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], Alberto Pérez-Luna[3, 4]

[1]Programa Institucional de Doctorado en Ciencias Agropecuarias y Forestales, Universidad Juárez del Estado de Durango, Río Papaloapan y Blvd. Durango s/n. Col. Valle del Sur. C.P. 34120, Durango, Durango, México.

[2]Facultad de Ciencias Forestales, Universidad Juárez del Estado de Durango, Río Papaloapan y Blvd. Durango s/n. Col. Valle del Sur. C.P. 34120, Durango, Durango, México.

[3]Colegio de Postgraduados, Postgrado en Ciencias Forestales, Km 36.5 carretera México-Texcoco. C.P. 56230 Montecillo, Texcoco, Estado de México, México.

[4]Centro de Bachillerato Tecnológico Industrial y de Servicios Número 89, Dirección General de Educación Tecnológica Industrial, Gerónimo Hernández s/n, Col. Francisco Villa, C.P. 34130, Durango, Durango, México.

Corresponding Author:
Alberto Pérez-Luna[1, 3]
Boulevard Durango S/N, Durango, Durango, 34120, México
Email address: aperez@ujed.mx

Abstract

Forest plantations and natural forests perform a relevant role in capturing CO_2 and reducing greenhouse gas concentrations. The objective of this work 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 significant higher growth rates, biomass and carbon accumulation at most evaluated years. After seven years of growth the lines of current annual increment (CAI) and mean annual increment (MAI) in basal diameter both the plantation and the natural regeneration have not yet intersected. Both forest plantations and

38   naturally regenerated stands of the studied tree species may be suitable alternatives to promote
39   CO_2 capture and increase timber production.
40   **Key words:** *Pinus durangensis* Martínez, Biomass, Carbon sequestration, Seed-tree cutting,
41   Clear-cutting.

42   **Introduction**

43   Plantations and natural forests are an excellent alternative for CO_2 capture and to reduce
44   greenhouse gas concentrations and to mitigate the effects of global warming (Patiño Forero *et*
45   *al*., 2018; González-Cásares *et al*., 2019).
46   Mexico is one of the highest emitters of greenhouse gases, which include 407,695 megatons of
47   CO_2 annually (INECC-SEMARNAT, 2015). Therefore, it is important to know the stocks and
48   flows of carbon in its forest areas. Biomass estimation can be calculated using indirect methods
49   such as the use allometric equations (Návar *et al*., 2004; Montes de Oca-Cano *et al*., 2008;
50   Vargas-Larreta *et al*., 2017), and remote sensing techniques (López-Serrano, Corral-Rivas &
51   López-Sánchez, 2015).
52   *Pinus durangensis* Martínez is one of the most commercially important tree species in northern
53   Mexico. It is also one of the forest species with the greatest potential to accumulate carbon
54   (Graciano-Ávila *et al*., 2019). Its performance and adaptability allow it to be used frequently in
55   commercial forest plantations in the state of Durango (Prieto Ruíz *et al*., 2016). Flores, Pineda &
56   Flores (2019) estimate that in Mexico, 1,400 hectares of *Pinus durangensis* are planted annually.
57   The success of the forest plantations depends to a large degree on the use of high-genetic-quality
58   plants (Stewart *et al*., 2016) with good adaptability to the plantation site (Grossnickle, 2012;
59   Vallejo *et al*., 2012). In Mexico, 57% of mortality in plantations is caused by poor-plant quality
60   (Prieto Ruíz *et al*., 2016), in addition to bad practices that occur during the plantation process
61   (Burney *et al*., 2015).
62   With the establishment of commercial forest plantations in Mexico, the aim is to increase the
63   country's timber production (Hernández-Zaragoza *et al*., 2019). They also constitute an
64   important element in carbon sequestration and the generation of other environmental services.
65   However, there are few studies related to the evaluation of their timber yield and their potential
66   for carbon sequestration (Soto-Cervantes *et al*., 2020).
67   The natural regeneration of pine species by means of the use of seed-tree cuttings or selective
68   fellings are the most used methods to achieve the establishment of the new seedlings in the areas
69   under forest management in the Mexican temperate forests (Ramírez Santiago *et al*., 2015). In
70   addition, they are appropriate options for the ecological rehabilitation of forests (Pensado-
71   Fernández *et al*., 2014), since they have the advantage to retain the germplasm's genetic memory
72   (genotype) to guarantee a higher percentage of survival and development than plantations
73   (Landis, 2011). However, few studies have compared tree growth and carbon sequestration
74   between forest plantations and natural regeneration of *Pinus durangensis* (Fernández-Pérez,
75   Ramírez-Marcial & González-Espinosa, 2013).
76   As a hypothesis of this study, we suppose that there are significant differences ($P < 0.05$) in
77   terms of the increase in the diameter at the base and carbon capture between plantation and

78 natural regeneration seedlings. Therefore, the objectives of this work were (i) to compare the
79 basic bioclimatic conditions (precipitation and temperature) of the study areas in the years of
80 growth of the seedlings evaluated, (ii) to compare the diameter increment at the base, (iii)
81 estimate and compare the accumulated content of biomass and carbon and (iv) estimate the
82 current annual increment (CAI) and mean annual increment (MAI) in basal diameter of *Pinus*
83 *durangensis* seedlings in a plantation and a stand of natural regeneration.

