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Research article

Efecto del aprovechamiento forestal en la estructura y producción de un bosque de pino en el estado de Chihuahua

Effect of forest harvesting on the structure and productivity of a pine forest in *Chihuahua* state

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Abstract

The objective of sustainable forest management is to meet social needs without compromising future ecosystem goods and services. The structure, composition and productivity of a pine forest under forest management in the Southwest of the state of *Chihuahua*, Mexico, is described. The information comes from nine permanent, circular plots (1 000 m^2), which were remeasured in three stages of forest management: Initial Condition [CI (2012)], Recruitment [Rec (2022)] and Final Condition [CF (2022)]. The Importance Value Index (*IVI*), productivity (*volume*), species richness and diversity were processed. In the study area, a total of four tree species are identified, three of 218 individuals in the CI, four of 297 individuals in the Rec and four of 195 individuals in the CF. The highest ecological importance and productivity in terms of volume for *Pinus arizonica* was recorded in the Recruitment stage with 151.38 m^3 ha^{-1}, with a similar percentage to the other stages varying between 1 and 2 %. According to the values of the different indexes used, the diversity is low.

Keywords: Composition, effect of forest harvesting, structure, forest management, *Pinus arizonica* Engelm., productivity.

Resumen

El objetivo del aprovechamiento forestal sostenible es satisfacer las necesidades sociales sin que se comprometan los bienes y servicios ecosistémicos futuros. En el presente trabajo se describió la estructura, composición y producción de un bosque de pino bajo aprovechamiento forestal en el suroeste del estado de Chihuahua, México. La información proviene de nueve parcelas permanentes circulares (1 000 m^2), que fueron remedidas en tres etapas del manejo forestal: Condición Inicial [CI (2012)], Reclutamiento [Rec (2022)] y Condición Final [CF (2022)]. Se estimaron los índices de Valor de Importancia (*IVI*), la producción (volumen), la riqueza de especies y la diversidad. Se identificaron cuatro especies arbóreas, de las cuales tres reunían 218 individuos en la etapa de CI; cuatro, con 297 individuos en la etapa de Rec y cuatro, con 195 individuos, en la etapa de CF. Se presentó mayor importancia ecológica y producción en cuanto a volumen para *Pinus arizonica* en la etapa de Reclutamiento con 151.38 m^3 ha^{-1}, un porcentaje similar a las otras etapas, que variaron entre uno y dos por ciento. En comparación con otros bosques similares y de acuerdo a los valores de los diferentes índices utilizados, la diversidad en el área de estudio resultó ser baja.

Palabras clave: Composición, efecto del aprovechamiento forestal, estructura, manejo forestal, *Pinus arizonica* Engelm., producción.

Introduction

Forests composed of taxa of the *Pinus* L. genus are among the most abundant and widely distributed in the *Sierra Madre Occidental* of Mexico (González-Elizondo et al., 2012). These ecosystems have been extensively studied, primarily due to logging activities (Sánchez et al., 2003). Of the 24.7 million hectares of the total surface area of the state of *Chihuahua* (Northern Mexico), 7.08 million (28.66 %) correspond to temperate forests (Instituto Nacional de Estadística y Geografía [Inegi], 2023). The temperate forests in this area of the country, in addition to species of the *Pinus* genus are also composed of species of the *Abies* , *Cupressus*, *Juniperus*, *Pseudotsuga* and *Quercus* genera (Challenger & Soberón, 2008). Due to the high demand for environmental goods and services by rural and urban communities, the main ecosystems exploited are primarily pine and pine-oak forests (García García et al., 2019), where sustainable forest management is sought (Monarrez-Gonzalez et al., 2020).

Understanding the structure, composition, and diversity of tree species in these forests is of utmost importance for planning sustainable management and conservation (Delgado Zamora et al., 2016). Factors influence the composition and structure of temperate forests, such as climate, soil, precipitation, and tree harvesting methods (Schaub et al., 2020). Thus, assessing diversity allows us to understand the effects of forest harvesting on tree species (Aguirre Calderón et al., 2008; García García et al., 2019).

Structural characterization estimates horizontal structural parameters, such as the Importance Value Index, dominance, frequency, and abundance (Jiménez et al., 2001). Vertical structural variables such as diameter, height, and cover are also included, generating quantitative indices that provide information for conservation purposes applied to an ecosystem (Tadeo-Noble et al., 2019).

