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Article

Efecto de cuatro tratamientos silvícolas en la producción maderable en un Bosque de Durango

Effect of four silvicultural treatments on timber production in a Forest in *Durango*

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Resumen

El manejo forestal a través de la aplicación de tratamientos silvícolas adecuados permite lograr la persistencia, el rendimiento sostenido y la máxima producción de los bosques. El objetivo de este trabajo fue evaluar el incremento en volumen fustal de árboles de *Pinus durangensis*, a partir del análisis de los anillos de crecimiento mediante la técnica del análisis troncal en rodales sometidos a cuatro tratamientos silvícolas; los cuales fueron cortas de regeneración con árboles Padre (realizada en 2007), matarrasa, selección y de aclareo aplicados en el año 2010. Se estudiaron 16 árboles muestra de *Pinus durangensis* recolectados en sitios de 100 m^2, distribuidos al azar por cada tratamiento. Para el análisis troncal, por individuo se obtuvo una rodaja a la base, otra a 1.3 m sobre el nivel del suelo y posteriormente cada metro hasta llegar a la punta. Se estimó el diámetro y la altura de los árboles cada dos anillos de crecimiento y se estimó el volumen, para finalmente conocer los incrementos (ICA e IMA) en intervalos de dos años. Los resultados de la prueba no paramétrica de *Kruskal Wallis* mostraron diferencias significativas ($p < 0.05$) en el ICA e IMA en la mayoría de los tratamientos silvícolas evaluados. La matarrasa resultó ser la práctica con los mayores valores de ICA e IMA para todas las edades estudiadas.

Palabras clave: Análisis troncales, anillos de crecimiento, Incremento Corriente Anual, Incremento Medio Anual, matarrasa, *Pinus durangensis* Martínez.

Abstract

Forest management through the use of the right forestry treatments allows achieving persistence, sustained yield and maximum production of forests. The objective of this work was to assess the increment in stem volume of *Pinus durangensis* trees, from the analysis of the growth- rings by means of the stem analysis technique in stands subjected to four forestry treatments. The treatments were clear-cutting, regeneration cut with parent trees (applied in 2007), selective cut and thinning, applied in year 2010. A total of sixteen sampling trees of *Pinus durangensis* collected in sites of 100 m^2 distributed randomly by treatment were used in the study. From each tree sections for ring growth analysis were obtained at the base, at 1.3 m and subsequently each meter until reaching the top. The diameter and height of the trees were estimated every two growth rings and later the volume was estimated, to finally estimate the values of ICA and the IMA growth in two-year intervals. The results of the non-parametric *Kruskal* Wallis test showed significant differences ($p < 0.05$) of ICA and IMA in most of the forestry treatments. The clear-cutting turned out to be the treatment with the highest ICA and IMA values for all ages studied.

Key words: Stem analyzes, growth rings, Annual Current Increase, Average Annual Increase, clear-cutting, *Pinus durangensis* Martínez.

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Introduction

The state of *Durango* has a forest area of 5.5 million hectares, of which approximately 2 million are under use (SRNyMA, 2011). In 2017, its net timber production was 2 559 297 m^3, which represents 28.4 % of the national total (Semarnat, 2017). The forest management methods mostly used in the forests of the state are the Forestry Development Method (MDS, for its acronym in Spanish), which is characterized by periodic harvesting to ensure that the forest is renewed, through planting or natural regeneration; and with this, contemporary tree masses are induced (Gadow *et al.,* 2004; Solís *et al*., 2006); and the Mexican Method for the Management of Irregular Forests (MMOBI, for its acronym in Spanish), which is aimed at the application of selective fellings that promote the maintenance of an irregular structure, composed of individuals of different size (Gadow and Pummalainen, 2000; Lira-Tuero *et al*., 2019).

