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

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## 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 were demolished (one per species), and were selected according the desired diameter. 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 the growth rings of the first cross-section was measured using a stereoscopic microscope with precision in microns (μm). The calculation of the basal diameter of each year per tree, biomass and carbon content was performed using allometric equations.

**Results.** The estimated survival was 75.2%. The results of the ANOVA showed significant differences between the width of the rings per year, the highest value corresponding to the year fifth. The average carbon content per year is 0.30 kg for both species.

**Conclusions.** *P. durangensis* and *P. cooperi* plantations adapt and develop well when they are established in areas that are subjected to clear-cutting.

**Comentado [P21]:** It is unimportant to evaluate survival in 8-year-old individuals

**Comentado [P22]:** indicate that the sample was distributed proportionally to the diametric categories?

**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-Barrón 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 mitigating 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 & Chagna, 2019)*.

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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)*.

Although commercial forest plantations represent a priority for forestry development in Mexico - with the aim of increasing timber production in the country - there are obstacles that will hinder reaching the proposed goal of 300,000 ~~hectares~~ ha by the year 2025 *(Velázquez et al., 2002)*. The main difficulty in increasing the area of forest plantations in Mexico is the lack of knowledge about the behavior of on-site species, since, in most cases, they are established in tropical sites where mainly fast-growing species are used *(Prieto et al., 2016; Pérez-Luna et al., 2020)*.

For the proper management of these forest ecosystems in Mexico, 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 *(Hernández-Díaz et al., 2008)*.

In sites covered by temperate forests with little or no slope, the use of a clear-cutting as a regeneration method is justified. It is characterized by having periodic crops, determined by commercial rotations *(Gadow, Sánchez Orois & Aguirre Calderón, 2004)*, and their regeneration can be natural or artificial. If the regeneration is artificial, then the use of fast-growing species is preferable.

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Although clear-cutting can be used successfully in Mexican forests, this silvicultural method is still considered inappropriate, considering that deforestation 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 and ecological 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 efficiently contribute to carbon sequestration by creating the conditions for optimal tree growth. The objective of this work was to evaluate survival, growth ring width 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.

# Materials & Methods

## Study area

This study was conducted in the municipality of San Dimas, Durango, Mexico, 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 stand has a slope of 9% and an altitude of 2803 ~~meters above sea level~~m. 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 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 characteristic 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 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*. The plantation was produced with germplasm collected from trees from 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 lines at a depth of 60 cm, equidistant to ~~two~~ 2 m, in the perpendicular direction ~~perpendicular~~ 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× ~~x~~ 2 m to generate a density of 2,500 seedlings~~/~~ha$^{-1}$ in the plantation.

## 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, height, crown width, etc. were recorded. The sample implied the demolition of 32 trees, according to the desired diameter (16 of each species). Two

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**Con formato:** Superíndice

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**Comentado [p8]:** Indicate measuring equipment of these variables and the units used cross-sections were obtained from each tree: 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 in the Universidad Juárez del Estado de Durango. The width of the growth rings was estimated by the average of tfour-way measurements. The measurements were performed by starting from the year 2017, looking back to previous years of growth.

**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 dry biomass*

*$a$ = 0.0199 y $b$ = 2.5488*

*$DB$ = Basal diameter*

The carbon content was calculated according to the percentages indicated by *Pompa-García et al. (2017)*, who indicate that, for the Pinaceae family, the carbon concentration is 48.29% of the total 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. Previously, the Shapiro-Wilk Normality Test was performed. When there were significant differences ($p \leq 0.05$), the Tukey Means Comparison Test was used. For the estimates of biomass and carbon content by year and by species, the Kruskal-Wallis Non-Parametric Test was used to evaluate possible significant differences between the median values, this was because these variables did not meet the normality test. These analyzes were performed on the R® statistical software *(Core Team, 2019)*.

## Results

Table 1 shows the descriptive statistics of the felled 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 have similar growth patterns.

**Table 1.**

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Eight years after the establishment of the plantation, an average survival of 75.2% was found, which corresponds to a density of 1,881 trees per ha (Table 2). From these sites stand out the 10 and 2 which had the highest and lowest survival rates, respectively.

**Comentado [p16]:** This variable makes no sense to evaluate, after 8 years

**Comentado [p17]:** In addition, the density of the stand requires aggressive thinning and decreases its density by at least half

**Table 2.**

The analysis of variance indicated that there are highly significant statistical differences ($p < 0.001$) in the width of the rings per year among the studied tree species. The Tukey test (Fig. 2), forms 6 groups, among these, the values of the first and fifth year stand out, which were, respectively, the minor and major. Starting from this year, the width of the growth 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 rings was slightly larger in *P. cooperi*, statistically no significant differences ($p = 0.9336$) were found between the tree species. However, in the sixth year, the width of the growth rings was greater in *P. durangensis*. The narrow value of the lines (standard deviation) recorded over the years and species indicate that their growth has been similar until the period of time evaluated.