To achieve timber harvesting objectives in forest management, the forest attributes that undergo the most modifications are their structure, composition, and diversity (Ramírez Santiago et al., 2019). A deep understanding of forest structure, diversity, and dynamics, along with the impact of logging on these aspects, is crucial when making informed decisions about forest management and protecting its ecological integrity (Lutz & Halpern, 2006). Therefore, proper forest protection for timber production requires appropriate management practices and reserves in areas available for forest management (Aguirre-Calderón, 2015). Therefore, the present study aimed to describe the structure, composition, and production of a pine forest under logging in the Southwest of the state of *Chihuahua*, Mexico.

Materials and Methods

Study area

The research was carried out on a private forest property, with an area of around 189.1 ha, corresponding to a cold-temperate forest dominated by *Pinus arizonica* Engelm., in the *Guachochi* municipality, state of *Chihuahua*, Mexico, within the *Sierra Madre Occidental* mountain range. The site is geographically located between 26°45’45.69” and 26°55’33.28” North and 107°7’15.97” and 107°8’26.23” West (Figure 1).

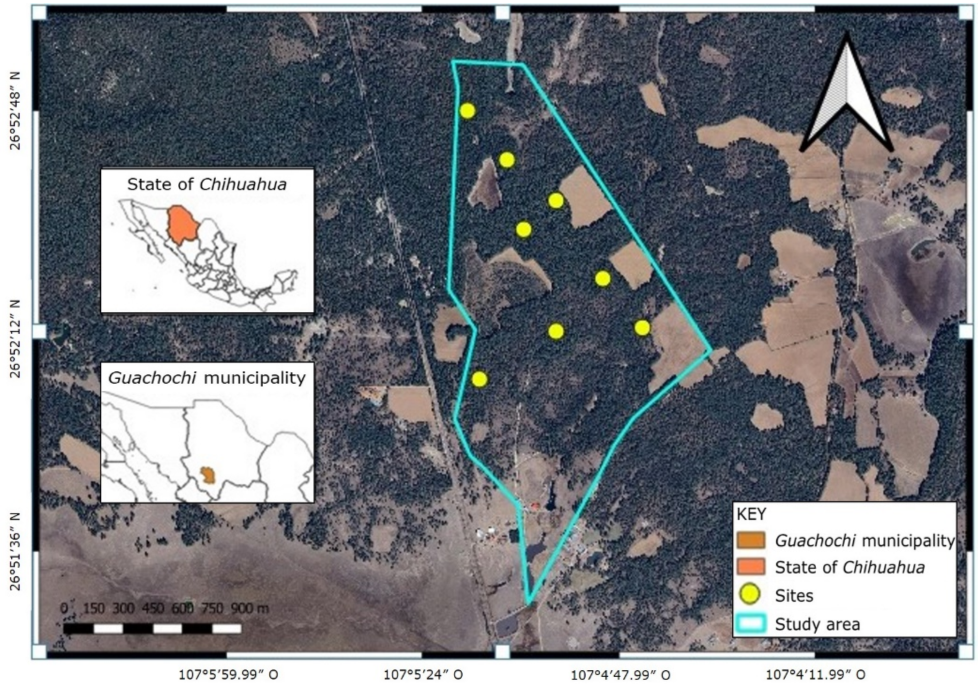

Figure 1. Location of the study area and permanent forestry monitoring plots.

The soil classifications are eutric Cambisol, eutric Regosol, and eutric Planasol, with a medium to fine texture (Inegi, 2024).

The climate is classified as C(E)(w_2)(x'), corresponding to a humid-semi-cold climate, with an average annual temperature of 5 to 12 °C (Instituto Nacional de Estadística, Geografía e Informática [INEGI], 2008).

Field assessment

The information comes from a forest inventory conducted in eight permanent circular monitoring plots (1 000 m^2) for forestry assessment and monitoring, established in an area designated for softwood production. The species and total height of each individual were determined using a model PM-5/1520 Suunto® hypsometer, and the diameter at breast height (*DBH*) was estimated using a model 283D Forestry Suppliers® diameter tape measure.

Three stages of forest management were defined for this analysis. The first stage was called Initial Condition [CI (2012)], which considered trees that remained standing after harvesting in autumn 2012. The second is described as Recruitment [Rec (2022)], which included unharvested individuals and those incorporated with a commercial size (*DBH*>7.6 cm); this information was recorded in the summer of 2022. The third stage was called Final Condition [CF (2022)] and consisted of individuals not selected for felling or residual trees from autumn 2022.

