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

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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 increase in diameter at the base and carbon content in *Pinus durangensis* Martínez seedlings from a young plantation (eight years) and naturally regenerated seedlings in a stand subject to regeneration felling (nine years). The data was collected in 32 sites of 100 m^2 (16 from each site) where seedlings distributed proportionally to the diameter categories were selected. A slice from the base of the stump was obtained from each tree. The width of the growth rings was measured with a stereomicroscope with precision in micrometers (µm). The ring width per year of each tree was recorded to obtain the diameter at the base and estimate the biomass and carbon content through allometric equations. The t test indicated that there are significant differences ($P \leq 0.05$) between the diameters at the base between the two types of seedlings studied in all years, except for the first and last year, with the individuals of the plantation showing better increases. The estimation of biomass and carbon content showed significant differences ($P \leq 0.05$) in all years, with the exception of the second year ($p = 0.6051$). The lines of current annual increment (CAI) and annual average increment (AAI) in basal diameter of the plantation and natural regeneration have not yet intersected. Forest plantations and natural regeneration promote CO_2 capture and increase wood production, among other ecosystem services.

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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 increase in diameter at the base and carbon content in *Pinus durangensis* Martínez seedlings from a young plantation (eight years) and naturally regenerated seedlings in a stand subject to regeneration felling (nine years). The data was collected in 32 sites of 100 m^2 (16 from each site) where seedlings distributed proportionally to the diameter categories were selected. A slice from the base of the stump was obtained from each tree. The width of the growth rings was measured with a stereomicroscope with precision in micrometers (µm). The ring width per year of each tree was recorded to obtain the diameter at the base and estimate the biomass and carbon content through allometric equations. The t test indicated that there are significant differences ($P \leq 0.05$) between the diameters at the base between the two types of seedlings studied in all years, except for the first and last year, with the individuals of the plantation showing better increases. The estimation of biomass and carbon content showed significant differences ($P \leq 0.05$) in all years, with the exception of the second year ($p = 0.6051$). The lines of current annual increment (CAI) and annual average increment (AAI) in basal diameter of the plantation and natural regeneration have not yet intersected. Forest plantations and natural regeneration promote CO_2 capture and increase wood production, among other ecosystem services.

Key words: *Pinus durangensis* Martínez, Biomass, Carbon sequestration, Regeneration cut, Clear-cutting.

Introduction

Plantations and natural forests are an excellent alternative for CO_2 capture, which makes it possible to reduce greenhouse gas concentrations and mitigate the effects of global warming (Patiño Forero *et al*., 2018; González-Cásares *et al*., 2019). At present, studies on carbon content have become highly relevant.

Mexico is one of the most emitters of greenhouse gas countries, including 407,695 megatons of CO_2 annually (INECC-SEMARNAT, 2015), so it is important to know the stocks and flows of carbon in its forest areas. Biomass estimation can be calculated using direct methods and the implementation of allometric equations (Návar *et al*., 2004; Montes de Oca-Cano *et al*., 2008; Vargas-Larreta *et al*., 2017).

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

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

The natural regeneration of pine species through regeneration fellings with parent trees or through selective fellings are the most used methods to achieve the establishment of a new mass in the areas under forest management in the temperate forests of Mexico (Ramírez Santiago *et al*., 2015). In addition, it is an appropriate option for the ecological rehabilitation of forests (Pensado-Fernández *et al*., 2014), which takes advantage of the genetic memory (genotype) of the germplasm to guarantee a higher percentage of survival and development (Landis, 2011).

However, few studies have compared growth and carbon sequestration between forest plantations and natural regeneration of *Pinus durangensis* (Fernández-Pérez, Ramírez-Marcial & González-Espinosa, 2013).

As a hypothesis of this study, we consider that there are significant differences ($p \leq 0.05$) in terms of the increase in the diameter at the base and carbon capture between seedlings from plantation and natural regeneration. Therefore, the objectives of this work were (i) to compare the basic bioclimatic conditions (precipitation and temperature) of the study areas in the years of growth of the seedlings evaluated, (ii) to compare the diameter at the base, (iii) estimate and compare the accumulated content of biomass and carbon and (iv) estimate the current annual increment (CAI) and average annual increment (AAI) in basal diameter of sample seedlings of Pinus durangensis from a plantation and natural regeneration.

