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Research Article

Effect of silvicultural treatment of individual selection on the horizontal structure of a pine-oak forest in northern Mexico

Joel RASCÓN-SOLANO[1,2], Samuel A. GARCÍA-GARCÍA[1,2], Viridiana S. GALVÁN-MORENO[1], Sandra PÉREZ-ÁLVAREZ[2*], Oscar A. AGUIRRE-CALDERÓN[3], Gerónimo QUIÑÓNEZ-BARRAZA[4]

[1]*Autonomous University of Nuevo León, Faculty of Forestry Sciences, Doctoral Program in Sciences with Orientation in Natural Resources Management, National Highway Km 145, ZIP 67700, Linares, Nuevo León, Mexico; jsolano@uach.mx; agarciag@uach.mx; viridiana2910@outlook.com*

[2]*Autonomous University of Chihuahua, Faculty of Agricultural and Forestry Sciences, Km 2.5 Delicias-Rosales highway, ZIP 33000, Delicias, Chihuahua, Mexico; spalvarez@uach.mx (*corresponding author)*

[3]*Autonomous University of Nuevo León, Faculty of Forestry Sciences, National Highway Km 145, ZIP 67700, Linares, Nuevo León, Mexico; oscar.aguirrecl@uanl.edu.mx*

[4]*National Institute of Agricultural and Livestock Forestry Research, Guadiana Valley Experimental Field (INIFAP-CEVAG), Km 4.5 Durango-Mezquital Highway, 34170, Durango, Durango, Mexico; quinonez.geronimo@inifap.gob.mx*

Abstract

In sustainable forest management it is essential to conserve and maintain biodiversity, the floristic composition and the mixture of its species. For this purpose, the objective of this study was to evaluate the effect of the selection silvicultural treatment as a function of time, on the horizontal structure of a Pine-Oak Forest in northern Mexico. Nine sampling points were established to analyze the structure of the Initial Condition of the forest in 2012, the Recruitment of 2022 and the Final Condition of 2022. In addition, the Jaccard similarity coefficient and the Margalef wealth index were estimated. Likewise, Shannon true diversity index, the importance value index and the forest value index were calculated for each species. The analysis of variance with a confidence of 95% was used to evaluate the studied variables, multiple comparisons were made with Duncan's test to group the species in ranges of statistical importance. The results indicated that the forest not presented a change in similarity, richness and diversity of species due to the application of the selection silvicultural treatment, without statistical differences according to the mix and distribution of the species in the forest, this indicates that selective logging does not change the composition of forest species. Regarding the indices of true diversity, value of importance and forest value by species, no significant differences were observed in terms of the application of silvicultural treatment. According to these results, it was possible to identify groups of forest importance and value, where *Pinus durangensis* Martínez was the most representative species.

Keywords: forest management; groups of importance; recruitment; residual structure; species diversity

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Introduction

In temperate forest ecosystems, many factors shape and define the composition of tree species. The wildlife is one of the important elements that defines forest ecosystems, shaping their structure, species composition and functioning (Brockerhoff *et al*., 2017; Faison *et al*., 2016; Schaub *et al*., 2020). For their part, disturbances that modify stands, such as fires and insect outbreaks, determine the dynamics, structure, and composition of forests (De Grandpré *et al*., 2018). The slope of the land, the frequency of fires and the depth of the organic horizon are environmental and temporal parameters that influenced the structures of the forests (Martin *et al*., 2018). Regarding anthropogenic activities, the application of silvicultural treatments and mechanized harvesting are also important disturbances that influence the dynamics within forests (Martin *et al*., 2020; Gresh and Courter, 2021; Molina *et al*., 2022). With silvicultural activities increase the structural complexity of the forest, since they determine its age, canopy coverage and can modify the diversity of species (Hardiman *et al*., 2011; Pérez-Suárez *et al*., 2014).

Most silvicultural methods have been developed with the primary goal of ensuring adequate regeneration of commercial tree species after harvest (Baker *et al*., 2013; Aguirre-Calderón, 2015; Bravo-Oviedo *et al*., 2020; Alder *et al*., 2023). In this sense, foresters claim that the practice of forestry should be considered as applied forest ecology (Boyle *et al*., 2016; Ashton and Kelty, 2018; Lībiete *et al*., 2023). A key ecological health metric in relation to forests is biodiversity, but because ecological forestry requires different solutions at multiple scales, assessing its overall impact on biodiversity is a difficult task (Bergeron and Fenton, 2012; Nolet *et al*., 2018). Selective cuttings, for example, are generally more appropriate in stands where the variation in tree size is wide and tree frequency decreases as tree diameter increases (Lexerød and Eid, 2006; Nordén *et al*., 2019).

In recent years more attention has been paid to the diversity of tree sizes in forests, mainly due to a greater focus on heterogeneous forest management, biodiversity conservation, social and ecosystem values (Lexerød and Eid, 2006). Therefore, forests management has shifted its focus towards multifunctional mixed-species forests (Dănescu *et al*., 2016; Salek and Sivacioğlu, 2018), the reasons behind this conceptual shift include global environmental change and biodiversity loss (Sintayehu, 2018; Weiskopf *et al*., 2020). Therefore, adequate conservation in forests in timber production requires appropriate management practices and reserves in those areas available for forest management (Lindenmayer and Franklin, 2002; Aguirre-Calderón, 2015).

Many studies have focused on how a selective treatment affects the taxonomic diversity, for example, species richness studied biodiversity measure, since it is a simple way to analyze the structure of the ecosystem and allows it to be extended to other diversity measures (Gamfeldt and Roger, 2017; Huang *et al*., 2019). Characterize these ecosystems and analyze the habitats that are often present in second growth stands (Boudreault *et al*., 2018), contributes to achieve a deep understanding of how the provision of resources related to biological diversity plays an important role in the ecological functioning of temperate forests (Jaroszewicz *et al*., 2021).