84 **Materials and methods**

85 **Characteristics of the study area**

86 The study area is located on the private property "Las Veredas" in the municipality of San Dimas, in
87 Durango, Mexico (Figure 1). Data collection was carried out in two sub-stands: (1) clear-cutting
88 with immediate plantation of 21.4 ha located at coordinates 24° 20' 40" N and 105° 51' 20" W with
89 an elevation of 2,600 m, and (2) seed-tree cutting of 10.2 ha located at 24° 20' 30" N and 105° 50'
90 58" W at 2,800 m altitude.
91 The climate in the study area is temperate with summer rains (CW) and the temperature ranges
92 between -3 and 18 °C (García, 2004). The average slope in the clearcut is 9%, while in the seed-tree
93 cutting is of 27%. The most frequent rains occur between July and September, which provide an
94 average annual rainfall of 1,000 mm. The soil of both stands is similar and may be classified as
95 Umbrisol (INEGI, 2007). The characteristic vegetation is mixed coniferous and broadleaf forests.
96 The first type is dominated by pines, of which the following stand out: *Pinus durangensis*, *P.*
97 *cooperi* C.E. Blanco, *P. teocote* Schl. et Cham. and *P. strobiformis* Engelm. Of the broadleaves, the
98 oaks stand out, among these: *Quercus rugosa* Née and *Q. sideroxyla* Bonpl. There are also trees of
99 some ecologically important species of the genera *Juniperus*, *Arbutus* and *Alnus*, among others
100 (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 50-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 m² 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 seven 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 (Equation 1, $R^2 = 0.86$).

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

140   Where:

141   Y_i = Total dry biomass

142   a = 0.0199 y b = 2.5488

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

144   Annual values of aboveground tree were derived from the difference of total biomass values

145   between two consecutive years. The carbon content was calculated according to the percentage

146   indicated by Hernández-Vera *et al*. (2017), who reported a concentration of 50.36% of the total

147   biomass *Pinus durangensis*.

148   **Tree increment estimation**

149   The increment for both studied kind of seedlings was assessed on the cross-sections collected at

150   the base of the sampled trees. The individual tree-ring width growth, individual tree current

151   annual diameter increment (CAI), and mean annual diameter increment (MAI) were accounted

152   for years 1 to 7. The tree-ring width growth corresponded with the individual tree annual ring

153   width average (mm), CAI represented the individual tree basal diameter increment observed for

154   each of the studied years (cm/year), while the MAI was the total individual tree diameter

155   increment up to a given age divided by that age (cm/year) (Cardalliaguet *et al*., 2019).

156   **Statistical analysis**

157   Due to the use of hierarchical data obtained from the same trees, differences in tree-ring width

158   growth, biomass and the carbon accumulation among seedlings of studied sites were evaluated

159   with a two-way mixed-effects analysis of variance model (Snedecor & Cochran 1989; Oberfeld

160   & Franke, 2013). In our data, the mixed-effects models attempt to generalize results beyond both

161   the sampled sites and seedlings. Thus, to take into account the possible temporal correlation

162   between data from the same individual, the studied sites (i.e. plantation or natural regeneration)

163   and evaluated years (1 to 7) were classified as the fixed factors, while the basal diameter of trees

164   at age *i* was used as a random factor. Multiple comparisons were conducted when there were

165   significant differences among means of plantation and natural regeneration seedlings with the

166   Tukey Means Comparison Test (P < 0.05). All statistical analyses were performed in the

167   statistical software $R^{®}$ version 3.5.3 (R Core Team, 2019).

168   **Results**

169   Figure 2 shows the historical data of the precipitation and temperature that occurred both in the

170   plantation and natural regeneration sites in their first seven years. It should be noted that no

171   significant differences ($p > 0.05$) were found neither in precipitation nor in temperature among

172   the studied sites.

173   **Tree-ring width growth**

174   Results of mixed-effects analysis of variance model indicated that both fixed and random factors

175   show significant effects on annual tree-ring width growth ($P < 0.01$), which means that there are

176   significant differences among studied sites and years when they are kept constant. Table 2 shows

177   the pairwise comparisons for annual tree-ring width growth. There were significant differences

178   on tree-ring width growth for most evaluated years, except at ages 1 and 7 (P > 0.01). Figure 3

179   shows that annual tree-ring width growth is significantly greater in seedlings from plantation

180   than in trees naturally regenerated at 2-6 years. It is interesting to observe that annual tree-ring
181   width growth of seedlings in the natural regeneration shows an upward growth tendency from the
182   beginning to the end of the evaluation period; whereas, the annual tree-ring width growth of trees
183   in plantation shows a decrease in growth at 6 and 7 years.

184   **Biomass and carbon accumulation**

185   Results of mixed-effects analysis of variance model indicated that both fixed and random factors
186   show significant effects on individual biomass and carbon accumulation ($P < 0.01$), which
187   means that both biomass and carbon accumulation differ among sites and annual rates when they
188   are kept constant. Table 3 shows the pairwise comparisons for annual biomass and carbon
189   accumulation of seedlings in plantation and natural regeneration sites. The significant differences
190   on biomass and carbon accumulation were observed at ages of 5, 6 and 7 ($P > 0.01$). Figure 4
191   shows that important values of biomass accumulation are observed at 4-7 years, especially in the
192   plantation as a product of a greater tree-ring width growth in comparison to the naturally
193   regenerated site. The estimates of biomass and carbon accumulation by tree age both for
194   plantation and natural regeneration are shown in Table 4. After seven years of evaluation, the
195   seedlings in the plantation contain twice the biomass and carbon allocation than those evaluated
196   in the natural regeneration. In the plantation, a 7-year-old tree has on average 4.38 and 2.21 kg of
197   biomass and carbon content, respectively; whereas a naturally-regenerated seedling at the same
198   age has on average 2.16 and 1.09 kg of biomass and carbon content, respectively (Table 4).