Materials and methods

Characteristics of the study area

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

The climate in the study area is temperate with summer rains (CW) and the temperature ranges between -3 and 18 °C (García, 2004). The average slope in the clearing is 9%, while in the regeneration felling it is 27% on average. The most frequent rains occur between July and September, with an average annual rainfall of 1,000 mm. The characteristic vegetation is mixed coniferous and broadleaf forests. The first type is dominated by pines, of which the following stand out: *Pinus durangensis*, *P. cooperi* C.E. Blanco, *P. teocote* Schl. et Cham. and *P. strobiformis* Engelm. Of the broadleaves, the oaks stand out, among these: *Quercus rugosa* Née and *Q. sideroxyla* Bonpl. There are also trees of some ecologically important shrub species of the generous *Juniperus*, *Arbutus* and *Alnus*, among others (González-Elizondo *et al*., 2012).

Forestry background

The clear-cutting was carried out in February 2010 and immediately in the rainy season (July and August) of the same year the plantation with *Pinus durangensis* was established. The plants were 12 months old at the time of establishment of the plantation, which was carried out with a density of 2,500 plants/ha. On the other hand, regeneration felling with parent trees was carried out in 2007 with an intensity of felling of standing trees of 58% for the genus *Pinus*, 100% for *Quercus*, 100% for *Juniperus* and 100% for *Arbutus*, leaving only the parent trees of *Pinus durangensis* with the aim of promoting the natural regeneration of the species.

The monthly climatic data of total precipitation, as well as 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 http://climexp.knmi.nl/ (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 sites of 100 m^2 were established (16 in the plantation and 16 in the regeneration cut). 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 site, variables such as diameter at the base (cm) and height (m) were measured using a Vernier and a 5 m tape measure, respectively. A type tree was selected from each site, distributed proportionally to the diameter category. The sampling of these seedlings involved their felling and obtaining a slice at their base. In total, 32 *Pinus durangensis* seedlings were felled (16 seedlings in the plantation and 16

in the natural regeneration site). Table 1 presents the descriptive statistics of the study areas and the type sampled seedlings.
The slices were labeled, dried and polished, and subsequently each growth ring was measured using a stereomicroscope with precision in μm in the dendroecology laboratory of the Facultad de Ciencias Forestales y Ambientales of the Universidad Juárez del Estado de Durango. The width of the growth rings was estimated by the average of the measurement in four directions. For the comparison of the width of the rings, only the first seven years of growth were taken into account, since the age of the seedlings in both sites is different. The data was obtained in July 2018, so the measurement of the rings was done retrospectively from the year 2017, because the last ring of the plantation was still under development.

Biomass estimation and carbon content

To obtain the total aerial biomass, the equation developed by Návar *et al*. (2004) for *Pinus durangensis*, which uses the basal diameter as a predictive variable (Equation 1, $R^2 = 0.86$).

$$Y_i = a(DB)^b \quad (1)$$

Where:
Y_i = Total dry biomass
a = 0.0199 y b = 2.5488
DB = Diameter at the base of the tree (cm)
The carbon content for this species was calculated according to the percentages indicated by Hernández-Vera *et al*. (2017), who indicate a concentration of 50.36% of the total biomass.

Increments estimation

The growth of the type seedlings was estimated using the diameter at the base, estimating the current annual increment (CAI), the average annual increment (AAI) and the ring width of the years studied. The CAI corresponds to the growth produced each year, while the AAI is the average of the total growth at a certain age of the trees (Cardalliaguet *et al*., 2019). For this, the following equations (2 and 3) were used.

$$CAI = BD_{i+1} - BD_i \quad (2)$$

$$AAI = \frac{BD}{A} \quad (3)$$

Where:
BD_i *y* BD_{i+1} = *Diameter to the current and next base of the slice*
A = Age.

Statistical analysis

Considering that the terrain of both stands is relatively flat and homogeneous, a t-test for independent samples was used to compare the means of the two groups of seedlings and find possible statistical differences in the response variables: diameter at the base, biomass and content of carbon ($p \leq 0.05$). The assumptions of data normality and equality of variance were analyzed using the Kolmogorov-Smirnov and Levene's tests, respectively (Steel & Torrie, 1980). All statistical analyzes were performed in the statistical software R® version 3.5.3 (R Core Team, 2019).