Data analysis

For the horizontal characterization of the plant community, the Importance Value Index (*IVI*) was calculated, estimating dominance (basal area occupied by a species), abundance (number of individuals of the species), and frequency (presence of the species). These values were used to estimate the importance of each species within the plant community (Curtis, 1959). Production was also calculated by estimating the volume per species (Jiménez, 1990).

Species richness was estimated using the Margalef index (*Mg*), where the higher the value, the greater the relative species richness in the area (Mulya et al., 2021). To quantify species diversity, the Shannon index (*H'*) was estimated (Magurran, 2004), which is used to evaluate changes in diversity over time; a higher value indicates greater diversity in the area. As a complement, the Evenness index (*E*) was calculated, which provides information on the Evenness in the distribution of individuals among species, ranging from 0 to 1. To measure the probability that two randomly selected individuals in the study area belong to the same species, the Simpson index (*D*) was estimated. A high value indicates a community dominated by a few species, and a low value indicates greater species diversity. For greater data clarity, the complementary index, expressed as *1–D*, was calculated, with a value close to 1 representing greater diversity and a value close to 0 indicating less diversity (Magurran, 2004). The formulas used to determine the structural, diversity, and similarity indices are presented in Table 1.

Table 1. Formulas used to determine the structural indexes, diversity, and similarity of the species.

Formula	Description of components
$A_i = \frac{N_i}{S}$ (1) $AR_i = \left[\frac{A_i}{\sum_{i-1}^{n} A_i}\right] \times 100$ (2)	A_i = Absolute abundance AR_i = Relative abundance by species N_i = Number of individuals of species S = Sampling surface area (ha)
$D_i = \frac{G_i}{S}$ (3) $DR_i = \left[\frac{D_i}{\sum_{i-1}^{n} D_i}\right] \times 100$ (4)	D_i = Absolute dominance DR_i = Relative dominance of the species regarding total dominance G_i = Basal area of the species S = Area (ha)
$F_i = \frac{P_i}{NS}$ (5)	F_i = Absolute frequency

$$FR_i = \left[\frac{F_i}{\sum_{i-1}^{n} F_i}\right] \times 100 \quad (6)$$

FR_i = Relative frequency of the species regarding total frequency

P_i = Number of sites in which the species is present

NS = Total number of sampling sites

$$IVI = \left[\frac{\sum_{n}^{i-1}(AR_i, DR_i, FR_i}{3}\right] \quad (7)$$

IVI = Importance Value Index

AR_i = Relative abundance by species regarding total density

DR_i = Relative dominance of the species regarding total dominance

FR_i = Relative frequency of the species regarding total frequency

$$I = \frac{S-1}{ln\, N} \quad (8)$$

I = Margalef index

S = Number of species

ln = Natural logarithm

N = Total number of individuals

$$H' = -\sum_{i-1}^{S} P_i \times ln\,(P_i) \quad (9)$$

$$P_i = \frac{n_i}{N} \quad (10)$$

H' = Shannon diversity index

S = Number of species

P_i = Species proportion

ln = Natural logarithm

N = Total number of individuals

n_i = Number of individuals of the species

$$E = \frac{-\sum_{i-1}^{S} P_i \times \ln\,(P_i)}{ln\, S} = \frac{H'}{ln\, S} \quad (11)$$

E = Evenness index

H' = Shannon diversity index

S = Number of species

P_i = Species proportion

ln = Natural logarithm

N = Total number of individuals

n_i = Number of individuals of the species

$$D = \sum {p_i}^2 \quad (12)$$

$$P_i = \frac{n_i}{N} \quad (13)$$

D = Simpson index

P_i = Species proportion

N = Total number of individuals

n_i = Number of individuals of the species

$$A = \frac{\pi}{4} \times d^2 \quad (14)$$

A = Basal area

π = Constant value (*Pi*=3.1416)

d = Diameter

$$V = g \times h \times CM \quad (15)$$

V = Volume

g = Circular area of the base diameter

CM = Morphic coefficient

Results

Horizontal structure

A total of four tree species were recorded. Three species with 218 individuals were in the CI stage, four species with 297 individuals were in the Rec stage, and four species with 195 individuals were in the CF stage (Table 2).