Sustainable forest management currently requires studies that describe the dynamics of increase and timber yield of forest masses (Návar-Cháidez, 2010; Fierros-Mateo *et al.,* 2017), in order that forestry practices favor the residual mass (Monárrez-González *et al*., 2018). In addition, it provides elements to improve productivity, based on the characteristics of the composition and structure of the forest (Solís *et al.,* 2006; Návar-Cháidez and González-Elizondo, 2009). Additionally, the main challenge of sustainable forest management is the correct application of cutting intensities that conserve the biological diversity of forests, their productivity, their regeneration capacity and their capacity to fulfill, in the present and in the future, other ecological, economic and social functions. (Aguirre-Calderón, 2015; Manzanilla *et al.,* 2020). In the same way, such studies should consider the conservation of species composition, of forest structure, of landscape and their added values; key factors in the new standards of sustainable forest management (Hernández-Salas *et al.,* 2013).

The assessment of the effects of forestry treatments in different types of forest stands is a key element for optimizing forest productivity in areas subject to timber harvesting (Gadow *et al.,* 2004). The volume and basal area per hectare are elements used to determine forest productivity, and their control is carried out through forestry practices such as thinning or selective felling (Daniel *et al.,* 1982). However, it must be considered that the optimal number of residual trees in a stand depends on biological, technological and operational factors (Diéguez-Aranda *et al*., 2009; Cabrera-Pérez *et al.,* 2019).

On the other hand, site quality is a factor, too, that influences the timber production of a stand, from the interaction of climatic, topographic and edaphic factors which, combined, are favorable for the development of trees (Clutter *et al.,* 1983; Castillo *et al.,* 2013).

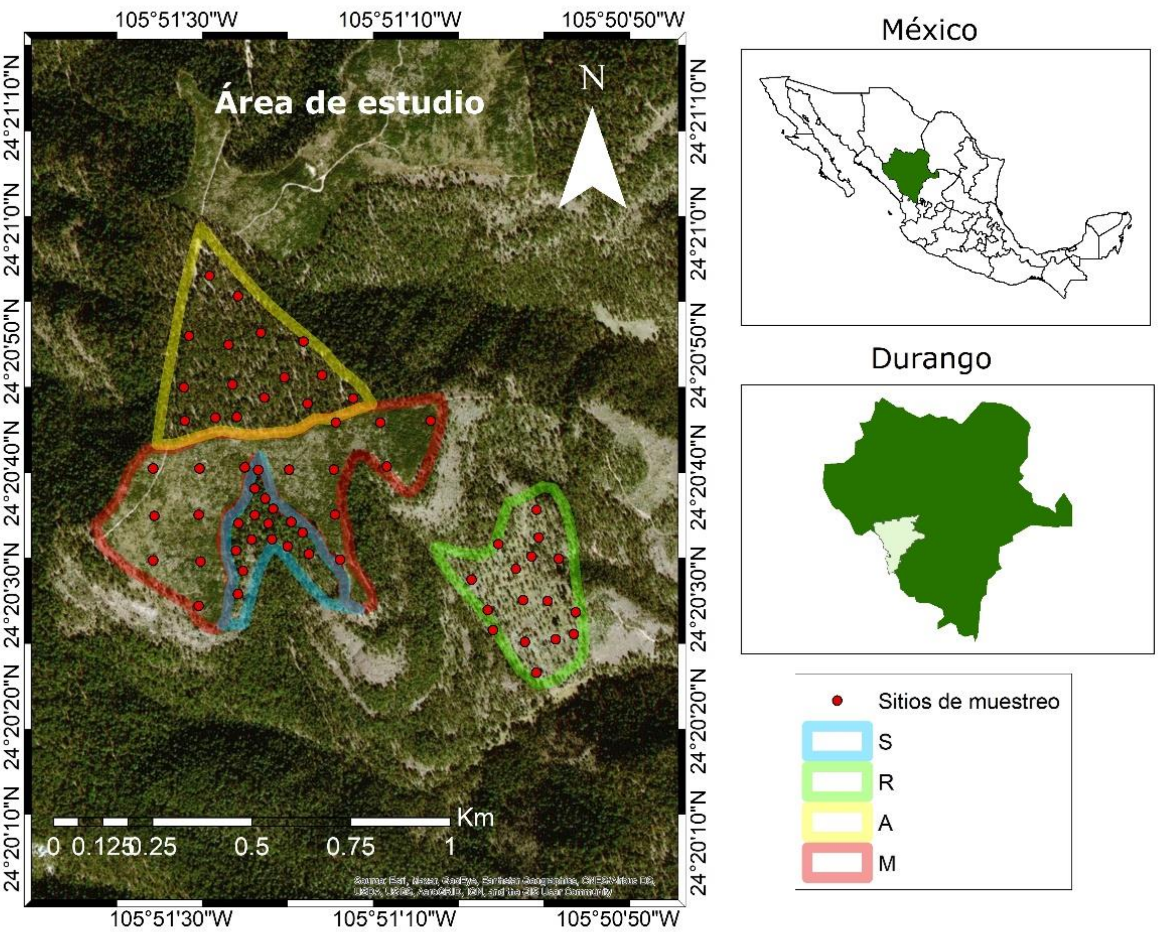
The Annual Current Increase (ICA, for its acronym in Spanish) and the Annual Average Increase (IMA, for its acronym in Spanish) allow knowing the optimal rotation or cutting age of a plantation and maximize the usable volume (Santiago-García *et al*., 2015; Cardalliaguet *et al.,* 2019). These estimates are a crucial element in forest management, as they help to calculate the harvest, the shift and the periodicity of forestry interventions. Through the ICA and IMA curves, the age with the maximum increase in diameter, height and volume (maximum performance shift) is known (Quiñonez-Barraza *et al*., 2015).