199   **CAI and MAI**

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

208   **Discussion**

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

215   The tree-ring width growth is the most used parameter to evaluate tree growing of forests
216   (Dobner, Huss & Tomazello, 2018).Both the kind and age of seedlings showed significant effects
217   on annual tree-ring width growth. The planted seedlings showed a constant increase from their
218   establishment until age 5, while in the natural regeneration, this behaviour was maintained
219   during all the evaluation period. The decrease in tree-ring width growth observed in the

220 plantation at 6-7 years may be due to the effect of competition that increases with stand age
221 (Soto-Cervantes *et al*., 2016), especially in areas established with a high density like the one used
222 in this work. On the other hand, the significantly lower tree density recorded in natural
223 regeneration explains the constant increase on annual tree-ring width growth observed during the
224 seven years. Results on annual tree-ring width growth observed in the plantation of *Pinus*
225 *durangensis* suggest that when a density of 2,500 plants ha^{-1} is used, a pre-commercial thinning
226 is needed at age 5 (one year before tree growth reduction) to reduce tree competition and
227 promote basal diameter growth. Studies have showed that a greater spacing between trees of pine
228 species generates high availability of light and nutrients, which benefits growth both in diameter
229 and height (Baldwin *et al*., 2000; Arias, 2005). The significantly higher tree-ring width growth
230 recorded in the plantation at most evaluated ages may be also explained by the fact that in this
231 site, seedlings have more light availability due to the absence of seed-trees in this site, and
232 therefore, light is better assimilated to develop their maximum growth capacity and variations
233 soil preparation activities during planting (Plateros-Gastélum *et al*., 2018; Moretti *et al*., 2019;
234 Landis, 2011; Pérez-Luna *et al*., 2020). However, significant differences in width growth may
235 also be partly due to variations in soil properties, slope, genetic differences, aspects that have not
236 been evaluated in this study due to data limitations. According to Måren *et al*. (2015) tree growth
237 is affected also by factors like climate, topography, aspect, inclination of slope and soil type. For
238 example, tree growth is expected to be lower on steeply sloping sites than on flat or gently
239 sloping sites because slope is one of the factors controlling the processes of infiltration of surface
240 water into the subsurface (Morbidelli *et al*., 2019).
241 Biomass and carbon allocation in forests are important elements for timber production, carbon
242 sequestration and the generation of other environmental services (Graciano-Ávila *et al*., 2019).
243 In this paper both the studied sites and seedlings age show significant differences in annual
244 biomass and carbon accumulation ($P < 0.01$). The significantly higher annual biomass and
245 carbon accumulation observed in the plantation trees may be due to the existence of a higher
246 light environment which produces a high photosynthetic ability and favor growth in seedlings in
247 comparison to the natural regeneration that has still seed-trees producing shadow (Poorter *et al*.,
248 2012). However, the observed significant differences in biomass and carbon may be also caused
249 by varying site conditions which greatly depend on soil quality, unfortunately such a soil data
250 was not available for the present study. Results show that a 7-year-old seedling growing in the
251 plantation produce an average of 2 times more biomass and carbon (i.e. 4.38 and 2.21 kg,
252 respectively) than a seedling of the same age growing in the natural regeneration (2.16 and 1.09
253 kg). Considering that the current stand density is of 1881 trees ha^{-1}, the potential for carbon
254 sequestration of the studied 7-year-old plantation of *Pinus durangensis* is of 4.15 tons ha^{-1}. These
255 estimates of biomass and carbon content are lower than the estimations reported by Pacheco-
256 Escalona *et al*. (2007) for a 6-year-old plantation of *Pinus greggii* Englem. with averages of 8.0
257 and 4.08 kg per tree, respectively. Higher biomass and carbon content in the *Pinus greggii*
258 plantation may be a reflection of the use of higher number of seedlings per hectare during
259 planting (4425), a better growth rate, and site conditions (Rodríguez-Vásquez *et al*., 2021).

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

272 Conclusions

273 The plantation and natural regeneration seedlings studied in this work showed significant
274 differences on annual tree-ring width growth and annual biomass and carbon accumulation, the
275 plantation exhibiting higher rates at most evaluated ages. Better tree growth rates observed in
276 plantation seedlings are attributed mainly to silvicultural practices but can be also caused by
277 variations in soil properties, slope and genetic differences, aspects that have not been evaluated
278 in this study due to data limitations. Both kind of seedlings still do not show their maximum
279 growth because the lines of CAI and MAI in basal diameter still do not intersect. The study
280 reveals that forest plantations of *Pinus durangensis* can be successfully established in the forests
281 of Durango, Mexico, favoring both CO_2 capture among other ecosystem services.

282 Acknowledgements

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

284 References

285 Arias D. 2005. Morfometría del árbol en plantaciones forestales tropicales. *Revista Forestal*
286   *Kurú* 2(5): 2-11. *Available at*
287   http://www.scielo.org.mx/scielo.php?script=sci_nlinks&ref=4447938&pid=S1405-
288   04712012000020000400006&lng=es (accessed 26 July 2022).
289 Baldwin VC, Peterson KD, Clark III A, Ferguson RB, Strub MR, Bower DR. 2000. The effects
290   of spacing and thinning on stand and tree characteristics of 38-year-old loblolly pine.
291   *Forest Ecology and Management* 137(1-3): 91-102. *Available at*
292   https://www.sciencedirect.com/science/article/abs/pii/S0378112799003400 (accessed 26
293   July 2022).
294 Burney O, Aldrete A, Álvarez Reyes R, Prieto Ruíz JÁ, Sánchez Velázquez JR, Mexal JG. 2015.
295   México—Addressing challenges to reforestation. *Journal of forestry* 113(4):404-413
296   DOI 10.5849/jof.14-007.
297 Cardalliaguet L, Muñoz AA, Humanes V, Aguilera-Betti I, Génova M, LeQuesne C, Rojas-
298   Badilla M, Veas C. 2019. Crecimiento radial de *Abies pinsapo* en el sur de Chile:
299   relaciones con el clima local y su comparación con poblaciones naturales en España.

300   *Bosque (Valdivia)* 40(2):141-152 DOI 10.4067/s0717-92002019000200141.

301 Chávez-Gándara MP, Cerano-Paredes J, Nájera-Luna JA, Pereda-Breceda V, Esquivel-Arriaga

302   G, Cervantes-Martínez R, Cambrón-Sandoval VH, Cruz-Cobos F, Corral-Rivas, S.

303   2017. Reconstrucción de la precipitación invierno-primavera con base en anillos de

304   crecimiento de árboles para la región de San Dimas, Durango, México. *Bosque*

305   *(Valdivia)* 38(2): 387-399 DOI 10.4067/S0717-92002017000200016.