Table 2. Inventoried species in the study area.

Family	Scientific name	Common name	Origin	Stages
Pinaceae	*Pinus arizonica* Engelm.	*Pino blanco*	Native	CI, Rec and CF
Pinaceae	*Pinus leiophylla* Schiede *ex* Schltdl. & Cham.	*Pino chino*	Native	CI, Rec and CF
Ericaceae	*Arbutus xalapensis* Kunth	*Madroño*	Native	CI, Rec and CF
Cupressaceae	*Juniperus deppeana* Steud.	*Táscate*	Native	Rec and CF

The species with the highest abundance was *Pinus arizonica*, with 194 individuals ha^{-1} in the CI stage, representing 71.10 % of the trees, with a basal area (abundance) of 75.77 % and a 50 % frequency, in the eight sites. 250 individuals ha^{-1} of the same species were counted in the Rec stage, equivalent to 67.34 % of the trees, with a basal area of 15.9 m^2 ha^{-1} (73.07 %), in the eight sites with a frequency of 44.44 %. On the other hand, 166 individuals ha^{-1} of this species were identified in the CF inventory, which total 68.21 % of trees, and 10.22 m^2 ha^{-1} of basal area (73.93 %), with 44.44 % frequency (presence in the eight sites).

Pinus leiophylla Schiede *ex* Schltdl. & Cham. recorded an abundance of 28.44 % for the CI stage with a basal area of 24.13 %; it presented a frequency of 43.75 % at seven sites. For Rec, the abundance was 31.99 %, with a basal area of 26.67 % and a frequency of 44.44 %, and it was observed at eight sites. On the other hand, for the CF stage, its abundance was 30.77 %, with a basal area of 26.67 %, and it was recorded at eight sites with a percentage of 44.44 %.

Arbutus xalapensis Kunth had an abundance and basal area percentage of >1 % in all three stages, with a frequency at one site of 6.25 % for the Initial stage, and 5.56 % for the Recruitment and Final stages. The same data were confirmed for *Juniperus deppeana* Steud. which was detected only in the recruitment and final stages (Table 3).

Table 3. Ecological parameters in a pine forest during three stages of forest management.

Species	Individuals	Abundance		Basal area		Frequency		*IVI*
		N ha^{-1}	%	m^2 ha^{-1}	%	Number of sites	%	
Initial Condition Stage [CI (2012)]								
Pinus arizonica Engelm.	155	194	71.10	10.24	75.77	8	50	65.62
Pinus leiophylla Schiede *ex* Schltdl. & Cham.	62	78	28.44	3.26	24.13	7	43.75	32.11
Arbutus xalapensis Kunth	1	1	0.46	0.01	0.10	1	6.25	2.27
Total	218	273	100	13.51	100	16.00	100	100
Recruitment stage [Rec (2022)]								
Pinus arizonica Engelm.	200	250	67.34	15.90	73.07	8	44.44	61.62
Pinus leiophylla Schiede *ex* Schltdl. & Cham.	95	119	31.99	5.81	26.67	8	44.44	34.37
Arbutus xalapensis Kunth	1	1	0.34	0.05	0.21	1	5.56	2.03
Juniperus deppeana Steud.	1	1	0.34	0.01	0.05	1	5.56	1.98
Total	297	371	100	21.76	100	18.00	100	100
Final Condition stage [CF (2022)]								
Pinus arizonica Engelm.	133	166	68.21	10.22	72.93	8	44.44	61.86

Pinus leiophylla Schiede *ex* Schltdl. & Cham.	60	75	30.77	3.74	26.67	8	44.44	33.96
Arbutus xalapensis Kunth	1	1	0.51	0.05	0.33	1	5.56	2.13
Juniperus deppeana Steud.	1	1	0.51	0.01	0.07	1	5.56	2.05
Total	195	244	100	14.01	100	18.00	100	100

Similar *IVI* values were found in all three stages, which implies greater importance for the first two species described below: *Pinus arizonica* with 65.62 %, 61.62 %, and 61.86 %, respectively, by stage; *Pinus leiophylla* with 32.11 %, 34.37 %, and 33.96 %, respectively, by stage. *Arbutus xalapensis* had the lowest *IVI*, with results ranging between 2 and 2.30 % in each of the three stages. Likewise, *Juniperus deppeana* showed results of 1.98 % and 2.05 % for the Recruitment and Final Condition stages, respectively (Table 3).