The objective of this investigation was to evaluate the increase in stem volume from the analysis of growth rings of trees in stands managed with four forestry treatments.

Materials and Methods

Study area

The study area was the *Las Veredas* private property, at *San Dimas* municipality, state of *Durango*, Mexico (Figure 1). It is located between 24°20'40” N and 105°51'20” W, in the physiographic *Sierra Madre Occidental* province, *16 Mesetas* and *Cañadas del Sur* subprovince. The area has an altitudinal range of 2 600 to 2 800 m; the climate is temperate, with rains in summer (C_W) (García, 2004), which commonly occurs between July and September, with accumulated average annual precipitation of 1 034.5 mm, according to the *Vencedores* locality weather station, located 15 km from the study area. Temperature varies from -3 to 18 °C; its topography is mountainous with defined or undulating 0 to 50 % slopes (Silva-Flores *et al.,* 2014). The vegetation is made-up by mixed coniferous and broadleaf forests; the dominant pine species are *Pinus durangensis* Martínez, *Pinus cooperi* Blanco, *Pinus teocote* Schiede ex Schltdl. and *Pinus strobiformis* Engelm. The characteristic oak taxa are *Quercus rugosa* Née and *Quercus sideroxyla* Bonpl, as well as *Juniperus* spp., *Arbutus* spp. and *Alnus* spp. trees, among others (González-Elizondo *et al.,* 2012).



Área de studio = Study area; *Sitios de muestreo* = Sampling sites; M = Clear-cutting; R = Regeneration cut with parent trees; A = Thinning; S = Selective cut.

Figure 1. Location of the study area.

Four felling areas were identified on the land, in which the treatment and the year of application were recorded. Next, the evaluated treatments are described: (i) clear-cutting, 2010, with immediate planting of *Pinus durangensis* and *Pinus cooperi*, with a 2 500 plants ha^{-1} (2 m × 2 m) density; (ii) regeneration cut with parent trees, 2007 and 70 % cutting intensity; (iii) selection cut, 2010, with 30 % cut intensity; and (iv) thinning, 2010 (third according to the management program), with 35 % cutting intensity.

Sampling sites

For the establishment and distribution of the sites, the methodology of the National Forest Commission (Conafor, 2013) was considered as a reference to assess the initial survival in plantations. This methodology was only used in the sub-stand of the clear-cutting treatment, since in the other ones; it was only used to have the same number of trees with similar characteristics. The destructive type of sampling was used to evaluate stem growth; thus, 16 trees or replications of *Pinus durangensis* were selected per treatment (one from each 100 m^2 sampling site) to add a total of 64 trees.