306 Comisión Nacional Forestal (CONAFOR). 2013. Metodología para realizar y presentar los

307   informes de sobrevivencia inicial (ISI) de las plantaciones forestales comerciales

308   (aspectos técnicos). *Available at*

309   *http://www.conafor.gob.mx/apoyos/index.php/inicio/download/1422* (accessed 3

310   February 2022).

311 Dobner M, Huss J, Tomazello Filho M. 2018. Wood density of loblolly pine trees as affected by

312   crown thinnings and harvest age in southern Brazil. *Wood Science and Technology*

313   52(2):465-485 DOI 10.1007/s00226-017-0983-9.

314 Fernández-Pérez L, Ramírez-Marcial N, González-Espinosa M. 2013. Reforestación con

315   *Cupressus lusitanica* y su influencia en la diversidad del bosque de pino-encino en Los

316   Altos de Chiapas, México. *Botanical Sciences* 91(2):207-216.

317 Flores A, Pineda Ojeda T, Flores Ayala E. 2019. Potencial de reforestación de seis especies de

318   pino para la restauración de zonas degradadas. Revista Mexicana de Ciencias Forestales

319   10(55): 171-179 DOI 10.29298/rmcf.v10i55.604

320 García ME. 2004. *Modificaciones al sistema de clasificación climática de Köppen*. 6 Ed.

321   Instituto de Geografía, Universidad Nacional Autónoma de México. *Available at*

322   *http://www.publicaciones.igg.unam.mx/index.php/ig/catalog/book/83* (accessed 3

323   February 2022).

324 González-Cásares M, Pompa-García M, Venegas-González A, Domínguez-Calleros P,

325   Hernández-Díaz J, Carrillo-Parra A, González-Tagle M. 2019. Hydroclimatic variations

326   reveal differences in carbon capture in two sympatric conifers in northern Mexico *PeerJ*

327   7:e7085 DOI 10.7717/peerj.7085.

328 González-Elizondo MS, González-Elizondo M, Tena-Flores JA, Ruacho-González L, López-

329   Enríquez IL. 2012. Vegetación de la Sierra Madre Occidental, México: Una síntesis.

330   *Acta Botánica Mexicana* 100:351-403 DOI 10.21829/abm100.2012.40.

331 Graciano-Ávila G, Alanís-Rodríguez E, Aguirre-Calderón OA, González-Tagle MA, Treviño-

332   Garza EJ, Mora-Olivo A, Buendía-Rodríguez E. 2019. Estimation of volume, biomass

333   and carbon content in a forest of temperate-cold climate of Durango, Mexico. *Revista*

334   *Fitotecnia Mexicana* 42(2):119-127.

335 Grossnickle SC. 2012. Why seedlings survive: influence of plant attributes. *New Forests*

336   43(5):711-738 DOI 10.1007/s11056-012-9336-6.

337 Hernández-Zaragoza P, Valdez-Lazalde JR, Aldrete A, Martínez-Trinidad T. 2019. Evaluación

338   multicriterio y multiobjetivo para optimizar la selección de áreas para establecer

339   plantaciones forestales. *Madera y Bosques* 25(2):1-17 DOI

340   10.21829/myb.2019.2521819.
341   Hernández-Vera D, Pompa-García M, Yerena-Yamallel JI, Alanís-Rodríguez E. 2017. Variación
342   de la concentración de carbono en tres especies mexicanas de pino. *Bosque (Valdivia)*
343   38(2):381-386. DOI 10.4067/S0717-92002017000200015.
344   Instituto Nacional de Ecología y Cambio Climático (INECC)-Secretaría de Medio Ambiente y
345   Recursos Naturales (SEMARNAT). 2015. Primer Informe Bienal de Actualización ante
346   la Convención Marco de las Naciones Unidas sobre el Cambio Climático. Ciudad de
347   México, México. *Available at*
348   *https://www.gob.mx/cms/uploads/attachment/file/40746/2015_bur_mexico.pdf* (accessed
349   3 February 2022).
350   Instituto Nacional de Estadística y Geografía (INEGI). 2007. Conjunto de datos vectorial
351   edafológico. Escala 1:250,000 Serie II. Continuo Nacional Durango. *Available at*
352   *https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=702825236007* (accessed 11
353   October 2022).
354
355   Landis TD. 2011. The target plant concepts-a history and brief overview. In: Riley LE, Haase
356   DL, Pinto JR, eds. *National Proceedings: Forest and Conservation Nursery*
357   *Associations-2010*. Fort Collins, Washington, DC.
358   López-Serrano PM, Corral-Rivas JJ, López-Sánchez CA. 2015. Programa Mexicano del
359   Carbono. Serie: Síntesis nacional. Estado actual del conocimiento del ciclo del carbono
360   y sus interacciones en México. Editores: Paz Pellat F, Wong González J, Torres
361   Alamilla R. Capítulo 1. Mapeo espacial de almacenes de carbono en el bosque templado
362   del estado de Durango, México. 158-163. Available at
363   https://www.researchgate.net/profile/Fernando-Ayala-
364   5/publication/331686242_Secuestro_de_carbono_en_suelos_con_deficit_hidrico_en_la
365   _cuenca_de_la_Paz_Baja_California_Sur_noroeste_de_Mexico/links/5c87e8eba6fdcc3
366   8174f8630/Secuestro-de-carbono-en-suelos-con-deficit-hidrico-en-la-cuenca-de-la-Paz-
367   Baja-California-Sur-noroeste-de-Mexico.pdf#page=158 (accessed 26 July 2022).
368   Måren IE, Karki S, Prajapati C, Yadav RK, Shrestha BB. 2015. Facing north or south: Does
369   slope aspect impact forest stand characteristics and soil properties in a semiarid trans-
370   Himalayan valley? J. *Journal of Arid Environments* 121: 112–123 DOI
371   10.1016/j.jaridenv.2015.06.004.
372
373   Mejía-Bojórquez M, García Rodríguez JL, Muñoz Flores HJ. 2015. Evaluación de plantaciones
374   de cuatro especies forestales en el estado de Durango. REAXION: Ciencia y Tecnología
375   Universitaria (Versión imprimible). *Available at http://*
376   *reaxion.utleon.edu.mx/Art_Impr_Evaluacion_plantaciones_cuatro_especies_forestales_*
377   *Durango.html* (accessed 3 February 2022).
378   Montes de Oca-Cano E, Ramírez-García P, Nájera Luna JA, Méndez-Gonzáles J, Graciano Luna
379   JDJ. 2008. Flujos y asimilación de CO_2 de *Pinus durangensis* (Martínez M.) en la

380   Región de El Salto, Durango, México. *InterSedes* 9(17):181-192.

381 Morbidelli R, Corradini C, Saltalippi, C, Flammini A, Dari J, Govindaraju RS. 2019. A New
382   Conceptual Model for Slope-Infiltration. *Water* 11(4): 678 DOI 10.3390/w11040678.