Results

The Figure 2 shows the historical data of the precipitation and temperature present in the different periods of growth of the plantation and natural regeneration, it should be noted that no significant differences ($p > 0.05$) were found in the precipitation or in the temperature between sites.

Width of growth rings

The results of the t-test indicated that there are significant differences in the average diameter at the base recorded in the seedlings of the plantation and of natural regeneration in most of the ages studied ($P < 0.05$). The Table 2 shows the statistical comparison between the diameter at the average base of the groups of seedlings in the plantation and the natural regeneration for each year. It is observed that in the first and last year there are no significant differences ($P > 0.05$), while in later years the diameter at the base is statistically different.

It is observed that the width of the rings is significantly greater in the seedlings of the plantation, with the exception of the first year. It is interesting to observe that the width of the rings of the seedlings of the natural regeneration shows an upward growth from the beginning to the end of the evaluation period.

Biomass and carbon content

The results of the t test indicated that there are significant differences in the estimations of biomass accumulation and carbon content between the seedlings of the plantation and natural regeneration in most of the ages studied ($P < 0.05$) with the exception of the second year ($p = 0.6051$) (Table 3).

The Figure 4 shows the biomass accumulation recorded in the type seedlings from both the plantation and the natural regeneration. Significant values of biomass accumulation are observed from the fourth year both in the plantation seedlings and in those of natural regeneration, product of a greater increase in the width of the growth rings of the analysed seedlings.

The estimates of biomass and carbon content per year in the sites are shown in Table 4. After seven years of evaluation, the seedlings from the plantation contain twice the biomass and carbon than those evaluated in natural regeneration, since in the plantation a tree has an average of 4.38 and 2.21 kg of biomass and carbon content, respectively; while a naturally regenerated tree has an average of 2.16 and 1.09 kg of biomass and carbon content, respectively.

CAI and AAI

The evolution of the CAI and the AAI in basal diameter with respect to the age of the seedlings evaluated from the plantation and natural regeneration is shown in Figure 5. The increase in diameter at the base of the plantation shows a linear trend, however, at six years a decrease is observed (Figure 5a). Seedlings from natural regeneration also show a linear trend up to seven years (Figure 5b). The maximum values of the CAI and the AAI in basal diameter of the seedlings evaluated were presented at five and seven years for plantation and natural regeneration, respectively.

Discussion

The increase in the width of the growth rings in the seedlings of the plantation registered a constant growth from its establishment until the fifth year, while in the seedlings of the regeneration felling this behaviour was maintained throughout the evaluation period. The slight decrease in the increase in the width of the rings observed in the plantation, as of the sixth year, is due to the effect of competition that increases with age (Soto-Cervantes *et al*., 2016), mainly in plantations established with high density like the one used in this work.

The width of the tree rings is the most used parameter to evaluate the growth rate of forests (Dobner, Huss & Tomazello, 2018). In this study, the lowest ring width increment value occurred during the first year of plantation, and this can be attributed to various factors, such as stress, drought, salinity and extreme temperatures that generate low development of the plantations in the first months or years of age (Pérez-Luna et al., 2020). In this sense, an annual rainfall of less than 700 mm was found during the first two years of growth of the plantation (Figure 2).

However, for the rest of the ages studied, the plantation showed significantly higher growth than those recorded in natural regeneration. This can be explained by the fact that in the plantation, seedlings have more light availability, which they assimilate to develop their maximum growth capacity (Plateros-Gastélum *et al*., 2018; Moretti *et al*., 2019), in addition to other benefits provided by forestry activities during planting, such as soil cleaning (Landis, 2011), or the possibility of establishing a selected plant from trees with superior genetic characteristics (Pérez-Luna et al., 2020).

The mean carbon content per tree for the plantation was estimated at 0.31 kg yr^{-1}, while for natural regeneration it was 0.15 kg yr^{-1}. Pompa-Garcia *et al*. (2018) estimated the carbon in adult trees of *Pinus arizonica* and *P*. *cembroides*, and found a carbon accumulation of 4.80 kg yr^{-1} and 4.84 kg yr^{-1}, respectively, which may be due to a certain point to the higher density of the species studied by these researchers compared to *P*. *durangensis*. Pacheco Escalona *et al*. (2007) also evaluated the accumulated biomass content in a six-year-old *Pinus greggii* Englem. plantation and found that the average aerial dry biomass was 8.0 kg per tree. On the other hand, the average carbon content per tree observed in natural regeneration at seven years of age was 1.09 kg. This average is higher than that reported by Montes de Oca-Cano *et al*. (2008), who estimated 0.30 kg per tree in a six-year-old *Pinus durangensis* natural regeneration area. This difference may be due mainly to the different patterns of adaptation and genotype-environment interaction of forest species (Rodríguez-Vásquez *et al*., 2021).