The intensity of sampling applied in the treatments for the characterization of the sub-stands ranged from 0.74 to 3.07 %, taken as good because the purpose of the study was to compare the stem increase between treatments with a sufficient number of replications, and not the estimation of stand variables such as volume or basimetric area. The sampled trees were sectioned to obtain 5 cm- wide slices at the following heights: (i) cut at ground level, (ii) cut at a height of 1.3 m above ground level, and (iii) cut along the shaft at each meter in length. Measurements were obtained using a Truper longimeter.

The normal diameter per individual was considered as the average of two cross measurements of the slice collected at a height of 1.3 m above ground level; while, the total height was calculated from the sum of all the sampled sections (Table 1). These measurements were made using a millimeter ruler.

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

Forestry treatment	Area (ha)	Substand				Sampled trees					
		N		G (m^2)		Age (years)		Diameter (cm)		Height (m)	
		Prom	Desv	Prom	Desv	Prom	Desv	Prom	Desv	Prom	Desv
M	21.4	1881	389	7.41	2.85	8	0	6.7	0.9	3.7	0.5
R	10.2	725	420	10.58	10.01	11	1.45	7.2	1.7	4.5	1.2
A	15.2	1412	291	30.77	11.35	51	17.8	11.4	1.8	10.0	2.2
S	5.21	1343	329	42.15	19.47	43	13.01	10.3	1.9	8.9	2.0

M = Clear-cutting; R = Regeneration cut with parental trees; A = Third clearing; S = Selection; N = Number of trees per hectare; G = Basimetric area per hectare (m^2), Prom = Average; Desv = Standard deviation.

Determination of diameter at different ages

Groups of rings were marked in the slices from the periphery inwards in two- years periods, this due to the young age of the sampled trees from the clear-cuting and regeneration felling treatments; for each age class, the diameter was recorded, estimated as the average of the measurement with the largest and smallest diameter, respectively. These measurements were made using a millimeter ruler.

Estimation of the real height of the tree at the cutting age

The true height of a tree at a certain age can hardly be obtained directly through the counting of slice rings at different heights, since the section of the cut does not coincide with the beginning of a year (Fabbio *et al*., 1994). To estimate the real or true height of a tree at a certain age, the method of Carmean (1972) modified by Newberry (1991) (equations 1, 2 and 3) was used, which is based on the assumptions: (i) between two sections, the tree grows at a constant rate, and (ii) the cut is made, on average, in the center of the growth in height of one year (Machado *et al*., 2010). The equations used to calculate the true height are shown below and vary depending on the section of the tree.

Stump:
$$H_{ij} = j * \frac{h_{i+1}}{0.5 + (r_i - r_{i+1})} \quad (1)$$

Log:
$$H_{ij} = h_i + \frac{h_{i+1} - h_i}{2 * (r_i - r_{i+1})} + (j-1) * \frac{h_{i+1} - h_i}{r_i - r_{i+1}} \quad (2)$$

Tip:
$$H_{ij} = h_i + \frac{h_{i+1} - h_i}{2 * (r_i - r_{i+1} - 0.5)} + (j-1) * \frac{h_{i+1} - h_i}{r_i - r_{i+1} - 0.5} \quad (3)$$

Where:

H_{ij} = Actual or true height of the tree at the cutting height of the *i* section

h_i y h_{i+1} = Heights of the lower and upper sections of the log

r_i *y* r_{i+1} = Number of rings in the lower and upper sections of the log

j = Number of rings or age of the upper section of the log (j = 1,2,…, r_i)

In order to facilitate the comparison between treatments of the increase in stem volume, the real heights of the sample trees were also estimated in two-year intervals, by means of a linear interpolation. Thus, the true heights estimated at the ages and cut diameters recorded in the sections of the sample trees were used as a reference; and the real height for each individual in two-year intervals was estimated by means of a linear interpolation (equations 4 and 5).

$$P = \frac{h_{i+1} - h_i}{r_{i+1} - r_i} \quad (4)$$

$$H_{ik} = P * (e_i - r_i) + h_i \quad (5)$$

Where:

P = Slope value

H_{ik} = True height of *i* tree section at two-year intervals

e_i = Reference age of the *i* section of the tree (every two years)

h_i and r_i = Heights and ages known at the *i* time

Volume estimation

With the diameter estimates at different heights and height per tree at two-year intervals, the volume per individual was calculated by measuring the intermediate sections with the Smalian formula and the tip with the cone equation. The total volume was considered as the sum of all the sections, plus the volume of the tip.