This study combined evidence-based insights with an analysis of the trade-off between structural heterogeneity and stand productivity as a function of time, spatial scale, and silvicultural management, while tree growth and species diversity have been examined in detail, as the role of forest structure and its interdependencies with stand dynamics has recently become a stronger research focus. Therefore, the objective of this study was to evaluate the effect of the selection silvicultural treatment as a function of time, on the horizontal structure of a Pine-Oak Forest in northern Mexico. It was analyzed the sustainable management of forests effect on the richness, diversity and distribution of the importance of species, likewise, it was analyzed the selective management and his effect in the distribution of species that define the structure of a second growth forest.

Materials and Methods

The study was carried out in 2022 in the cutting area of the Aboreachi ejido forest located in the municipality of Guachochi (province of the Sierra Madre Occidental), southwest of Chihuahua state, Mexico. Geographical coordinates of experimented site are between 27°11'47"N 107°22'58"O and 27°12'01"N 107°22'40"O. The study area corresponds to a heterogeneous cold temperate forest, the soils are of the eutric cambisol, eutric planosol and eutric regosol type, of medium to fine texture (Instituto Nacional de Estadística Geografía e Informática (INEGI), 2014). The climate is template subhumid semi-cold with an average annual temperature of 5 to 12 °C and an average annual rainfall of 621.3 millimeters (Instituto Nacional de Estadística Geografía e Informática (INEGI), 2020).

Data used in the analysis

The database was compiled in the forest inventory of nine permanent silvicultural monitoring circular plots of 1000 square meters, which were established in an area destined for timber production. For this analysis, three stages of forest management were considered as shown in Table 1, the first stage was called "Initial Condition" [IC (2012)] in which the trees that remained standing after harvesting in 2012 are considered. The second stage of management is described as "Recruitment" [Rec (2022)] in which unharvested individuals and new trees that have a commercial dimension (diameter at breast height [dbh > 7.6 cm]), this database was collected during the year 2022. The third stage was called "Final Condition" [FC (2022)] and made up of individuals not selected for the logging in the year 2022.

Table 1. Recorded values of density, basal area and canopy coverage by period

Plot	Forest management stage	TPH (trees ha^{-1})	TPH (STD)	Basal area (m^2 ha^{-1})	Basal area (STD)	Canopy coverage (m^2 ha^{-1})	Canopy coverage (STD)
1	IC (2012)	440		19.44		8419.50	
	Rec (2022)	720	164.62	32.02	6.94	16509.10	4214.39
	FC (2022)	430		20.65		10414.40	
2	IC (2012)	300		10.01		6118.30	
	Rec (2022)	880	290.06	19.73	5.20	116710	2903.62
	FC (2022)	580		11.68		7422.00	
3	IC (2012)	640		30.69		14435.70	
	Rec (2022)	820	146.40	42.65	8.37	21315.80	4821.44
	FC (2022)	530		26.53		12024.50	
4	IC (2012)	570		12.14		6872.30	
	Rec (2022)	790	136.50	16.92	2.90	12377.90	2822.52
	FC (2022)	540		11.71		8545.20	
5	IC (2012)	200		11.70		4366.80	
	Rec (2022)	610	208.41	18.49	3.88	9991.50	2821.14
	FC (2022)	470		11.84		6793.70	
6	IC (2012)	270		13.36		4893.00	
	Rec (2022)	490	113.72	19.82	3.43	7359.20	1301.74
	FC (2022)	330		14.57		5403.60	
7	IC (2012)	130		14.16		6243.90	
	Rec (2022)	450	166.53	19.39	3.36	9252.00	1670.95
	FC (2022)	370		13.11		6487.10	

8	IC (2012)	690		33.73		11137.00	
	Rec (2022)	1040	191.57	52.84	11.40	18828.00	4216.45
	FC (2022)	730		32.51		11987.20	
9	IC (2012)	310		10.45		4304.00	
	Rec (2022)	550	124.90	16.99	3.58	7492.70	1797.36
	FC (2022)	370		11.21		4461.10	

Where: TPH: Trees Per Hectare; IC (2012): Initial Condition; Rec (2022): Recruitment; and FC (2022): Final Condition; and STD; Standard Deviation

Diameter at breast height (dbh) of all trees of the three fixed forest conditions was measured at 1.3 m above ground level with a Forestry Suppliers Inc® diameter tape. The total height (H) was recorded with a Suunto hypsometer ® PM5 -1520, the crown diameter was measured with 50 meters using a Truper® tape and the species of each tree was identified according to taxonomic keys. Table 2 showed the values related to the diameter at breast height, total height, number of trees per hectare and accumulated basal area per hectare in the study area.

Table 2. Parameters recorded by species in the silvicultural monitoring plots

Registered species	Forest management stage	Dbh (cm)	Dbh (STD)	H (m)	H (STD)	TPH (trees ha^{-1})	TPH (STD)	Basal area (m^2 ha^{-1})	Basal area (STD)
Pinus durangensis Martínez	IC (2012)	22.60		12.15		238		12.64	
	Rec (2022)	23.29	0.37	13.74	0.85	322	55.18	17.84	3.33
	FC (2022)	22.72		13.45		218		11.63	
Pinus strobiformis Engelm.	IC (2012)	14.82		8.66		92		2.09	
	Rec (2022)	14.15	0.43	9.23	0.29	223	65.61	4.39	1.15
	FC (2022)	14.01		8.82		164		3.21	
Quercus sideroxyla Bonpl.	IC (2012)	17.05		7.91		34		0.98	
	Rec (2022)	15.99	1.36	8.37	0.24	70	19.29	1.78	0.52
	FC (2022)	14.35		8.03		40		0.8	
Quercus laeta Liebm.	IC (2012)	32.66		10.40		11		1.13	
	Rec (2022)	12.59	12.05	5.19	2.98	40	14.53	0.39	0.46
	FC (2022)	11.06		5.29		27		0.28	
Arbutus xalapensis Kunth	IC (2012)	12.46		5.24		7		0.12	
	Rec (2022)	20.71	5.69	10.03	2.87	21	7.57	1.39	0.71
	FC (2022)	23.37		10.37		9		0.21	
Quercus rugosa Née	IC (2012)	15.76		6.11		6		0.16	
	Rec (2022)	15.73	0.92	7.53	0.71	9	2.08	0.21	0.22
	FC (2022)	14.16		6.78		10		0.57	
Juniperus deppeana Steud.	IC (2012)	12.17		4.17		4		0.05	
	Rec (2022)	17.37	2.63	7.78	1.81	9	2.52	0.27	0.11
	FC (2022)	15.41		6.30		6		0.13	
Pinus leiophylla Schiede ex Schltdl. & Cham.	IC (2012)	13.15		3.70		3		0.04	
	Rec (2022)	38.72	13.66	20.00	8.61	2	0.58	0.09	0.03
	FC (2022)	34.28		16.67		2		0.09	
Pinus arizonica Engelm.	IC (2012)	26.11		10.00		1		0.05	
	Rec (2022)	7.78	9.66	4.07	3.01	6	2.52	0.09	0.02