The carbon content per tree estimated in this study reinforces what was established by Ramírez Santiago *et al*. (2015) who point out that the natural regeneration of pine species should be considered as an important complement to the regeneration of areas under forest management in the temperate forests of Mexico; however, it is important to highlight the best increases in forest plantation, which is why this practice should not be ruled out to improve forest management of forests in Mexico (Prieto Ruíz *et al*., 2018).

The study of different types of increase in forests (for example, current annual increment (CAI) and average annual increment (AAI)), makes it possible to distinguish the different levels with which it is possible to define the optimum harvest age if it is desired to maximize forest production (Santiago-García *et al*., 2015; Cardalliaguet *et al*., 2019). In this study, the maximum point of CAI in basal diameter of seedlings in the evaluation period occurred at five and seven years for plantation and natural regeneration, respectively. Likewise, it was observed that the curves of the CAI and AAI in basal diameter did not intersect during the evaluation period. Vasquez-Garcia *et al*. (2016) found that in a *Pinus greggii* Engelm. plantation the CAI and AAI curves intersected before the eighth year of age; however, it is important to consider that the growth of the species of Australis subsection is faster than the species of the Ponderosae subsection. In this sense, in commercial forest plantations of *Pinus durangensis* less than 15 years old, the intersection between the CAI and AAI curves was not reported (Mejía-Bojórquez, García & Muñoz, 2015).

The results of this research suggest that the clear-cutting method is adequate in terms of growth for regional forests, provided that an immediate plantation is carried out and initial, intermediate and advanced protection and management are provided to it (fenced, fire breaks, pest prevention, fertilizer application, weeding, pruning and thinning), since not carrying out silvicultural activities in commercial forest plantations generates a risk of soil and biodiversity loss (Monárrez-González et al., 2018)..

Conclusions

The plantation and natural regeneration seedlings studied in this work showed significant differences regarding the diameter at the base, presenting better growth values in the plantation. Biomass and carbon content estimates were statistically different except for the second year. At seven years, the seedlings evaluated in the plantation contained twice the biomass and carbon content than those evaluated in natural regeneration. The plantation and natural regeneration still do not show their maximum growth, because the lines of CAI and AAI in basal diameter still do not intersect. The study reveals that forest plantations can be successfully established in the forests of Durango, Mexico, favouring CO_2 capture and increased wood production, among other ecosystem services.

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Table 1 (on next page)

Table 1. Descriptive statistics of the mixture of species found in the plantation and natural regeneration, as well as the type seedlings that were destructively sampled.

N= Name of trees for hectare, BA= Basal Area for hectare (m^2), DB= diameter at the base, SD = Standard deviation.

Table 1. Descriptive statistics of the mixture of species found in the plantation and natural regeneration, as well as the type seedlings that were destructively sampled.

Study Areas	Surf. (ha)	Sub-stand				Sampled seedlings					
		N		BA (m^2)		Age (Years)		DB (cm)		Height (m)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Plantation	21.40	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

N= Name of trees for hectare, BA= Basal Area for hectare (m^2), DB= diameter at the base, SD = Standard deviation.

Table 2 (on next page)

Table 2. Results of the statistical comparison of the diameter at the base per year according to the t-test.

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

Table 2. Results of the statistical comparison of the diameter at the base per year according to the t-test.

Comparison	Year	t value	p value
Plantation-Regeneration	1	1.1989	0.240^{ns}
Plantation-Regeneration	2	-2.4767	0.019*
Plantation-Regeneration	3	-5.1851	0.00001***
Plantation-Regeneration	4	-3.8973	0.0005***
Plantation-Regeneration	5	-4.7596	0.00004***
Plantation-Regeneration	6	-3.6115	0.001**
Plantation-Regeneration	7	-1.1998	0.2396^{ns}

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

Table 3(on next page)

Table 3. Results of the t test for the estimation of the annual accumulation of biomass and carbon content, in *Pinus durangensis* seedlings from plantation and natural regeneration.