A key parameter is stem diameter, whose analysis, based on diameter classes recorded according to the number of individuals, revealed significant patterns. In the Initial Condition stage, the 25-29.99 cm and 30-34.99 cm categories stood out for concentrating the largest number of individuals, with 48 and 45 specimens, respectively. For the Recruitment stage, the largest number of individuals was found in the 30-34.99 cm categories with 50 individuals and the 35-39.99 cm categories with 49 individuals, with the largest number of individuals concentrated between 15-39.99 cm. For the Final Condition stage, the largest number of individuals was concentrated in the 30-34.99 cm categories with 37 individuals and 35-39.99 cm with 35 individuals, showing very similar values in the three stages where the largest number of individuals falls in the categories that range between 30 cm in diameter with a descending curve passing 40 cm. Only the Initial stage did not present high values in the 35-39.99 cm category, presenting a community of immature trees for the three stages (Figure 2).

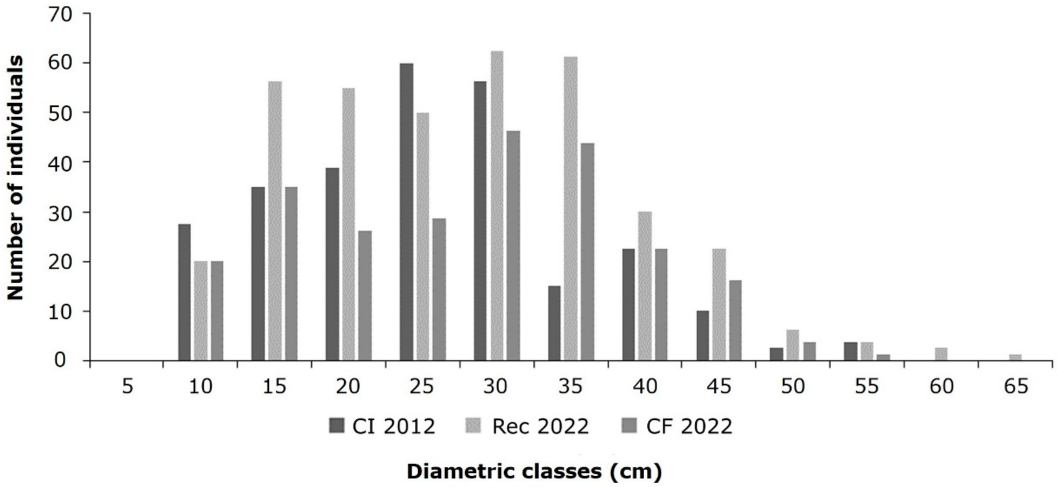

Figure 2. Number of individuals by diameter class (cm) across the three stages.

The results of the height classes of the tree community showed for the Initial stage a concentration of the highest number of individuals between 12-23.99 m with 166 of 218 inventoried individuals. For the later stages (Rec and CF), the highest concentration of individuals shows a height between 16 and 21.99 m, with 142 and 99 individuals, respectively, in each of the inventoried stages, following the same trend as the diameter classes (Figure 3).

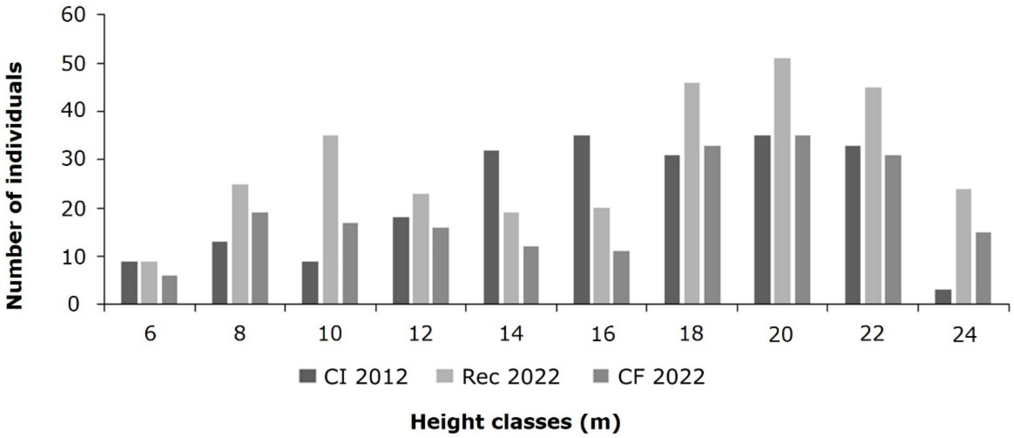

Figure 3. Number of individuals by height class (m) in the three stages.