**Figure 2.**

The Kruskal-Wallis Test indicated that there are significant differences in the estimates of biomass and carbon content among years ($p$ ≤~~<~~$0.05$). The comparison of medians using the Bonferroni method does not show significant differences in those years whose observations were consecutive except for years 5-7. In contrast, comparisons between discontinuous years showed significant differences ($p < 0.01$) (Table 3).

**Table 3.**

Estimates per year of biomass and carbon content by species did not show significant statistical differences ($p = 0.8206$). The accumulation of biomass shows higher values from 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).

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**Figure 3.**

Estimates of biomass and carbon content per year of the studied species are also shown in Table 4.

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**Table 4.**

## Discussion

The results of survival reordered in this work is greater than the one reported by *Prieto et al. (2016)*, who reported a 43% in average of annual survival in forest plantations in Durango ~~the state~~ State~~of Durango~~. These survival results are also superior to those indicated by *Bojórquez, Rodríguez & Flores (2015)* in 25-year-old plantations of *P. durangensis*, *P. engelmannii*, *P. cooperi* and *P. arizonica* in ~~the State of~~ Durango State. Although different species were dealt with in a similar study, the our results are also greater than that indicated by *Vásquez-García et al. (2016)*, who report 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.

Although this work does not include an analysis that correlates ecological factors with tree growth, studies by *Anchukaitis et al. (2013), Gutiérrez-García & Ricker (2019)* document 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 *(Pompa-García & Sígala-Rodríguez, 2017)*. 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 site *(Miranda, 2006; Thomas et al., 2015)*.

*Prieto-Ruiz 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)*. Although there is no history of plant cultivation in the nursery, 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, and is more noticeable in *P. cooperi*. *Crecente-Campo et al. (2007)* document that the decrease in plant growth is influenced by the competition that trees experience from other trees, and that competition increases according to the age of the trees *(Soto-Cervantes et al., 2016)*.

*Delgado et al. (2005)*~~,~~ indicate that there is a close allometric relationship between diameter and biomass. The results show an exponential growth in biomass content and consequently in carbon accumulation. The above coincides with *Rodríguez-Larramendi et al. (2016)* who argue that as the diameter increases, a greater accumulation of biomass is expected.

Intensive forestry is key to maintaining or increasing productivity in the future, since biomass is increased in shorter periods *(Thiers, Gerdinga & Schlatter, 2007)*. However, intensive forest management impacts the conservation of plant diversity and the regulation of water flows *(Monárrez-González et al., 2018)*. Taking this into account, the results of this research suggest that the method of clear-cutting is convenient in regional forests if an immediate plantation is carried out and when certain measures are taken to protect it (fencing, firebreaks, pest prevention, etc.). Failure to do so runs the risk of soil erosion and the loss of biodiversity. The estimates of carbon content made in this study coincide with the results reported by *Pacheco et*

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*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 survival percentage is considered high, which indicates that both *P~~.~~inus durangensis* and *P. cooperi* adapt and develop well in areas subjected to clear-cutting. Estimates of biomass and carbon sequestration indicate that these species can be considered for the environmental services payment program due to their efficient contribution to carbon sequestration. The study reveals that the total number of cuts in the study area, together with immediate planting, can be applied as long as they comply with the established norms, since they help to generate regular masses and increase the productivity of the forests in this region.

**Comentado [p23]:** Based on this conclusion, then it would be important to provide biomass accumulation rates, based on the growth of the rings, indicating amounts per hectare


## 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.


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**Con formato:** Fuente: Cursiva

**Comentado [P226]:** There´s no concordance with: Návar …

**Código de campo cambiado**

**Comentado [P227]:** No alphabetical order

Dgo. *Unidad de Conservación y Desarrollo Forestal No. 4 "La Victoria – Miravalles", S. C. Durango, México.*

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**Comentado [P228]:** Incorrect cited: There´s no concordance with: *Ramírez & Chagna, 2019*

**Con formato:** Fuente: Cursiva

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**Comentado [P229]:** Core Team? There´s no coincidence

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**Table 1.** Descriptive statistics for the diameter and height of the *Pinus~~.~~ durangensis* and *P. cooperi* trees analyzed in this study (eight years old).

| Species | Trees | DB (cm) | | | | Height (m) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | M | Min | Max | Std | M | Min | Max | Std |
| *P. durangensis* | 16 | 8.20 | 6.39 | 9.80 | 1.06 | 3.47 | 2.50 | 4.30 | 0.58 |
| *P. cooperi* | 16 | 8.17 | 5.57 | 10.31 | 1.50 | 3.30 | 2.14 | 4.70 | 0.82 |

