es/72124326-Resumen-publicode-certificacion-compania-silvicola-chapultepec-s-de-r-l-de-cv.html#show_full_text.

Gadow Kv, Sanchez OS, Aguirre ÓA. 2004. Manejo forestal con bases científicas. Madera y Bosques 10:3–16 DOI: 10.21829/myb.2004.1021271.

García ME. 2004. Modificaciones al sistema de clasificación climática de Köppen, 6 ed. *Instituto de Geografía: Universidad Nacional Autónoma de México, México*: Serie Libros, 1–98.

García-Suárez AM, Butler CJ, Baillie GL. 2009. Climate signal in tree-ring chronologies in a temperate climate: A multi-species approach. *Dendrochronologia* 27: 183–198 DOI: 10.1016/j.dendro.2009.05.003.

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* 7:1-19 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 Botanica Mexicana* 100:351–404 DOI: 10.21829/abm100.2012.40.

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

Gutiérrez-García G, Ricker M. 2019. Influencia del clima en el crecimiento radial en cuatro especies de coníferas en la sierra de San Antonio Peña Nevada (Nuevo León, México). *Revista Mexicana de Biodiversidad* 90:1–14 DOI: 10.22201/ib.20078706e.2019.90.2676.

Haghshenas M, Mohadjer MR, Attarod P, Pourtahmasi K, Feldhaus J, Sadeghi SM. 2016. Climate effect on tree-ring widths of Fagus orientalis in the Caspian forests, northern Iran. *Forest Science and Technology* 12:176–182 DOI: 10.1080/21580103.2016.1144542.

Halifa-Marín A, Pérez-Cutillas P, Almagro M, Martínez-Mena M, Boix-Fayos C. 2019. Dinámica geomorfológica fluvial y cambios de usos del suelo: impacto en los reservorios de carbono de suelos y sedimentos. *Bosque (Valdivia)* 40:3–16 DOI: 10.4067/s0717-92002019000100003.

Hart JF. 2010. A review of the effects of silviculture on wood quality. *Forestry* 75: 107–138 DOI: 10.14288/1.0103111.

Hernández UF, Jaeger D, Samperio JI. 2017. Bioenergy potential and utilization costs for the supply of forest woody biomass for energetic use at a regional scale in Mexico. *Energies* 10:1–25 DOI: 10.3390/en10081192.

Hernández-Díaz JC, Corral-Rivas JJ, Quiñones-Chávez A, Bacon-Sobbe JR, Vargas-Larreta B. 2008. Evaluación del manejo forestal regular e irregular en bosques de la Sierra Madre Occidental. *Madera Bosques* 14:25–41.

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)* 38:381–386 DOI: 10.4067/S0717-92002017000200015.

Keenan RJ, Kimmins JP. 1993. The ecological effects of clear-cutting. *Environmental Reviews* 1:121–144 DOI: 10.3390/en10081192.

Lanza MG, Chartier MP, Marcora PI. 2018. Relación clima-crecimiento radial de *Polylepis*