383 Moretti AP, Olguín FY, Pinazo M, Gortari F, Vera Bahima J, Graciano C. 2019. Supervivencia y
384   crecimiento de un árbol nativo maderable bajo diferentes coberturas de dosel en el
385   Bosque Atlántico, Misiones, Argentina. *Ecología Austral* 29(1):099-111 DOI
386   10.25260/ea.19.29.1.0.779.

387 Návar JDJ, González N, Graciano Luna JDJ, Dale V, Parresol B. 2004. Additive biomass
388   equations for pine species of forest plantations of Durango, Mexico. *Madera y Bosques*
389   10(2):17-28 DOI 10.21829/myb.2004.1021272.

390 Oberfeld D, Franke T. 2013. Evaluating the robustness of repeated measures analysis: The case
391   of small sample sizes and nonnormal data. Behav Res. 45:792–812.

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

395 Patiño Forero S, Suárez Santos LN, Andrade Castañeda HJ, Segura Madrigal MA. 2018. Captura
396   de carbono en biomasa en plantaciones forestales y sistemas agroforestales en Armero-
397   Guayabal, Tolima, Colombia. *Revista de Investigación Agraria y Ambiental* 9(2):121-
398   134 DOI 10.22490/21456453.2312.

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

402 Pérez-Luna A, Wehenkel C, Prieto-Ruíz JÁ, López-Upton J, Hernández-Díaz JC. 2020. Survival
403   of side grafts with scions from pure species *Pinus engelmannii* Carr. and the *P.*
404   *engelmannii*× *P. arizonica* Engelm. var. arizonica hybrid. *PeerJ* 8:e8468 DOI
405   10.7717/peerj.8468.

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

409 Poorter H, Niklas KJ, Reich PB, Oleksyn J, Poot P, Mommer L. 2012. Biomass allocation to
410   leaves, stems and roots: metaanalyses of interspecific variation and environmental
411   control, New Phytologist, vol. 193, no. 1, pp. 30–50, 2012.

412 Prieto Ruíz JÁ, Aldrete A, Sánchez Velázquez JR, Hernández Díaz JC. 2016. Antecedentes
413   sobre las reforestaciones en México. In: Prieto Ruíz JÁ, Goche Télles JR, eds. *Las*
414   *reforestaciones en México, problemática y alternativas de solución*. Durango, México:
415   Universidad Juárez del Estado de Durango.

416 Ramírez Santiago R, Ángeles Pérez G, Clark Tapia R, Cetina Alcalá VM, Plascencia Escalante
417   O, Hernández de La Rosa P. 2015. Efectos del manejo forestal en la repoblación de
418   *Pinus* spp. en la Sierra Norte de Oaxaca, México. *Revista Mexicana de Ciencias*
419   *Forestales* 6(32):49-62.

420   Rodríguez Flores, FJ, Pompa-García M, Mallén Rivera C, Goche Télles, R. 2014. Modelos
421   dendroclimáticos para crecimiento radial forestal. *Revista Mexicana de Ciencias*
422   *Forestales* 5(26): 30-37.
423   R Core Team. 2019. R: A language and environment for statistical computing. Vienna: R
424   Foundation for Statistical Computing. *Available at https://www.R-project.org/*
425   (accessed 3 February 2022).
426   Rodríguez-Vásquez ME, Rodríguez-Ortiz G, Enríquez-Del Valle JR, Campos-Ángeles GV,
427   Velasco-Velasco VA, Hernández-Hernández A. 2021. Ensayos de progenies y huertos
428   semilleros de especies forestales en México. *Revista Mexicana de Agroecosistemas*
429   8(1):79-88.
430   Santiago-García W, de los Santos-Posadas HM, Ángeles-Pérez G, Valdez-Lazalde JR, Corral-
431   Rivas JJ, Rodríguez-Ortiz G, Santiago-García E. 2015. Modelos de crecimiento y
432   rendimiento de totalidad del rodal para *Pinus patula*. *Madera y Bosques* 21(3):95-110
433   DOI 10.21829/myb.2015.213459.
434   Snedecor, GW, Cochran, WG. 1989. Statistical methods. Ames, Iowa: Iowa State Univ Press.
435   Soto-Cervantes JA, López-Sánchez CA, Corral-Rivas JJ, Wehenkel C, Álvarez-González JG,
436   Crecente-Campo F. 2016. Desarrollo de un modelo de perfil de copa para *Pinus cooperi*
437   Blanco en la UMAFOR 1008, Durango, México. *Revista Chapingo Serie Ciencias*
438   *Forestales y del Ambiente* 22(2):179-192 DOI 10.5154/r.rchscfa.2015.09.040.
439   Soto-Cervantes JA, Carrillo-Parra A, Rodríguez-Laguna R, Corral-Rivas JJ, Pompa-García M,
440   Domínguez-Calleros PA. 2020. Survival, growth and carbon content in a forest
441   plantation established after a clear-cutting in Durango, Mexico. *PeerJ* 8:e9506 DOI
442   10.7717/peerj.9506.
443   Stewart JF, Will R, Crane BS, Nelson CD. 2016. Occurrence of shortleaf×loblolly pine hybrids
444   in shortleaf pine orchards: implications for ecosystem restoration. *Forest Science*
445   63(2):225-231 DOI 10.5849/forsci.15-167.
446   Van Oldenborgh GJ, Burgers G. 2005. Searching for decadal variations in ENSO precipitation
447   teleconnections. *Geophys Res Lett* 32(15):L15701 DOI 10.1029/2005GL023110.
448   Vargas-Larreta B, López-Sánchez CA, Corral-Rivas JJ, López-Martínez JO, Aguirre-Calderón
449   CG, Álvarez-González JG. 2017. Allometric equations for estimating biomass and
450   carbon stocks in the temperate forests of North-Western Mexico. *Forests* 8(8):269 DOI
451   10.3390/f8080269.
452   Vallejo VR, Smanis A, Chirino E, Fuentes D, Valdecantos A, Vilagrosa A. 2012. Perspectives in
453   dryland restoration: approaches for climate change adaptation. *New forests* 43(5):561-
454   579 DOI 10.1007/s11056-012-9325-9.
455   Vásquez-García I, Cetina-Alcalá VM, Campos-Bolaños R, Casal-Ángeles LF. 2016. Evaluación
456   de plantaciones forestales en tres comunidades de la Mixteca Alta oaxaqueña. *Agro*
457   *Productividad* 9(2):12-19.
458