	FC (2022)	11.67		6.11		4		0.09	
Alnus acuminata Kunth	IC (2012)	25.56		10.00		1		0.05	
	Rec (2022)	21.67	2.25	11.00	0.58	2	0.58	0.08	0.02
	FC (2022)	21.67		11.00		2		0.08	
Prunus serotina Ehrh.	IC (2012)	0.00		0.00		0		0.00	
	Rec (2022)	9.11	5.26	4.44	2.56	1	0.58	0.01	0.01
	FC (2022)	9.11		4.44		1		0.01	

Where: TPH: Trees Per Hectare; IC (2012): Initial Condition; Rec (2022): Recruitment; and FC (2022): Final Condition; and STD; Standard Deviation.

Methods

A very simple mathematical expression to represent the similarity between communities is the coefficient proposed by Jaccard (Kent and Coker, 1992). This index was used to measure the presence-absence relationship between the number of common species between sampling areas and the total number of species. This index is expressed in Equation 1:

$$IS_J = \left[\frac{c}{(a+b+c)}\right]100 \qquad (1)$$

Where IS_J = Jaccard Similarity Index; a = number of species exclusive to community A; b = number of species exclusive to community B; and c = number of species common to both communities.

To study and describe the composition of tree species of the temperate Pine-Oak Forest, the Margalef index were used to estimate species richness and the Shannon index to define the true diversity of taxa. The Equation 2 was used to measure species richness with the Margalef index (Margalef, 1972):

$$D_{mg} = \frac{(S-1)}{\ln(N)} \qquad (2)$$

Where D_{mg} = Margalef Index; S = number of species; and N = total number of trees.

To determine the true diversity, the Shannon-Wiener entropy index was calculated with the expression described by (Shannon, 1948), the result of this procedure was elevated to its exponential quotient to describe the diversity of taxa in the study area (Equations 3, 4 and 5). Jost (2006) coined the term true diversity to refer in a particular way to measures that retain the intuitively expected properties of the concept of diversity.

$$D' = \exp(H') \qquad (3)$$

$$H' = \sum_{i=1}^{S} p_i \ln(p_i) \qquad (4)$$

$$p_i = \frac{n_i}{N} \qquad (5)$$

Where D′= Shannon true diversity; H′ = Shannon-Wiener index; S = number of species; p_i = proportion of individuals of species i with respect to the total number of individuals; N = total number of individuals; and n_i = number of individuals of species i.

The horizontal structure of the stand was determined by characterizing the distribution of measured diameter classes, the number of individuals for each of the taxa was also quantified using Asigbaase *et al*. (2019) and Rascón-Solano *et al*. (2022) methods. The abundance was calculated based on the number of trees per species and the dominance based on the basal area. Finally, to evaluate the frequency of the species, it was counted how many sites each recorded species was repeated. With the aforementioned indicators, the importance value index (IVI) was estimated according to the formula developed by Curtis and McIntosh (1951) (Equation 6), with the percentage average from 0 to 100 of the previous ecological indicators (Alanís-Rodríguez *et al*., 2011; García *et al*., 2020):

$$IVI = \frac{\sum_{i=1}^{n} (RA_i,\ RD_i,\ RF_i)}{3} \qquad (6)$$

Where IVI = Importance Value Index; RA_i = relative abundance; RD_i = relative density; and RF_i = relative frequency.

The forest value index (FVI) was estimated with the purpose of evaluating the two-dimensional structure of the arboreal vegetation considering three measurements: the first at the level of the lower stratum in the horizontal plane (dbh), the second that includes the lower and upper strata in the vertical plane (H), and the third at the level of the upper stratum in the horizontal plane (coverage) (Equation 7) (Corella Justavino *et al*., 2001; Graciano-Avila *et al*., 2017; Oré Cierto *et al*., 2021).

$$FVI = \frac{(\sum_{n}^{i=1} Rdbh_i,\ \sum_{n}^{i=1} RH_i,\ \sum_{n}^{i=1} RCC_i)}{3} \qquad (7)$$

Where FVI = forest value index; RND_i = relative dbh; RTH_i = relative H; and RCC_i = relative canopy coverage.

Statistical analysis of the variables

To carry out the analysis of the collected information, we considered the effect of the natural recruitment (new young trees integrated in the forest) of trees and their growth in dbh and H, later we measured the effect of selective treatment on the redistribution of species, their dbhs and Hs. We analyzed the Margalef and Shannon true diversity indices, Importance Value index and Forest Value Index. We built dendrograms to identify the similarity of species between plots, we used the Jaccard similarity index to measure the turnover between the Initial Condition (2012), tree Recruitment (2022) and Final Condition (2022) stages. The Shapiro-Wilk test ($p \leq 0.05$) was used to determine the normality of the observations included in the analysis variables. The homogeneity of the variances of the analyzed variables was evaluated using Levene's test at a significance value of 5%. Subsequently, we implemented ANOVA analyzes at a significance level of 5% too, the variables that were included were treated with Duncan's test to compare the means of the levels of a factor at a significance level ≤ 0.05. The statistical package IBM-SPSS version 25 to develop the information analysis was used (IBM Corp., 2017).