Production

The highest production volume was recorded for *Pinus arizonica* during the recruitment stage, with 151.38 m^3 ha^{-1}, although this value represented a similar percentage to that of the other stages and varied between 1 and 2 %. In a similar way, *Pinus leiophylla* showed a volume of 44.80 m^3 ha^{-1} in the Recruitment stage, with a variation of less than 2 % compared to the other assessed stages. *Arbutus xalapensis* presented a contribution of less than 0.20 % in all three stages, while *Juniperus deppeana* had values of less than 0.02 % in both the Recruitment and final felling stages (Table 4).

Table 4. Volume production for each species and by stage.

Species	CI (2012)		Rec (2022)		CF (2022)	
	m^3 ha^{-1}	%	m^3 ha^{-1}	%	m^3 ha^{-1}	%
Pinus arizonica Engelm.	91.30	79.20	151.38	77.09	96.92	76.64
Pinus leiophylla Schiede *ex* Schltdl. & Cham.	23.95	20.78	44.80	22.82	29.36	23.22
Arbutus xalapensis Kunth	0.03	0.02	0.16	0.08	0.16	0.13
Juniperus deppeana Steud.	-	-	0.02	0.01	0.02	0.02

Richness, diversity and Evenness

The indices show notable variations in species richness, diversity, and Evenness between the Initial Condition stages and the Recruitment and Final Condition stages in 2022. The estimated richness, assessed using the Margalef index, revealed a progressive increase from CI to CF, indicating a slight improvement in species diversity with progress through the recovery stages. In a similar way, species diversity values, represented by the Shannon index, also show a slight increase from CI to CF, suggesting a positive trend in the ecological complexity of the plant community.

In regard to Evenness (*E*), the values suggest a relatively even distribution of species in CI, which decreases slightly in Rec and CF, which could indicate a slight dominance of certain species in the recovery stages. Likewise, the Simpson index (*D*) and its complementary index (*1-D*) corroborate this low diversity, with consistent values between Rec and CF, revealing a community structure dominated by a few species (Table 5).

Table 5. Number of species, richness (*Mg*), diversity (*H'*), Evenness (*E*), true diversity (*D*) and *1-D*.

Feature	Inventoried stages		
	CI (2012)	**Rec (2022)**	**CF (2022)**
Number of species	3	4	4
Richness (*Mg*)	0.37	0.52	0.57
Diversity (*H'*)	0.62	0.66	0.67
Evenness (*E*)	0.56	0.48	0.48
True diversity (*D*)	0.59	0.56	0.56
1-D	0.41	0.44	0.44

Discussion

The species with the highest *IVI* were *Pinus arizonica* and *Pinus leiophylla*, suggesting that the *Pinus* genus is the most important. It forms forests with a tendency toward pure stands, as its species constitute most of the plant composition, although they may coexist with others in smaller proportions. In this same region, Rascón-Solano et al. (2023) recorded this genus as having the greatest ecological importance (70.81 %); likewise, Rascón-Solano et al. (2022) also calculated values above 50 % for this genus near the study area. In contrast, García García et al. (2021) indicated that the *Pinus* genus is of lower ecological importance in the temperate forests of Northern Mexico (30 %), with high ecological value represented by species in conservation status.

The abundance of these species may be associated with the physiography of the area, the average annual rainfall, and forest management that favors the most notable commercial species.

Pinus arizonica is a representative species of the temperate forests of Northern Mexico; it is the main species in the pine and pine-oak ecosystems (Hernández-Salas et al., 2018). Martínez-Salvador et al. (2013) point out that this species has high productive potential, as it allows for sustainable timber production with selective methods and intensive silvicultural interventions applied for its development and increased production.

The presence of *Juniperus deppeana* in the Recruitment stage and its absence in the previous stage could be associated with disturbance processes, given its opportunistic nature and ability to colonize disturbed areas as a primary species (Rubalcava-Castillo et al., 2020). While their incorporation increases the number of recorded species, their presence does not necessarily reflect greater functional diversity or ecosystem resilience, but rather a response to the conditions generated by selective silvicultural interventions (Rascón-Solano et al., 2023). This shows that silvicultural treatments can favor the establishment of secondary species, although without yet producing a substantial transformation in the overall composition of the forest.