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

N= Number of trees per hectare, BA= Basal area per hectare (m²), DB= diameter at the base, SD = Standard deviation.

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

Study sites	Area (ha)	Stand variable				Sampled seedlings					
		N		BA (m²)		Age (years)		DB (cm)		Height (m)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Plantation	21.40	1881	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

2 *N= Number of trees per hectare, BA= Basal area per hectare (m²), DB= diameter at the base, SD = Standard*

3 *deviation.*

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

(P < 0.05) *, (P < 0.01) **, (P < 0.001) ***, ns= not significant.

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

3   *(P < 0.05) *, (P < 0.01) **, (P < 0.001) ***, ns= not significant.*

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

(P < 0.05) *, (P < 0.01) **, (P < 0.001) ***, ns= not significant.

1   Table 3. Pairwise comparisons for the annual accumulation of biomass and carbon of seedlings
2   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***

3   *(P < 0.05) *, (P < 0.01) **, (P < 0.001) ***, ns= not significant.*

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

SD = Standard deviation.

1 Table 4. Annual average biomass and carbon accumulation in seedlings of *Pinus durangensis* in
2   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**

3 *SD = Standard deviation.*

Figure 1

Figure 1. Location of the study area.

Source: Available in the 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#
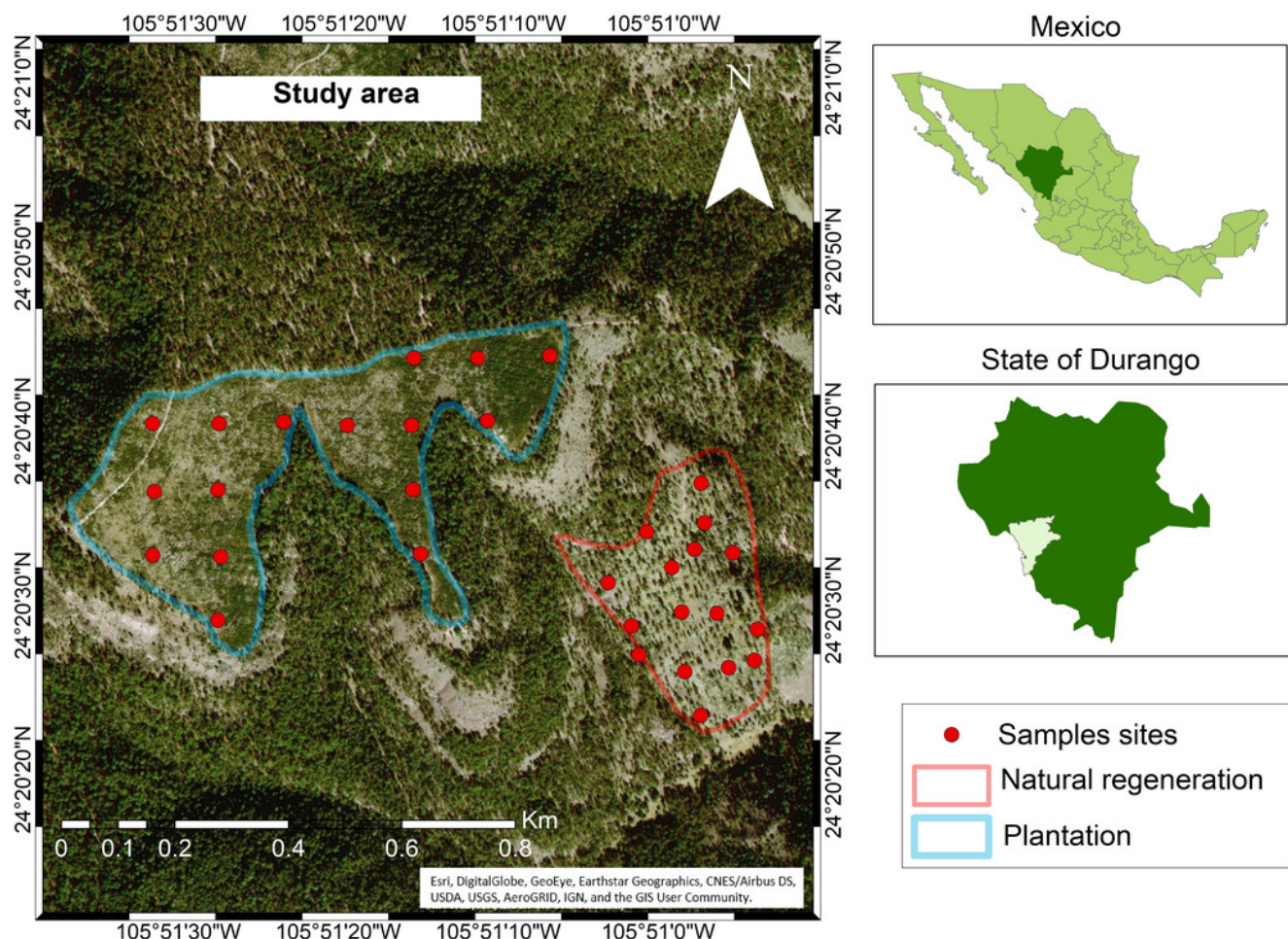
Figure 2