Results and Discussion

Effect of selective silvicultural treatment on the similarity of species between sampling plots

Results of the estimated similarity indices showed, in general, values greater than or equal to 66% for Jaccard, which denotes a homogeneity of species between the analyzed sampling plots, the similarity value represents a mean similarity (MS). Likewise, these results are obtained by the resilience capacity of the ecosystem and the environmental homogeneity of the study are (Figure 1a). Santana *et al*. (2014) attributed the differentiation of groups to the environmental heterogeneity present in a mountain cloud forest analyzed in the Transversal Volcanic System of Michoacan in Mexico. Instead, Ghiloufi *et al*. (2015) concluded that the absence or presence, in terms of species composition, presents inequalities due to the recruitment of new sets of species. Another identified factor that has led communities towards a differentiated assemblage of species is anthropogenic, Williams-Linera (2002) indicated that human activities exert an important influence on the type and degree of fragmentation of ecosystems, reflected in the inequality and turnover of species.

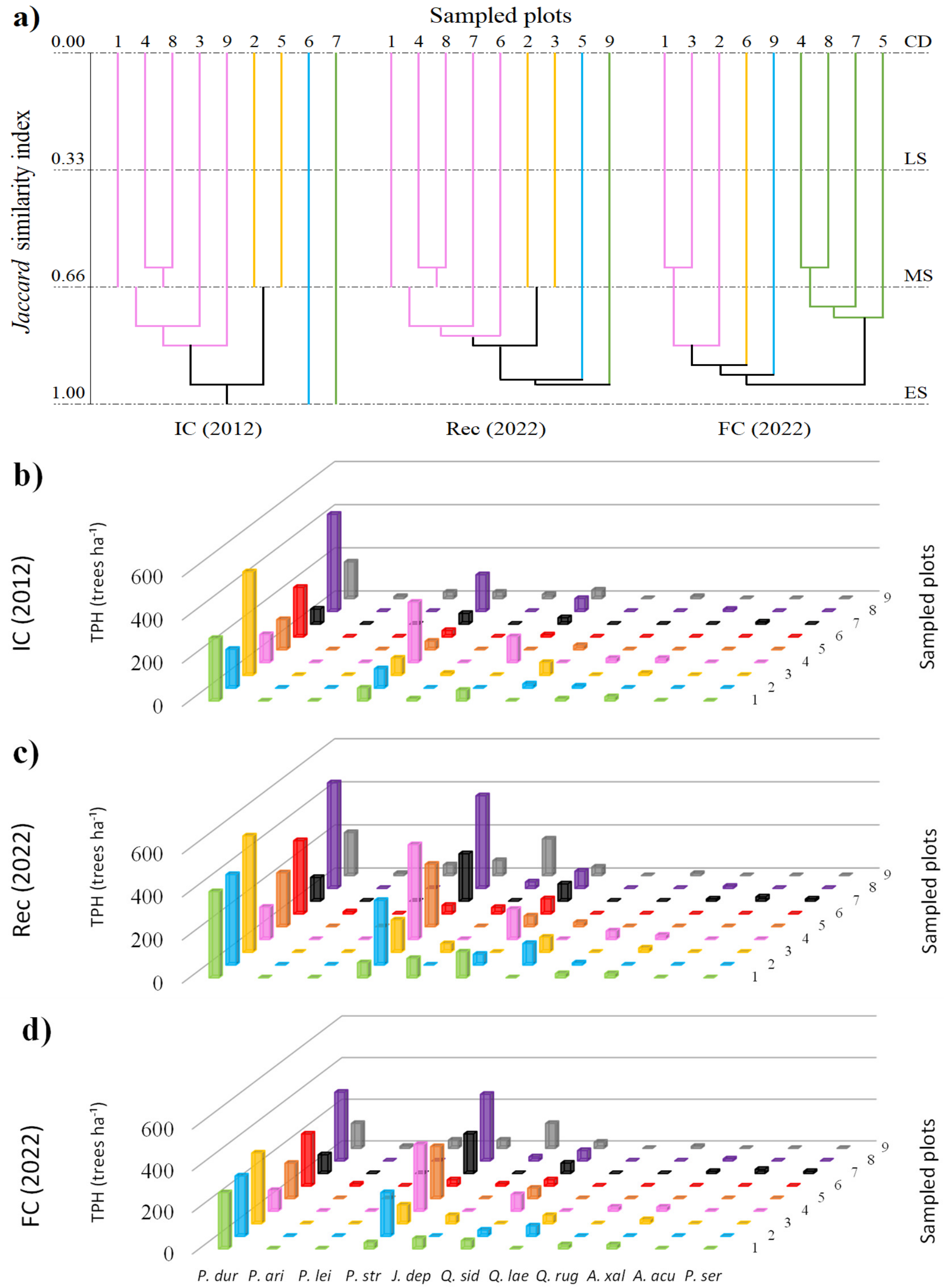

Figure 1. Contrast of the *Jaccard* similarity index as a function of the selection silvicultural treatment Where: IC (2012): Initial Condition; Rec (2022): Recruitment; FC (2022): Final Condition; CD: Completely different; LS: Low similarity; MS: Medium similarity; ES: equal similarity. *P. dur*: *Pinus durangensis* Martínez.; *P. ari*: *Pinus arizonica* Engelm.; *P. lei*: *Pinus leiophylla* Schiede ex Schltdl. & Cham.*;* *P. str*: *Pinus strobiformis* Engelm; *J. dep*: *Juniperus deppeana* Steud.; *Q. sid*: *Quercus sideroxyla* Bonpl.; *Q. lae*: *Quercus laeta* Liebm.; *Q. rug*: *Quercus rugos*a Née; *A. xal*: *Arbutus xalapensis* Kunth; *A. acu*: *Alnus acuminata* Kunth; *P. ser*: *Prunus serotina* Ehrh.