ICA and IMA estimation

In order to guarantee comparability for each tree sample independent of the forestry treatment, the annual current increase (ICA) and the mean annual increase (IMA) were estimated (equations 6 and 7), in two-year intervals (two, four, six and eight years). The ICA corresponded to the increase produced every two years, while the IMA is the average of the total increase at a certain age of a tree (Cardalliaguet *et al.,* 2019).

$$ICA_i = \frac{v_{i+1} - v_i}{2} \quad (6)$$

$$IMA_i = \frac{v_i}{2} \quad (7)$$

Where:

v_{i+1} and v_i = Total volume of the *i* tree in dm^3 for the upper and lower age classes, respectively

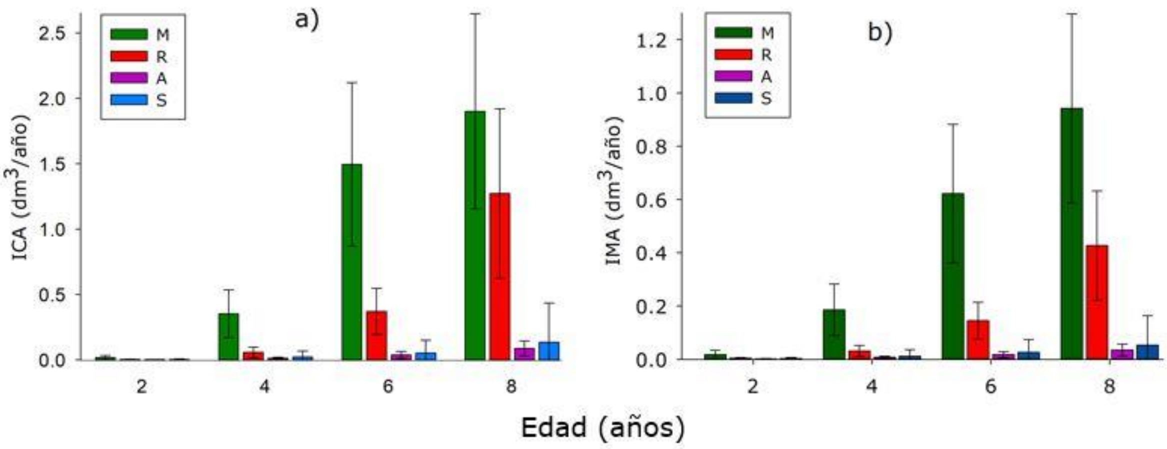
Statistical analysis

The ICA and IMA data of the sampled trees were classified by age class and by type of forestry treatment. In addition, they were statistically analyzed by means of an experimental design of a single block completely at random by sub-stand or study area. This experimental design was used, since possible confounding factors are separated through blocks (for example, differences in age or densities) that can negatively affect the values of the response variables of the treatments. The

Shapiro-Wilks test ($P \geq 0.05$) was used to assess whether the data on the growth of the trees corresponded to a normal distribution. However, the assumption of normality was rejected in all the forestry treatments evaluated, so the non-parametric Kruskal-Wallis test was used to determine the existence of significant differences between the comparable treatments, using the Bonferroni mean comparison test. ($\alpha = 0.05$). Statistical analyzes were carried out with the statistical program R version 3.5.3 (R Core Team, 2019).