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

Table 3. Results of the t test for the estimation of the annual accumulation of biomass and carbon content, in *Pinus durangensis* seedlings from plantation and natural regeneration.

Comparison	**Year**	**Biomass**		**Carbon**	
		t value	**p value**	**t value**	**p value**
Plantation-Regeneration	1	2.1093	0.045*	2.1093	0.045*
Plantation-Regeneration	2	-0.52311	0.6051[ns]	-0.52311	0.6051[ns]
Plantation-Regeneration	3	-2.3398	0.026*	-2.3398	0.026*
Plantation-Regeneration	4	-2.9175	0.006**	-2.9175	0.006**
Plantation-Regeneration	5	-3.8167	0.0006***	-3.8167	0.0006***
Plantation-Regeneration	6	-4.2009	0.0002***	-4.2009	0.0002***
Plantation-Regeneration	7	-3.8376	0.0006***	-3.8376	0.0006***

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

Table 4(on next page)

Table 4. Biomass and average carbon content per year in *Pinus durangensis* seedlings from plantation and natural regeneration.

SD = Standard deviation.

Table 4. Biomass and average carbon content per year in *Pinus durangensis* seedlings from plantation and natural regeneration.

Year	Biomass (kg/tree)				Carbon (kg/tree)			
	Plantation		Regeneration		Plantation		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**

SD = Standard deviation.

Figure 1

Figure 1. Location of the study area.