The value of the Jaccard similarity index allowed to define four groups for each of the studied periods. In the IC (2012) period two groups were defined that have unique plots, the first includes plot 7 and the second, plot 6, which present an equal similarity of species (ES), however, the number of individuals representing each species was different as shown in Figure 1b. The rest of the fragments showed a low and medium similarity (LS and MS) values, so they were grouped into two different fragments. The Rec (2022) condition increased the relationship of species existing between plots, groups with a DM were generated, the results indicated an assemblage greater than or equal to 66% in seven of the nine analyzed plots. The recovery period of 10 years allowed the integration of new individuals in the plots (Figure 1c), which also results in an increase in the similarity of the studied areas. With the application of the selective silvicultural treatment [FC (2022)], a change was presented in the similarity of the plots, after forest management it was possible to increase the similarity of the analysis areas and it was possible to conserve the same number of species recruited as shown in Figure 1d. According to the analysis of variance, there were not significant differences between the number of species identified between the management periods ($p = 0.8572$). This shows that the selective management system is ecologically sustainable since it allows conserving the species that constitute the stands.

Effect of selective felling on species richness between sample plots

The studied plots presented richness values from 0.61 to 1.75 for the period IC (2012), which was measured after the silviculture treatment was applied; 0.73 to 1.50 for the period Rec (2022); and values that oscillate from 0.52 to 1.66 after the selective use of forest masses in FC (2022). According to these results, it is defined that the richness of species is low, as indicated by Margalef (1972). The low species richness is mainly related to the environmental conditions of temperate ecosystems, the forests in northern Mexico are dominated mainly by Pine-Oak tree structures (Alfaro-Reyna *et al*., 2020; Alfaro-Reyna *et al*., 2019; Wehenkel *et al*., 2014). Regarding the effect of the recruitment of new individuals and the application of selective treatments in the study area, the ANOVA carried out shows that there are no significant differences ($p = 0.9125$) between the different periods of analysis, which shows that the applied harvesting does not modify species richness; instead, it promotes the recruitment of new species through the opening of the canopy and the removal of soil derived from forestry operations.

The species richness results of this analysis are lower than those presented in regions close to the study area. In the same region of Aboreachi (Rascón-Solano *et al*., 2022), evaluated a Pine-Oak forest that has been preserved for 30 years, they estimated a species richness of 1.76 according to the Margalef index, the difference is mainly due to the conservation status of the stand they analyzed. For his part, Holguín-Estrada *et al*. (2021) estimated species richness values of the Margalef index of 3.10, 3.30 and 1.53 for three altitudinal intervals in Chihuahua, Mexico, these results are higher than those described in the present study, the difference is attributed to climatic conditions and height are heterogeneous among the analyzed populations. On the other hand, Forsman *et al*. (2016) have reported dramatically higher species richness values in mature forests compared to newly cleared forests. Nevertheless, Hernández-Salas *et al*. (2013) indicate that species richness does not show any significant differences through forest management over time, a result similar to what we found, since selective management does not significantly affect species richness, on the other hand, ecologically sustainable management of forest masses promoted the increase of this index as shown in Figure 2.

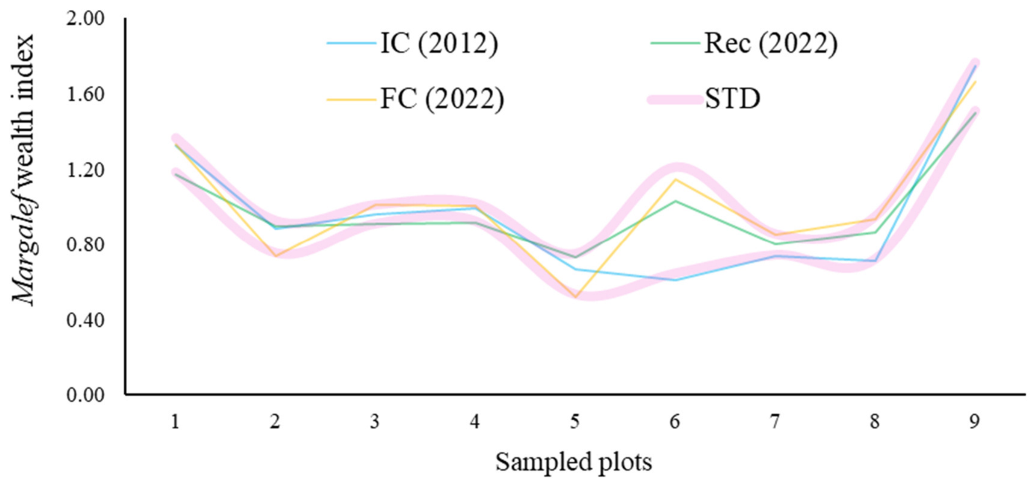

Figure 2. Flow of species richness per sampling plot for management periods
Where: IC (2012): Initial Condition; Rec (2022): Recruitment; FC (2022): Final Condition; STD: Standard deviation.