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).
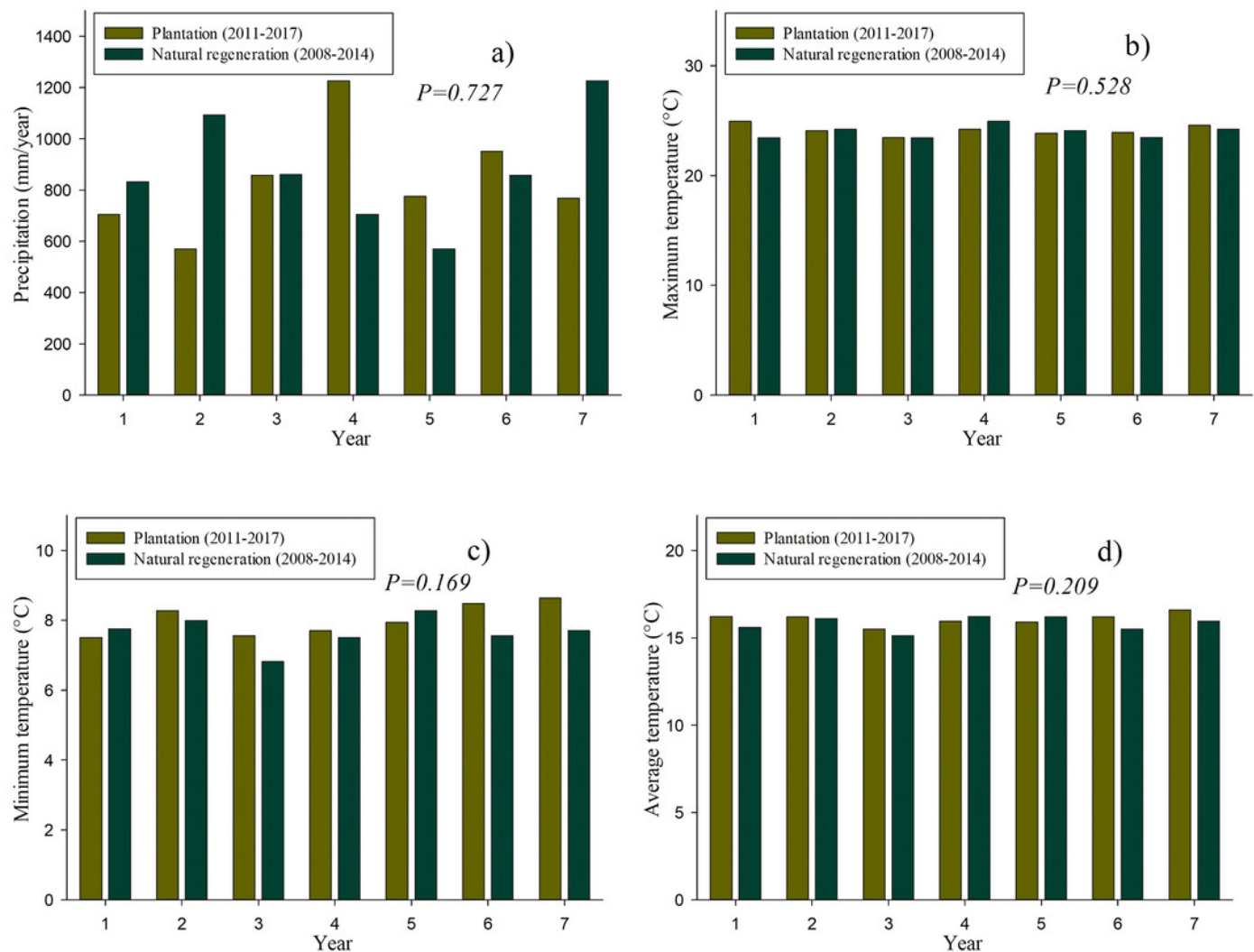
Figure 3