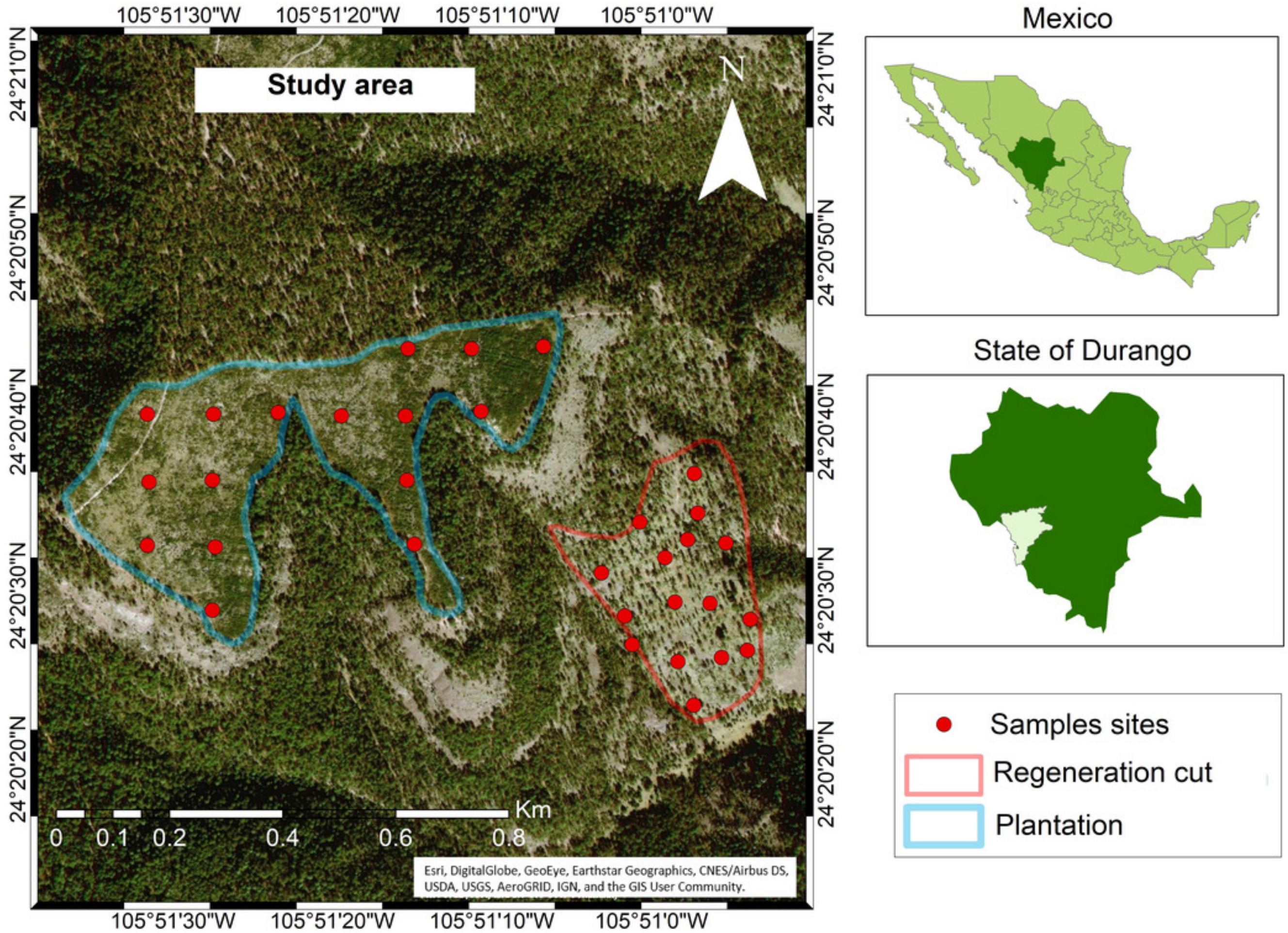

Figure 2

Figure 2. Historical climate data on the plantation (2011-2017) and natural regeneration (2008-2014): Precipitation (a), maximum temperature (b), minimum temperature (c) and average temperature (d).