Results and Discussion

The average and the standard deviation of the ICA and IMA for the different forestry treatments at two, four, six and eight years are shown in Figure 2, where it is observed that the kills had higher ICA and IMA values for all classes of age studied; highlights its increase after four years and the highest values (1.9 dm^3 $year^{-1}$ and 0.9 dm^3 $year^{-1}$, respectively) at eight years. The regeneration cut follows in order of importance, also at eight years with records of 1.27 dm^3 $year^{-1}$ (ICA) and 0.46 dm^3 $year^{-1}$ (IMA).



Edad (años) = Age (years).

a) Annual Current Increase (ICA); b) Average Annual Increase (IMA); M = Clear-cutting; R = Regeneration cut with parent trees; A = Third thinning; S = Selection.

Figure 2. Average (bar) and standard deviation (line) of the increases observed for the evaluated treatments.

The highest ICA and IMA values corresponded to the clear-cutting and regeneration cutting treatments with parent trees, respectively. This situation is explained because they promote more light availability, an essential factor to produce optimal yields in the increase of heliophilic plants, as is the case of the assessed pine species (Stuiver *et al*., 2016; Ruslandi *et al*., 2017; Plateros -Gastélum *et al.,* 2018).

The results of the Kruskal-Wallis test indicated that there are significant differences in the mean increase observed between forestry treatments and in most ages ($p< 0.05$ and $p< 0.01$). Table 2 shows a comparison between forestry treatments using the Bonferroni means comparison method.

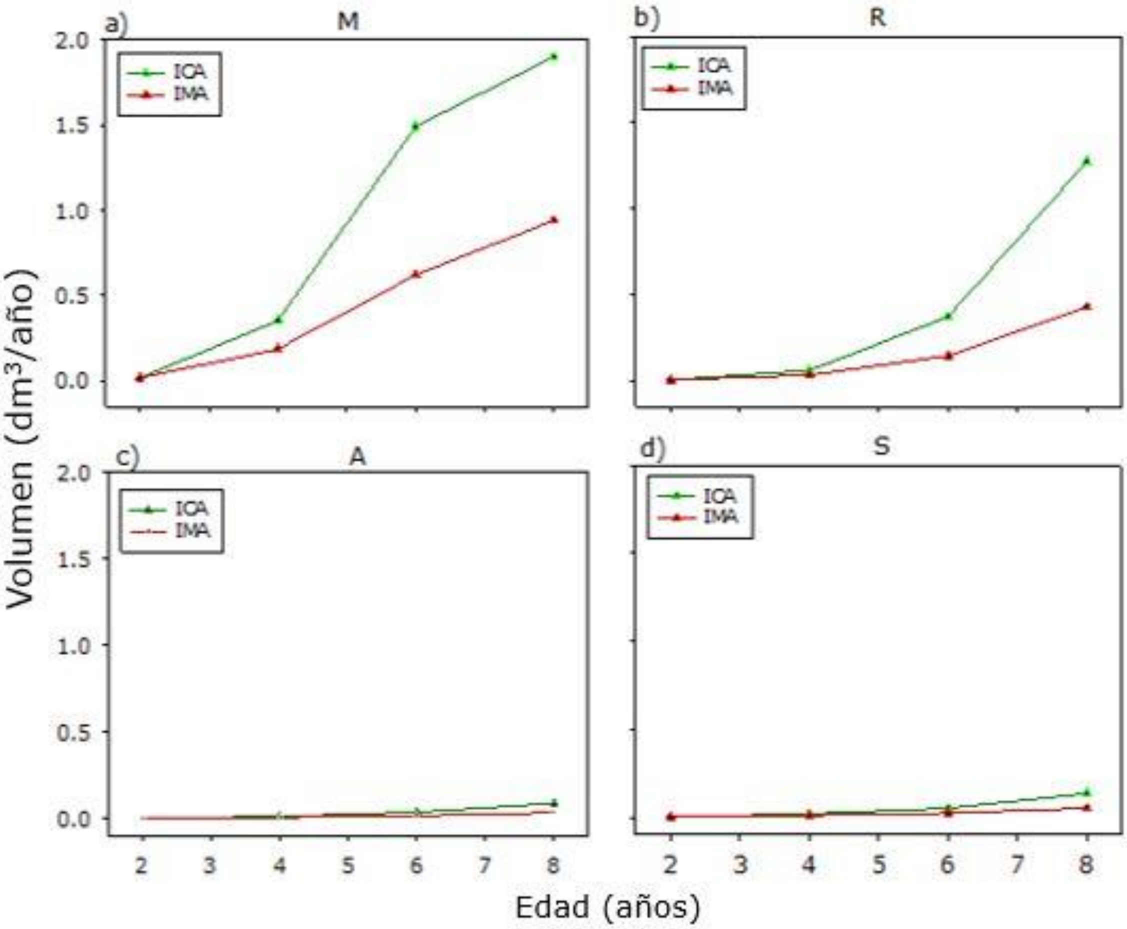
Table 2. Statistical comparison of ICA and IMA between the different forestry treatments evaluated according to the Bonferroni mean comparison test.