The *DBH* and total height of tree species are predictors of forest volume (Pacheco Escalona et al., 2007). In the distribution of individuals by diameter classes, the largest number is clustered between the 15 and 35 cm classes in all three stages. Starting at diameters of 40 cm and increasing, the forest structure decreases in density, implying the presence of some young individuals that will eventually replace larger specimens. This describes irregular masses because they are reflected in normal distribution curves. This is similar to what Delgado Zamora et al. (2016) recorded for temperate forests in the state of *Durango*. Although all height categories exist, the largest proportion of individuals is clustered between 18 and 22 m. This structural pattern corresponds to a community in transition toward a more mature structure and confirms that the applied treatments allow for a natural renewal process without significantly altering the vertical and horizontal distribution.

As expected, the species with the highest production across all three stages was *Pinus arizonica*, which recorded greater abundance and basal area. Some authors point out that production volume increases with increasing density of individuals (Návar-Cháidez & González-Elizondo, 2009); however, it is important to consider that, as density increases, significant competition for light, water, and nutrients may arise, which could eventually limit production. This is consistent with the results of this study, in which the Recruitment stage, characterized by a high density of young individuals, showed the highest number of individuals without yet showing signs of intense competition. This suggests that, while harvesting has allowed for dense regeneration, future growth will need to be monitored to avoid negative effects due to intraspecific competition.

Species richness ranging from 0.37 to 0.57 suggests low diversity, consistent with Margalef's (1977) reference values. This reflects the environmental conditions of the analyzed forest in Northern Mexico, characterized by low diversity and dominated by pine and oak species (Alfaro-Reyna et al., 2020). Higher values have been reported in studies of temperate forests in the state of *Chihuahua*, such as 1.52 by García García et al. (2020) and 1.23 by Hernández-Salas et al. (2013). Rascón-Solano et al. (2023) documented values ranging from 0.61 to 1.75 across three management stages: an initial period (2012), a recovery stage after forestry treatment (2022), and a forest stand management stage (CF, 2022). In the *Aboreachi ejido*, state of *Chihuahua*, a pine-oak forest conserved for 30 years reported a value of 1.76, indicating that species richness can be significantly increased with long-term conservation (Rascón-Solano et al., 2022). However, other studies indicate that forest management does not always lead to changes in species richness over time (Hernández-Salas et al., 2013; Rascón-Solano et al., 2023). In this study, the stability in species richness and diversity suggests that the applied treatments maintain the composition without generating significant short-term effects. This could be interpreted as a sign of structural stability, but also as a limitation to promoting greater ecological complexity.

Conclusions

Forest composition remained relatively stable before and after the silvicultural treatments, with a marked dominance of *Pinus arizonica* and *Pinus leiophylla*. These species maintained their proportions throughout the three stages of forest management, indicating a forest structure centered on these taxa. The appearance of *Juniperus deppeana* in the Final Condition stage suggests a slight incorporation of secondary species, although without significantly affecting the overall composition. The richness and diversity indexes showed low values throughout the stages evaluated. Although richness improved slightly with the addition of *Juniperus deppeana*, no significant changes were observed in the Evenness or overall diversity of the ecosystem. This indicates that current forest management has not promoted substantial species diversification in the short term.

The horizontal structure was characterized by the predominance of individuals in medium diameter classes (CF, 2022: 24.38 cm), while greater heights were observed vertically (CF, 2022: 19.5 m), suggesting that the stand is in transition to a more mature structure. The stable distribution of volume (m^3 ha^{-1}) between stages indicates that there was no significant increase in biomass, reflecting a stable structure, but with low complexity. This suggests that, although current management maintains forest production and stability, it does not yet significantly promote greater structural differentiation.

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Conflict of interests

The authors declare no conflicts of interest. Eduardo Alanís Rodríguez declares not having participated in the editorial process of this document.

Contribution by author

Christian Fabián Chapa Arce: writing and analysis of results; Samuel Alberto García García: data analysis; Joel Rascón Solano: development of the database and georeferencing data for the study site; Eduardo Alanís Rodríguez: supervision of general reviews and coordination of the work team; Gabriel Graciano Ávila: support in the review and general writing of the manuscript.

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