australis en un gradiente altitudinal en las Sierras Grandes de Córdoba, Argentina. *Ecología Austral* 28: 278–290.
López-Reyes LY, Domínguez-Domínguez M, Martínez-Zurimendi P, Zavala-Cruz J, Gómez-Guerrero A, Posada-Cruz S. 2016. Carbono almacenado en la biomasa aérea de plantaciones de hule (Hevea brasiliensis Müell. Arg.) de diferentes edades. *Madera y Bosques* 22:49–60 DOI: 10.21829/myb.2016.2231456.
Martínez RA, Aguirre ÓA, Vargas LB, Jiménez PJ, Treviño EJ, Yamallel JI. 2016. Modelación de biomasa y carbono arbóreo aéreo en bosques del estado de Durango. *Revista Mexicana de Ciencias Forestales* 7:91–105 DOI: 10.29298/rmcf.v7i35.77.
Medrano MdJ, Hernández FJ, Corral S, Nájera JA. 2017. Diversidad arbórea a diferentes niveles de altitud en la región de El Salto, Durango. *Revista Mexicana de Ciencias Forestales* 8:57–68.
Melandri JL, Dezzeo N, Espinoza de Pernía N. 2007. Periodicidad de los anillos de crecimiento en *Pinus caribaea* var. hondurensis proveniente de una plantación del estado Mérida, Venezuela. *Revista Forestal Venezolana* 51: 57–66.
Miranda AR. 2006. Características genéticas de los materiales de reproducción. Influencia sobre la calidad de la planta. *In* Calidad de planta forestal para la restauración en ambientes mediterráneos, estado actual de conocimientos. *Organismo Autónomo de Parques Nacionales*. 47–66.
Monárrez-González JC, Pérez-Verdín G, López-González C, Márquez-Linares MA, González Elizondo MdS. 2018. Efecto del manejo forestal sobre algunos servicios ecosistémicos en los bosques templados de México. *Madera y Bosques* 24:1–16 DOI: 10.21829/myb.2018.2421569.
Návar JdJ, González N, Graciano JdJ, Dale V, Parresol B. 2004. Additive biomass equations for pine species of forest plantations of Durango, Mexico. *Madera y Bosques* 10:17–28 DOI: 10.21829/myb.2004.1021272.
Pacheco FC, Aldrete A, Gómez A, Fierros AM, Cetina VM, Vaquera H. 2007. Almacenamiento de carbono en la biomasa aérea de una plantación joven de *Pinus greggii* Engelm. *Revista Fitotecnia Mexicana* 30:251–254.
Patiño S, Suárez LN, Andrade HJ, Segura MA. 2018. Captura de carbono en biomasa en plantaciones forestales y sistemas agroforestales en Armero-Guayabal, Tolima, Colombia. *RIAA* 9:1–14.
Pérez-Luna A, Prieto-Ruíz JÁ, López-Upton J, Carrillo-Parra A, Wehenkel C, Chávez-Simental JA, Hernández-Díaz JC. 2019. Some factors involved in the success of side veneer grafting of *Pinus engelmannii* Carr. *Forests* 10:112 DOI: 10.3390/f10020112.
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: Article 8468 DOI: 10.7717/peerj.8468.
Pérez-Rodríguez F, Vargas-Larreta B, Aguirre-Calderón OA, Corral-Rivas JJ, Rojo-Alboreca A. 2013. Proceso analítico jerárquico para seleccionar métodos de manejo forestal en Durango. *Revista Mexicana de Ciencias Forestales* 4:1–18 DOI: 10.29298/rmcf.v4i15.448.
Pérez-Verdín G, Hernández-Díaz JC, Márquez-Linares MA, Tecle A. 2009. Aplicación de técnicas multicriterio en el manejo integral forestal en Durango, México. *Madera y Bosques* 15:27–46 DOI: 10.21829/myb.2009.1511195.
Pompa-García M, Sígala-Rodríguez JA, Jurado E, Flores J. 2017. Tissue carbon concentration of 175 Mexican forest species. *iForest-Biogeosciences and Forestry* 10: 754–758 DOI:

10.3832/ifor2421-010.
Pompa-García M, Sígala-Rodríguez JA. 2017. Variation of carbon uptake from forest species in Mexico: a review. *Madera y Bosques* 23: 225–235 DOI: 10.21829/myb.2017.2321512.
Pompa-García M, Venegas-GonzáLez A, Júnior, AA, Sigala-Rodríguez JA. 2018. Dendroecological approach to assessing carbon accumulation dynamics in two Pinus species from northern Mexico. *Tree-Ring Research* 74: 196–209 DOI: 10.3959/1536-1098-74.2.196.
Pompa-García M, Yerena-Yamalliel JI. 2014. Concentración de carbono en *Pinus cembroides* Zucc: fuente potencial de mitigación del calentamiento global. *Revista Chapingo Serie Ciencias Forestales y del Ambiente* 20:169–175 DOI: 10.5154/r.rchscfa.2014.04.014.
Prieto JA, Aldrete A, Sánchez JR, Hernández JC. 2016. Antecedentes sobre las reforestaciones en México. In Las reforestaciones en México, problemática y alternativas de solución. Prieto JA, Goche JR, eds. *Universidad Juárez del Estado de Durango*. Durango, México. 14–22.
Prieto JA, Domínguez-Calleros PA, Cornejo-Oviedo EH, Návar-Cháidez JDJ. 2007. Efecto del envase y del riego en vivero en el establecimiento de *Pinus cooperi* Blanco en dos condiciones de sitio. *Madera y Bosques* 13:79–97 DOI: 10.21829/myb.2007.1311237.
Prieto JA, Duarte SA, Goche JR, González MM, Pulgarín MA. 2018. Supervivencia y crecimiento de dos especies forestales, con base en la morfología inicial al plantarse. *Revista Mexicana de Ciencias Forestales* 9:151–168 DOI: 10.29298/rmcf.v9i47.182.
Programa de manejo forestal (PMF). 2010. P.P. Lotes números Cuatro, Cinco y Ocho fracciones Oriente del fraccionamiento del predio rústico "Las Veredas", municipio de San Dimas, Dgo. *Unidad de Conservación y Desarrollo Forestal No. 4 "La Victoria – Miravalles", S. C. Durango, México*.
R Core Team. 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing, *Vienna, Austria*. URL https://www.R-project.org/.
Ramírez-López JL, Chagna-Avila EJ. 2019. Secuestro de carbono en la biomasa aérea de una plantación de *Eucalyptus grandis* W. Hill. *Revista Cubana de Ciencias Forestales* 7:86–97.
Reyes JL, León MA, Herrero G. 2019. Influencia de la fertilización mineral sobre la retención de carbono en una plantación de pino. *Revista Mexicana de Ciencias Forestales* 10:4–22 DOI:10.29298/rmcf.v10i51.147.
Rodríguez-Larramendi LA, Guevara-Hernández F, Reyes-Muro L, Ovando-Cruz J, Nahed-Toral J, Prado-López M, Campos Saldaña RA. 2016. Estimación de biomasa y carbono almacenado en bosques comunitarios de la región Frailesca de Chiapas, México. *Revista Mexicana de Ciencias Forestales* 7:77–94 DOI: 10.29298/rmcf.v7i37.53.
Rodríguez-Ortiz G, García-Aguilar JA, Leyva-López JC, Ruiz-Díaz C, Enríquez-del Valle JR, Santiago-García W. 2019. Biomasa estructural y por compartimentos en regeneración de *Pinus patula* en áreas con matarrasa. *Madera y Bosques* 25:1–11 DOI: 10.21829/myb.2019.2511713.
Rodríguez-Ortiz G. 2010. Efecto de aclareos en el crecimiento de una plantación de *Pinus patula* Schl. *et* Cham. en Ixtlán, Oaxaca. Colegio de Postgraduados. Montecillo. Texcoco, Estado de México, México. 134 p. *Available at* https://nanopdf.com/download/efecto-de-aclareos-en-el-crecimiento-de_pdf
Rossi S, Morin H, Deslauriers A. 2012. Causes and correlations in cambium phenology: towards an integrated framework of xylogenesis. *Journal of Experimental Botany* 63: 2117–2126 DOI: 10.1093/jxb/err423.
Solís MR, Aguirre ÓA, Treviño EJ, Jiménez PJ, Jurado YE, Corral-Rivas J. 2006. Efecto de dos tratamientos silvícolas en la estructura de ecosistemas forestales en Durango, México.