Effect of selective treatment on species diversity

Roswell *et al*. (2021) indicates that it is important to choose the relative sensitivity of the metric towards rare and common species, for this reason, the diversity was estimated at the species level, when performing the ANOVA, we identified significant differences ($p < 0.0001$) between the diversity values that species contribute. According to Duncan's separation of means, four groups of uniform true diversity were generated, this means that two or more species contribute a diversity value similar to the total diversity sum for the *Shannon-Wiener* true diversity index. Based on the analysis carried out, we found that the first group, made up of *Pinus durangensis* Martínez and *Pinus strobiformis* Engelm, and the second group made up only of *Quercus sideroxyla* Bonlp., are the ones that contribute the highest proportion of diversity to the plots studied (Figure 3). For their part, the third and second groups are made up of species that can be considered rare for the study area; however, they are common species in the Pine-Oak forests of northern Mexico. Additionally, the period described as IC (2012) presented a value that ranges from 1.78 to 3.73 in species diversity; the integration of new individuals during the Rec (2022), resulted with values of 2.67 to 4.31 in terms of true diversity; Finally, the result of the application of the selective treatment FC (2022) showed diversity values that vary from 2.36 to 5.00. In this sense, depending on the analyzed periods, the values of species diversity presented a growth trend through selective forest management over time. Likewise, the analysis of variance showed non-significant differences ($p = 0.6291$), on the other hand, Duncan's separation of means test indicates that the true diversity values of the IC (2012) differ from those estimated for the Rec (2022) and FC (2022). This result denotes that selective management allows increasing the diversity of species, this is mainly due to the fact that the silvicultural treatment promotes the use of all the species present and in the various existing dimensions.

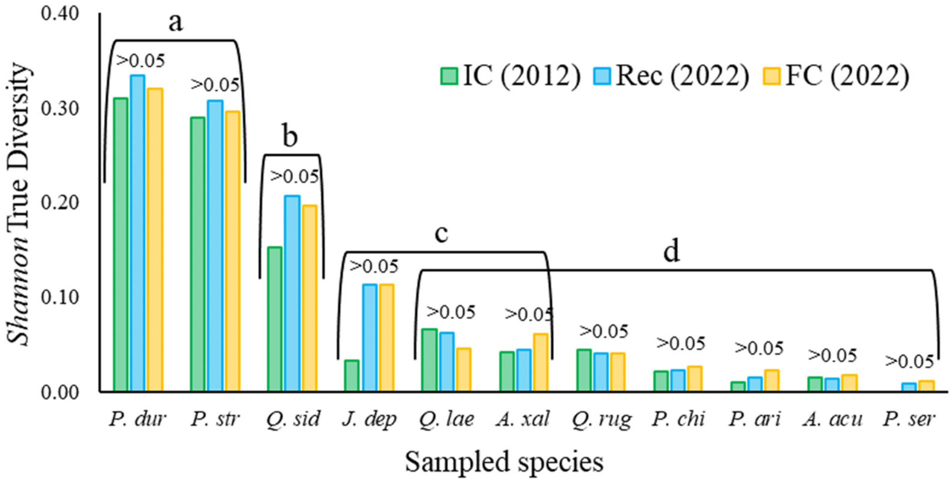

Figure 3. Differentiation of groups of uniform true diversity with Duncan's test of separation of means. *Groups with the same letter represent non-significant differences

Where: IC (2012): Initial Condition; Rec (2022): Recruitment; FC (2022): Final Condition; *P. dur*: *Pinus durangensis* Martínez.; *P. ari*: *Pinus arizonica* Engelm.; *P. lei*: *Pinus leiophylla* Schiede ex Schltdl. & Cham.; *P. str*: *Pinus strobiformis* Engelm; *J. dep*: *Juniperus deppeana* Steud.; *Q. sid*: *Quercus sideroxyla* Bonpl.; *Q. lae*: *Quercus laeta* Liebm.; *Q. rug*: *Quercus rugos*a Née; *A. xal*: *Arbutus xalapensis* Kunth; *A. acu*: *Alnus acuminata* Kunth; *P. ser*: *Prunus serotina* Ehrh.

Kumar *et al*. (2022) used the *Shannon-Weiner* index to characterize the relative distribution of the species in different transects, they estimated global values that oscillated between 0.74 and 2.06, the results are below and above our analysis when we take the values to their exponential expression. Asigbaase *et al*. (2019) obtained similar values (when expressed in its exponential form) regarding the species diversity index, with values ranging from 1.03 to 1.41 for stands managed under an agroforestry regime. For his part, Martin *et al*. (2021) found that the Shannon diversity index was lower in high-elevation areas and higher in the low-elevation area. The range of species diversity found by these authors was from 1.83 to 2.47, and discarded to our results in the studied region. In the sense of forest harvesting, Molina *et al*. (2022) indicated that logging has modified the succession pathways of the stands, leading to changes in the composition of the original forests dominated by conifers to predominantly mixed and hardwood forests, this is mainly due to the degree of utilization of the existing species, in this analysis *Arbutus xalapensis* Kunth was recorded, a broad-leaved present in various regions dominated by Pine-Oak in Mexico, however, it is a not harvested species, which leads to an increase in the stands density (Figure 3) and contributed consequently to increase in hardwoods. In accordance with Asbeck *et al*. (2021) and Schall *et al*. (2020) the diversity of species and orders in different taxonomic groups was influenced only to a small extent by the intensity of forest management, and that's why silvicultural cover treatments do not tend to affect the diversity of species that inhabit the forest.