DB = ~~Basal~~ basal diameter, M = Average, Min= Minimum, Max = Maximum, Std = Standard deviation

**Comentado [P21]:** There is no point in reporting these values, it is better to use the standard error and the coefficient of variation in order to compare de variability

**Table 2.** Number of trees observed by site and by species.

| Site | Trees | | *Pinus durangensis* | | *P. cooperi* | |
|---|---|---|---|---|---|---|
| | N | % | N | % | N | % |
| 1 | 19 | 76 | 14 | 56 | 5 | 20 |
| 2 | 10 | 40 | 7 | 28 | 3 | 12 |
| 3 | 18 | 72 | 11 | 44 | 7 | 28 |
| 4 | 20 | 80 | 12 | 48 | 8 | 32 |
| 5 | 15 | 60 | 7 | 28 | 8 | 32 |
| 6 | 18 | 72 | 13 | 52 | 5 | 20 |
| 7 | 19 | 76 | 13 | 52 | 6 | 24 |
| 8 | 21 | 84 | 12 | 48 | 9 | 36 |
| 9 | 20 | 80 | 8 | 32 | 12 | 48 |
| 10 | 24 | 96 | 13 | 52 | 11 | 44 |
| 11 | 23 | 92 | 16 | 64 | 7 | 28 |
| 12 | 23 | 92 | 21 | 84 | 2 | 8 |
| 13 | 18 | 72 | 12 | 48 | 6 | 24 |
| 14 | 11 | 44 | 8 | 32 | 3 | 12 |
| 15 | 23 | 92 | 18 | 72 | 5 | 20 |
| 16 | 19 | 76 | 15 | 60 | 4 | 16 |
| Promedio | 18,81 | 75,2 | 12,50 | 50 | 6,31 | 25,25 |

N= Number of trees found per site, %= Percentage of survival.

**Comentado [P21]:** It must be inferred to hectare

**Comentado [P22]:** Mean?

**Table 3.** Comparison of the estimation of biomass and carbon content per year according to the Bonferroni medians comparison test.

| Comparison (year) | Biomass | Carbon |
|---|---|---|
| 1-2 | 0.9507 ns | 0.9507 ns |
| 1-3 | 0.0013** | 0.0013 ** |
| 2-3 | 0.9816 ns | 0.9816 ns |
| 1-4 | <0.0001*** | <0.0001*** |
| 2-4 | 0.0034** | 0.0034** |
| 3-4 | 1 ns | 1 ns |
| 1-5 | <0.0001*** | <0.0001*** |
| 2-5 | <0.0001*** | <0.0001*** |
| 3-5 | <0.0001*** | <0.0001*** |
| 4-5 | 0.1064 ns | 0.1064ns |
| 1-6 | <0.0001*** | <0.0001*** |
| 2-6 | <0.0001*** | <0.0001*** |
| 3-6 | <0.0001*** | <0.0001*** |
| 4-6 | <0.0001*** | <0.0001*** |
| 5-6 | 1 ns | 1 ns |
| 1-7 | <0.0001*** | <0.0001*** |
| 2-7 | <0.0001*** | <0.0001*** |
| 3-7 | <0.0001*** | <0.0001*** |
| 4-7 | <0.0001*** | <0.0001*** |
| 5-7 | 1 ns | ns |
| 6-7 | 1 ns | ns |

*($p < 0.01$) **, ($p < 0.001$) ***, ns = not significant.*

**Comentado [P21]:** The Journal use . versus ,

**Comentado [P22]:** (*p > 0.05*)?: Indicate

**Table 4.** Biomass and carbon content per year of two *Pinus* species ~~*P. durangensis* and *P. cooperi*~~ planted in a site established after a clear-cutting.

| Age (year) | Biomass (kg/Tree) | | Carbon (kg/Tree) | |
|---|---|---|---|---|
| | *P. durangensis* | *P. cooperi* | *P. durangensis* | *P. cooperi* |
| 1 | 0.006 | 0.008 | 0.003 | 0.004 |
| 2 | 0.047 | 0.060 | 0.023 | 0.029 |
| 3 | 0.164 | 0.223 | 0.079 | 0.108 |
| 4 | 0.404 | 0.429 | 0.195 | 0.207 |
| 5 | 0.934 | 1.014 | 0.451 | 0.490 |
| 6 | 1.324 | 1.366 | 0.639 | 0.660 |
| 7 | 1.509 | 1.362 | 0.729 | 0.658 |
| Total | 4.388 | 4.461 | 2.120 | 2.155 |

**Comentado [P21]:** It is important to add standard error and separation test used