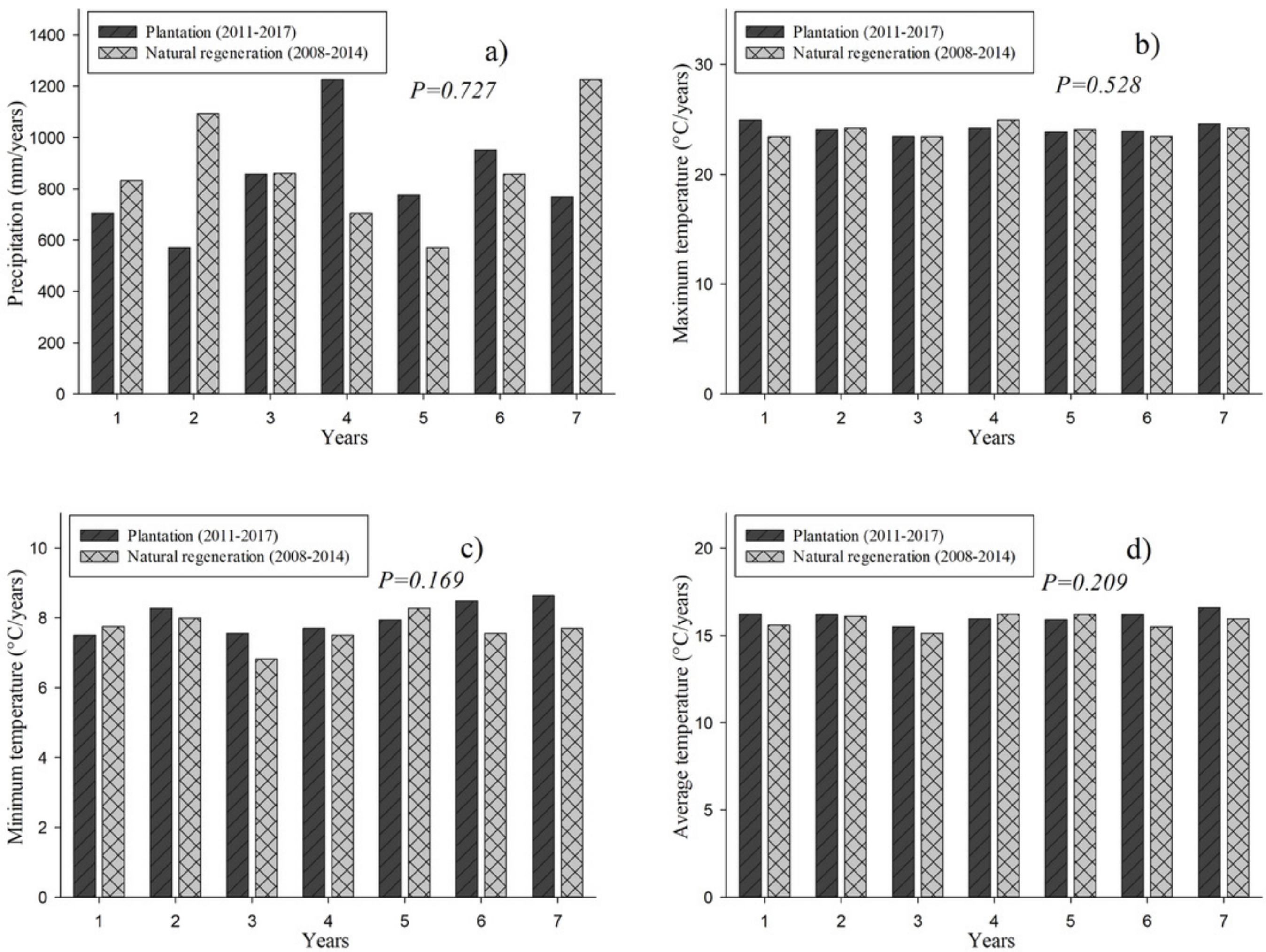

Figure 3

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.