Changes for the IVI

The absolute abundance (trees. ha^{-1}) presented statistically significant differences (p < 0.0001) depending on the species registered in the study area. The *Pinus* and *Quercus* species presented the highest abundance. The species with the highest number of individuals was *Pinus durangensis* Martínez, followed by *Pinus strobiformis* Engelm. and *Quercus sideroxyla* Bonlp. The least abundant genera were *Alnus* and *Prunus*, with absolute values equal to or less than 2 individuals per hectare. This limited number of trees is due to species requiring conditions that are not adequately favorable in the analyzed plots (Aulestia-Guerrero *et al*., 2018; Guzmán *et al*., 2020). Regarding the relative abundance of species as a function of time and the selective management applied, there were no significant differences ($p = 0.8362$), which indicates that the adequate application of silvicultural treatment does not modify the distribution of individuals per species, nor the species proportionality. The species with the highest absolute dominance (basal area in m^2 ha^{-1}) were *Pinus durangensis* Martínez, *Pinus strobiformis* Engelm and *Quercus sideroxyla* Bonlp. However, only the first species presented a basal area greater than 10.00 m^2 ha^{-1}, for this reason statistical differences ($p < 0.0001$) are presented in this parameter. The relative dominance of the genera *Pinus*, *Arbutus*, *Alnus* and *Prunus* showed a slight tendency to increase, while the genera *Quercus* and *Juniperus* decreased after the application of the individual selection treatment. The increase in dominance of the hardwoods is mainly due these species are not contemplated in forest management programs. Finally, the least dominant species was *Alnus acuminata* Kunth and *Prunus serotina* Ehrh., this result is related to the number of individuals and their diameter (dbh < 10 cm). The relative frequency was similar before and after the application of selective treatment ($p = 0.7173$). The most frequent species were *Pinus durangensis* Martínez, *Pinus strobiformis* Engelm, *Quercus sideroxyla* Bonlp. and *Quercus laeta* Liebm., while the less frequent species were *Alnus acuminata* Kunth, *Pinus arizonica* Engelm. and *Prunus serotina* Ehrh.

The Importance Value Index denotes the genera with values of greater ecological importance, the region where the plots of this analysis are located is mainly represented by the genus *Pinus* (70.81%), this result is related to what was described by Hernández-Salas *et al*. (2013) and Rascón-Solano *et al*. (2022) who found values greater than 50% for the genus *Pinus*. Instead, Monárrez-González *et al*. (2020) evaluated temperate forests in northern Mexico and found a greater ecological importance of the genus *Quercus* (> 50%). For his part, García *et al*. (2020) indicate that the genus *Quercus* and *Pinus* reach an ecological importance of less than 30% in the temperate forests of northern Mexico. When performing a variance analysis, significant differences ($p < 0.0001$) were identified between the ecological index values provided by the species. According to Duncan's separation of means, five groups of uniform ecological value were generated, this allows defining which species present some difference compared to the others, in relation to the ecological value they contribute to a given ecosystem. The analysis also makes it possible to define groups of ecological value, this means that two or more species contribute equally to the Importance Value Index of a specific forest (Figure 4).

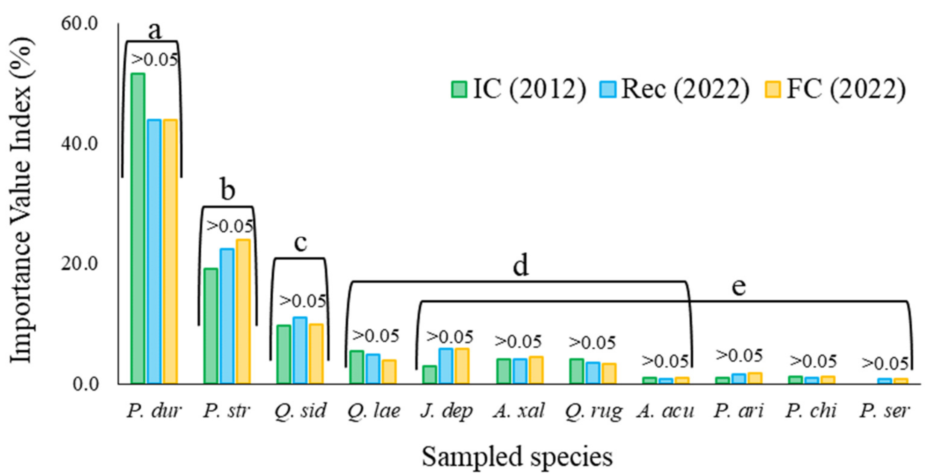

Figure 4. Uniform ecological value groups for the Importance Value Index. *Groups with the same letter represent non-significant differences

Where: IC (2012): Initial Condition; Rec (2022): Recruitment; FC (2022): Final Condition; *P. dur*: *Pinus durangensis* Martínez.; *P. ari*: *Pinus arizonica* Engelm.; *P. lei*: *Pinus leiophylla* Schiede ex Schltdl. & Cham.; *P. str*: *Pinus strobiformis* Engelm; *J. dep*: *Juniperus deppeana* Steud.; *Q. sid*: *Quercus sideroxyla* Bonpl.; *Q. lae*: *Quercus laeta* Liebm.; *Q. rug*: *Quercus rugos*a Née; *A. xal*: *Arbutus xalapensis* Kunth; *A. acu*: *Alnus acuminata* Kunth; *P. ser*: *Prunus serotina* Ehrh.

According to the groups of uniform ecological value generated, *Pinus durangensis* Martínez is the species most representative this ecosystem, with a maximum importance value of 51.60% in IC (2012), 10 years later, through Rec (2022), the ecological value decreased to 43.88% and with the application of the selection silvicultural treatment a value of 43.96% was obtained in FC (2022), however, the effect of time and forest management is not significant (p = 0.8492). The result indicates that the species gives way to the increase of ecological values of other species, through natural regeneration, mainly of heliophilous genera such as *Quercus* and *Arbutus*. In this sense, Ramírez *et al*. (2019) have described that the application of selective silvicultural treatments to coniferous and broad-leaved species allows improving and maintaining the ecological balance of mixed stands. The second ecological important species was *Pinus strobiformis* Engelm. according to the analysis, this species increased its value of importance from 19.08, 22.32 to 23.85% depending on the time and the management applied respectively (p = 0.9318), initially the species presented a better response to the recruitment of new individuals, due to a greater abundance of regeneration that reached a commercial dimension (dbh > 7.6 cm), additionally, the selective use presented a bias in the distribution of this species, promoting the increase of abundance and dominance values. In relation to this, Hernández-Salas *et al*. (2013) indicate that this behavior is normal in developing masses, treated with practices focused on timber production, which supposes a compensation of the species by the forester (Monárrez-González *et al*. 2018).