Madera y Bosques 12:49–64 DOI:10.21829/myb.2006.1221242.
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* 22:179–192 DOI: 10.5154/r.rchscfa.2015.09.040.
Thiers O, Gerdinga V, Schlatter J. 2007. Exportación de nitrógeno y calcio mediante raleo en un rodal de *Eucalyptus nitens* de 5 años de edad, Chile. *Bosque (Valdivia)* 28:256–262 DOI: 10.4067/S0717-92002007000300011.
Thomas E, Jalonen R, Loo J, Bozzano M. 2015. Cómo evitar el fracaso en la restauración forestal: la importancia de disponer de un germoplasma genéticamente diverso y adaptado a los sitios de plantación. *Unasylva* 66:29–36.
Vallejo VR, Smanis A, Chirino E, Fuentes D, Valdecantos A, Vilagrosa A. 2012. Perspectives in dryland restoration: approaches for climate change adaptation. *New Forests* 43:561–579 DOI: 10.1007/s11056-012-9325-9.
van Minnen JG, Strengers BJ, Eickhout B, Swart RJ, Leemans R. 2008. Quantifying the effectiveness of climate change mitigation through forest plantations and carbon sequestration with an integrated land-use model. *Carbon Balance and Management* 3:1–20 DOI: 10.1186/1750-0680-3-3.
Vásquez-García I, Cetina-Alcalá VM, Campos-Bolaños R, Casal-Ángeles LF. 2016. Evaluación de plantaciones forestales en tres comunidades de la Mixteca Alta oaxaqueña. *AgroProductividad* 9:12–19.
Wang XW, Weng YH, Liu GF, Krasowski MJ, Yang CP. 2015. Variations in carbon concentration, sequestration and partitioning among Betula platyphylla provenances. *Forest Ecology and Management* 358:344–352 DOI: 10.1016/j.foreco.2015.08.029.
Zambrano A, Franquis F, Infante A. 2004. Emisión y captura de carbono en los suelos en ecosistemas forestales. *Rev. For. Lat* 35:11–20.
Zhang SY, Chauret G, Swift DE, Duchesne I. 2006. Effects of precommercial thinning on tree growth and lumber quality in a jack pine stand in New Brunswick, Canada. *Canadian Journal of Forest Research* 36: 945–952 DOI: 10.1139/x05-307.
Żywiec M, Muter E, Zielonka T, Delibes M, Calvo G, Fedriani JM. 2017. Long-term effect of temperature and precipitation on radial growth in a threatened thermo-Mediterranean tree population. *Trees* 31: 491–501 DOI: 10.1007/s00468-016-1472-8.