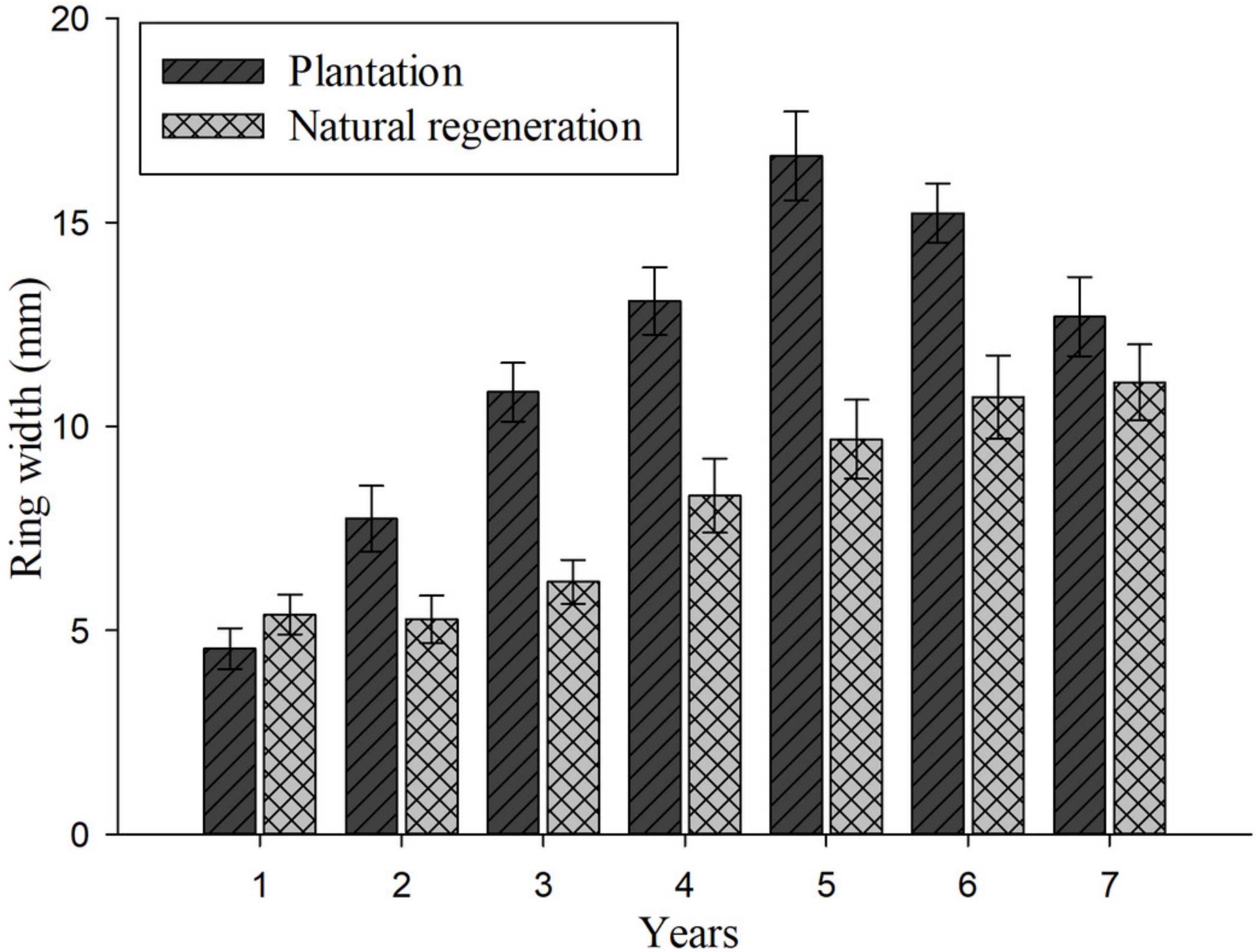

Figure 4

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

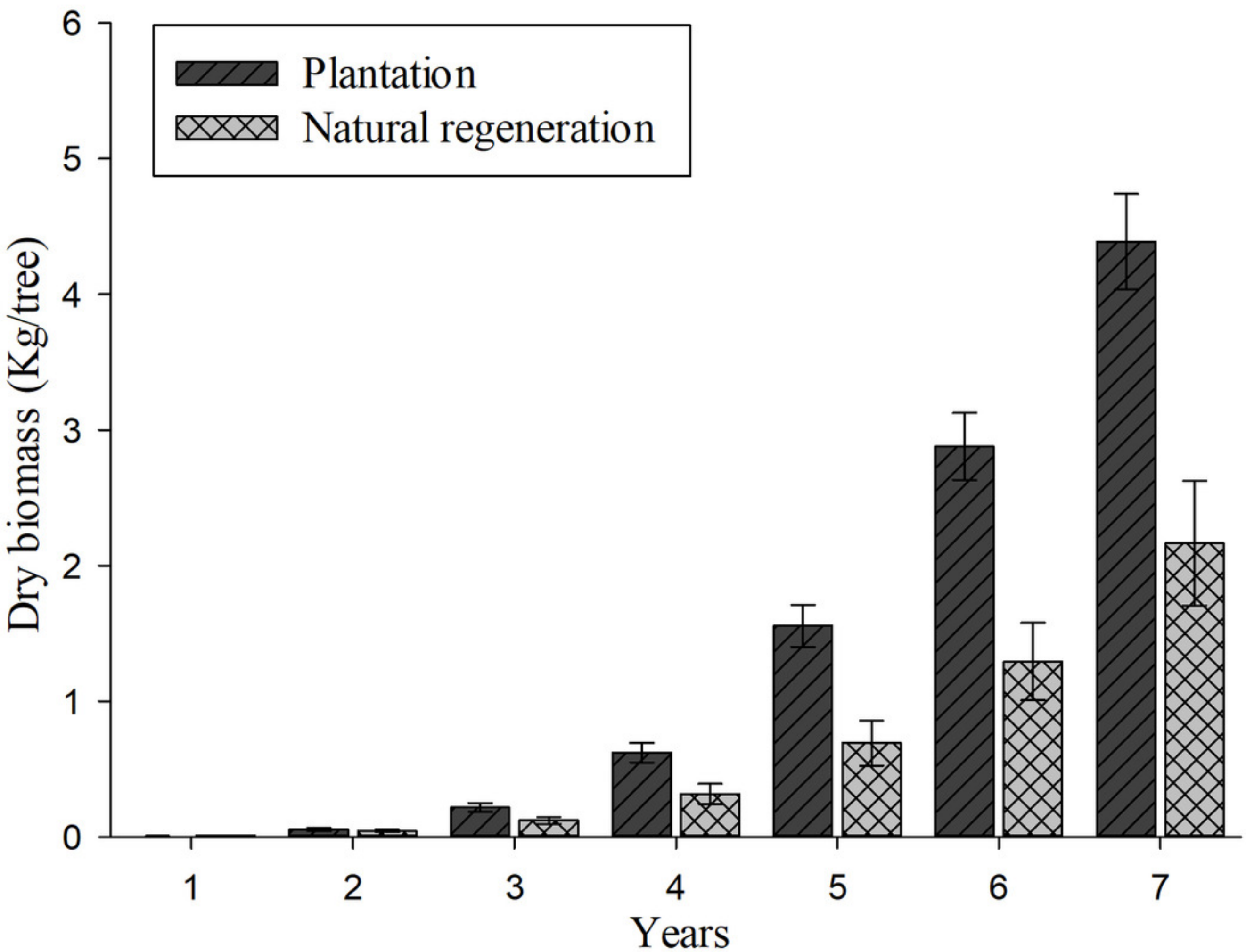

Figure 5

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).