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.
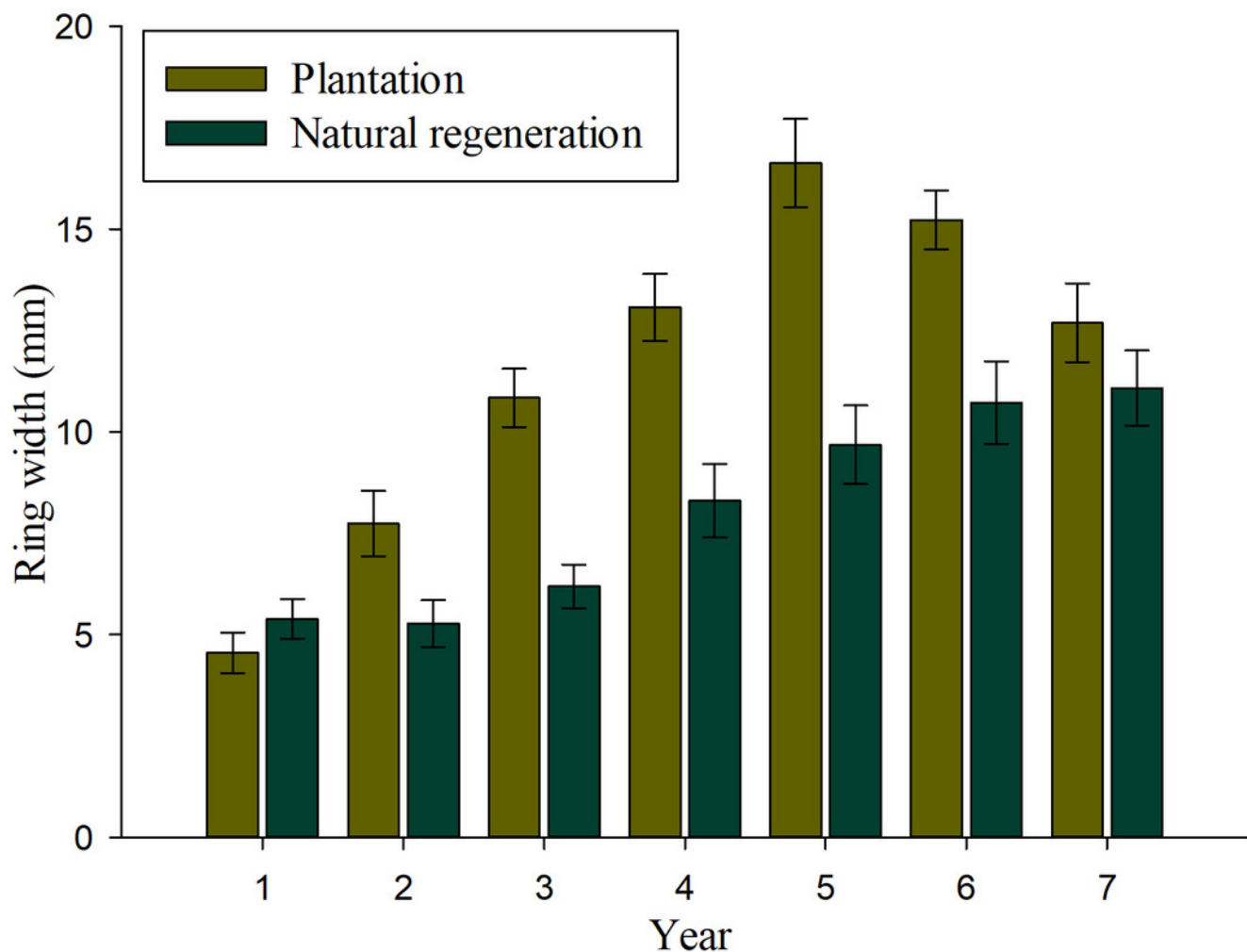
Figure 4

Figure 4. Average values (bars) and standard error (whiskers) of the total aerial biomass accumulated in *Pinus durangensis* seedlings from plantation and natural regeneration.
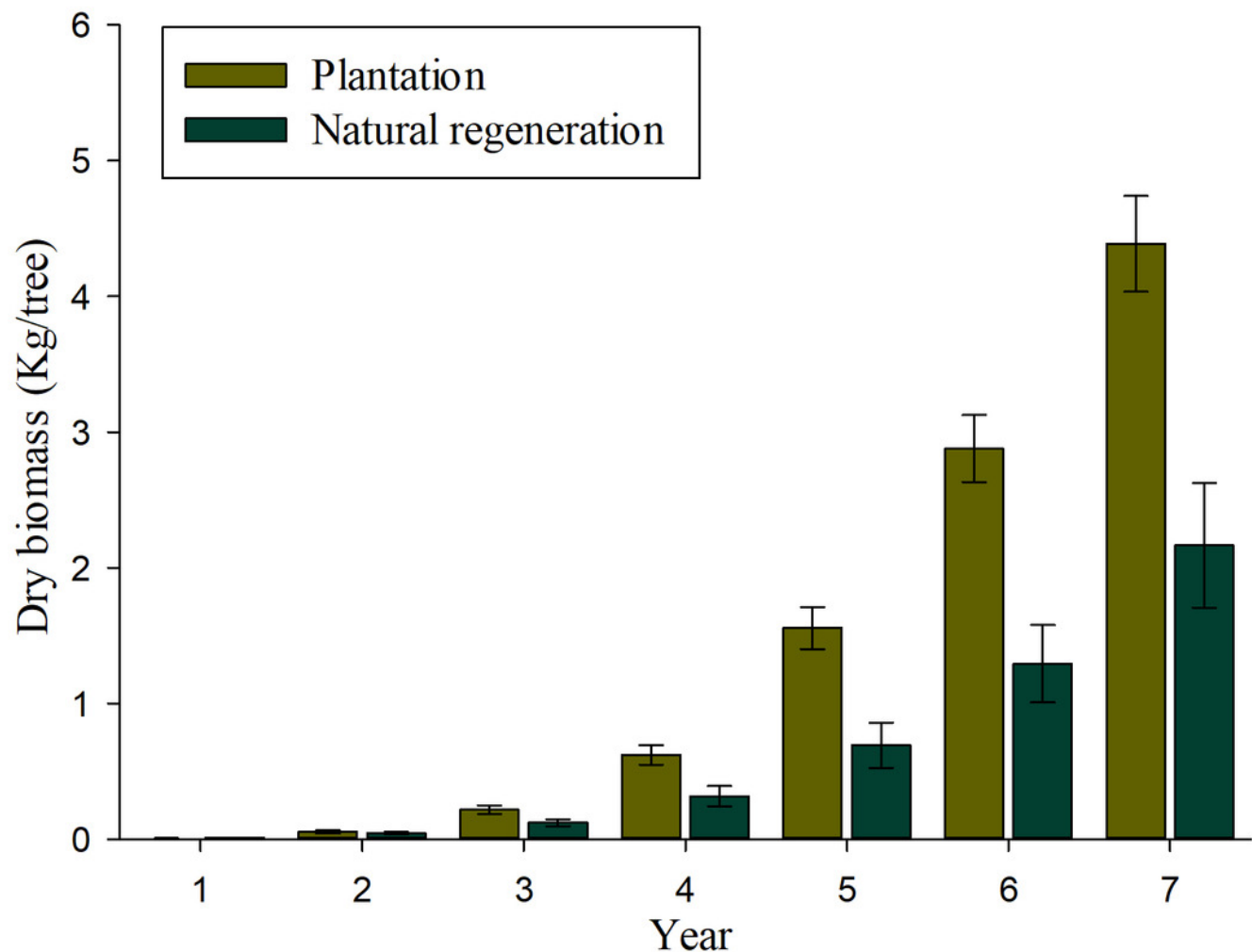
Figure 5

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).