Comparison	2 years		4 years		6 years		8 years	
	ICA	IMA	ICA	IMA	ICA	IMA	ICA	IMA
A–R	0.205 ^{ns}	0.205 ^{ns}	<0.050*	<0.050*	<0.050*	<0.050*	<0.050*	<0.050*
A–M	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
R–M	<0.050*	<0.050*	<0.050*	<0.050*	<0.050*	<0.050*	<0.050*	<0.050*
A–S	1.000^{ns}	1.000^{ns}	1.000^{ns}	1.000^{ns}	1.000^{ns}	1.000^{ns}	1.000^{ns}	1.000^{ns}
R–S	0.072^{ns}	0.072^{ns}	< 0.010**	< 0.010**	< 0.010**	< 0.010**	< 0.010**	< 0.010**
M–S	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***

($P < 0.05$) *; ($P < 0.01$) **; ($P < 0.001$) ***; *ns* = Non- significant, ICA = Annual Current Increase; IMA = Average Annual Increase; M = Clear-cutting; R = Regeneration cut with parent trees; A = third thinning; S = selection.

The results show that the average increase observed in the slaughterhouse treatment is significantly higher than the average increase observed in the rest of the treatments in all the evaluated ages (p <0.05 for the case of the regeneration cut with parent trees, and p < 0.01, in selection and thinning). In regard to the average increase of the trees from the regeneration cut treatment with parent trees, except at the age of 2 years, it was significantly higher than that observed in the third thinning and selection treatments (p <0.05). These did not show significant differences in growth for any of the ages considered.

The evolution of the ICA and the IMA in relation to the age of the trees for each treatment is shown in Figure 3. The growth of the trees of the plantation established in the clear-cutting treatment, as well as with the regeneration cut with parent trees showed a linear trend, with higher values in all the evaluated ages, compared to the thinning and selection treatments (Figure 3a and 3b). From the linear trend observed in the growth data, the maximum values of ICA and IMA were presented at 8 years in all cases, the reason why new studies are required at more advanced ages for the clear- cutting and regeneration cutting with parent trees sites, in order to confirm if they continue to have greater volume increases, compared to the other two treatments.



Volumen = Volume; *Edad (años)* = Age (years).

ICA = Annual Current Increase; IMA = Average Annual Increase; M = Clear-cutting; R = Regeneration cut with parent trees; A = Thinning (c); S = Selection (d).

Figure 3. Evolution of the Annual Current Increase (ICA) and Annual Average Increase (IMA) by forestry treatment evaluated up to the age of eight years.

According to the results of the study, the clear-cutting treatment recorded, in a significant way, the highest rate of tree volume increment in all age classes of the four forestry treatments studied, for an ICA estimate of 3.58 m^3 ha $year^{-1}$ at the age of 8 years and with a linear tendency to discharge; thus, it is a good option to optimize timber yield and reduce the time between harvests. Therefore, the clear-cutting treatment can be used successfully in forest areas of good site quality in the state of *Durango* and in which the regular management method is used, provided that an immediate planting is carried out and maintenance is given to it through fencing, fire cut gaps, pest prevention, etcetera; otherwise, there is a risk of losing soil and biodiversity (Monárrez-González *et al.,* 2018; Soto-Cervantes *et al*., 2020).

In this context, it is recommended that the clear-cutting treatment be developed for forestry purposes, in parallel, with the application of others such as regeneration cuts, thinning and selection cuts to generate a mosaic of varied structures and thus, promote the conservation of diversity of flora and fauna (Politi and Rivera, 2019). This is due to the fact that the abuse of intensive management (clear-cutting and regeneration cuts) would generate contemporary and monospecific masses, which would impact the structural diversity of the stands (Kovács *et al*., 2018; Moon *et al*., 2018).

The treatment of regeneration cutting with parent trees was the second best option to optimize the growth of *P. durangensis* up to the age of eight years; since, like the clear-cutting, it had significantly higher increases than the thinning and selection treatments. Although authors such as Ramírez *et al*. (2015) argue that the natural repopulation of pine species should be considered as an important complement to regeneration in areas under forest management of the temperate forest of Mexico.

The results of this work show that the planted trees had greater development than those that were naturally repopulated. This can be explained as in the clear-cutting treatment the individuals are favored by a great availability of light, which is assimilated by them to the maximum of what their genetic condition and age allow; that is, they develop to the maximum of their growth ability (Cifuentes *et al*., 2016; Plateros-Gastélum *et al.,* 2018; Moretti *et al.,* 2019).

The thinning and selection treatments did not register significant differences in growth (*p*> 0.05); this may be due to the fact that during its execution, in both cases, very similar forestry criteria are used, which to a large extent are more related to the application of selective felling, than with thinning. In this regard, Corral-Rivas *et al.* (2019) cite that on many occasions, the treatments applied in the forests of the state of *Durango* are limited to selection cuttings and that they do not necessarily correspond to the thinning cuttings that are programmed in the authorized management plans.

Although Freitas *et al.* (2017) point out that the application of low-impact forestry techniques encourages the growth of tree species of high commercial value, without negatively interfering with natural regeneration, the results of this research indicate that the lower the intensity of felling, the timber increment decreases in the assessed regeneration, that is why density management is a key element to optimize forest production in the forests of *Durango* (Padilla-Martínez *et al.,* 2020).

Guevara *et al.* (2021) evaluated the effect of clear-cuttings with immediate plantations on the tree diversity of regeneration in the state of *Durango*, and observed that they keep species richness, despite the fact that only *Pinus durangensis* and *Pinus cooperi* specimens were planted, the species similarity between adjacent stands was high, which came from the spontaneous emergence of other native taxa present before felling and the influence of neighboring stands. Rodríguez-Ortiz *et al.* (2019) studied the behavior in areas treated with clear-cutting in the state of *Oaxaca* and concluded that this treatment promotes the regeneration and renewal of the forest, which, in turn, favors ecosystem services. However, it should be noted that such treatment, so far in Mexico has been studied mainly in high productivity stands or sites; for this reason, the results of this and other investigations should not be generalized to all production forest areas, since in most of them the best forestry alternative, in environmental and social terms, will continue to be selective logging.

Conclusions

In the study, significant differences are registered in the ICA and IMA variables for most of the evaluated treatments and ages, with the exception of the thinning and selection cuttings, which recorded the lowest stem increase in the analyzed trees. The site treated with clear-cutting corresponds to the highest timber increase during the period of interest. The study reveals that clear-cutting with immediate planting can be used successfully in sites of good site quality in the forests of *Durango*, and that its use represents a good option to increase their forest production.

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Conflict of interests

The authors declare no conflict of interest.

Contribution by author

Jesús Alejandro Soto Cervantes: data collection in the field, data analysis and writing of the manuscript; Jaime Roberto Padilla Martínez, Emily García Montiel and José Javier Corral-Rivas: study design, coordination of data analysis, writing and review of the manuscript; Pedro Antonio Domínguez Calleros, Artemio Carrillo Parra, Rodrigo Rodríguez Laguna and Marín Pompa-García: advisory on data analysis and review of the manuscript.

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