Quercus sideroxyla Bonlp. was the third species in the ecological value order estimated, according to the analysis, this taxon was found to have increased its importance value from the period IC (2012) to the period Rec (2022), this indicates that this oak presented a good ability to regenerate compared to other recorded species of the same genus, on the other hand, selective management caused a non-significant reduction (p = 0.8347) of the ecological value that the species represents. Luna *et al*. (2020) indicate that *Quercus sideroxyla* Bonlp. is a species that represents a significant proportion in the stocks of Pine-Oak forests managed in northern Mexico, in the same way, for the analysis that we carried out, this species contributes significantly to the composition of the plots under study. For its part, the estimated fourth group is made up mainly of species that are commonly found, to a lesser extent, in the Pine-Oak forests of northern Mexico and other forested regions of the country (García *et al*., 2019; Graciano-Avila *et al*., 2017; Martin *et al*., 2021). Finally, the fifth group of ecological importance is made up of species that we have considered of little relevance; these seven species have a low presence for the plots, however, they fulfill productive, environmental and ecological functions that go beyond contributing to the species composition of a given forest. Aulestia-Guerrero *et al*. (2018) indicate that *Alnus acuminata* Kunth is a species that can contribute significantly to the reduction of CO_2 content in the atmosphere, in addition to being a species of great forestry interest, due to its good vegetative development and its usefulness for industrial purposes. For his part, Pacheco-Agudo and Quisbert-Guarachi (2016) mention that this species has the ability to associate with different productive systems, due to its conservation and adaptation skills. As for *Pinus arizonica* Engelm., it is a very common species in other regions of northern Mexico, even becoming the main species of Pine and Pine-Oak ecosystems. Hernández-Salas *et al*. (2018), Hernández-Salas *et al*. (2013) and Martínez-Salvador *et al*. (2013) indicate that *Pinus arizonica* Engelm. has a high productive potential, since it allows sustaining timber production with selective and intensive silvicultural interventions applied for its development and increased productivity. The species of least ecological importance was *Prunus serotina* Ehrh., however, it is a taxon that has been considered underutilized, since its potential has been registered in the pharmacological, nutraceutical and forestry industries, likewise, it has a high potential to evaluate and mitigate the effects of climate change (Guzmán *et al*., 2020).

Changes in the Forest Value Index

The FVI is made up of the relative values of diameter, height and cover of the species registered in the studied area. The largest relative diameter was registred for *Pinus durangensis* Martínez in the three stages of forest development and management, the values obtained were 67.21, 56.86 and 56.70%, this indicates that the mentioned species is the one that contributes the highest percentage of the diameters present in the plots. *Pinus strobiformis* Engelm was the second in importance of this parameter, with values of 17.03, 23.94 and 26.31% for the three evaluated temporal and management cycles. We found an increase in the number of individuals and significant diameter growth in *Pinus strobiformis* Engelm.

This indicates that forest cover management maintains a relative diameter proportion of the species. The highest accumulation of height was presented by *Pinus durangensis* Martínez in the three periods analyzed, the estimated values were 68.96% in the Initial Condition (2012), the Recruitment (2022) was reduced to 57.36% due to the incorporation of new individuals of other species. to the forest mass, regarding the Final Condition (2022) it was estimated 57.23%, which indicates that the accumulation of heights was not affected by forest management. The second species that contributed to the sum of height was *Pinus strobiformis* Engelm, the sum of relative heights was 19.00, 26.69 and 28.23% for the indicated periods. For their part, the rest of the species contribute with a relative accumulation of height of 12.03, 15.95 and 14.59%, this indicates that time has an effect on the accumulation of species and forest management tends to maintain the proportionality of the values.

Regarding the accumulation of relative canopy coverage, *Pinus durangensis* Martínez was the most representative, in the Initial Condition period (2012) it represented 64.76% of the total, later with Recruitment (2022) 53.85% was obtained as a result, with the application of management this parameter registered 54.56%. For its part, *Pinus strobiformis* Engelm was the second species that contributed significantly to this component, initially 22.08% of the coverage was recorded, with the integration of new individuals and crown growth in the Recruitment period (2022) the value obtained increased to 28.83%, the management of the mass increased the canopy coverage of this species to 31.61% as part of the Initial Condition (2012). This is due to the ability of this species to develop wide crowns, likewise, it supposes a compensation on the part of the forester (Monárrez-González *et al*., 2018).

When performing a variance analysis, significant differences ($p < 0.0001$) were identified between the forest index values provided by the species. According to Duncan's separation of means, four groups of standardized forest value were generated. This adjustment allows defining which species are more important from a productive approach, in relation to the values shown by other species, for a given forest mass. The separation of means also makes it possible to define groups of importance, separates the most important species and groups the taxa of less productive relevance (Figure 5). According to the results obtained, *Pinus durangensis* Martínez is significantly ($p < 0.0001$) the species with the greatest forest value for the study area, followed by *Pinus strobiformis* Engelm; together, these two groups of forest value represent more than 80% of stocks present in the study area. In accordance with Silva-González *et al*. (2022), the mentioned species are of high productive value for the Pine and Pine-Oak forests of northern Mexico, Rascón-Solano *et al*. (2022) for his part, he mentions that both species groups present that order of productive importance in the pine forests of northern Mexico. The third group is made up of *Quercus sideroxyla* Bonlp. and *Quercus laeta* Liebm., both species added approximately 10% of the forest value, according to Silva-González *et al*. (2021) *Quercus sideroxyla* Bonlp. is one of the main species found in the Pine-Oak forests of northern Mexico. Finally, the fourth group integrated eight of the registered species (including *Quercus laeta* Liebm.), this group represents values of less than 10% of forest importance. Taking the results as a reference, the species of greatest productive importance is *Pinus durangensis* Martínez, Graciano-Avila *et al*. (2017) indicate that for Pine-Oak forests, this same species is the one with the greatest forest contribution, with values close to 70% of forest importance.

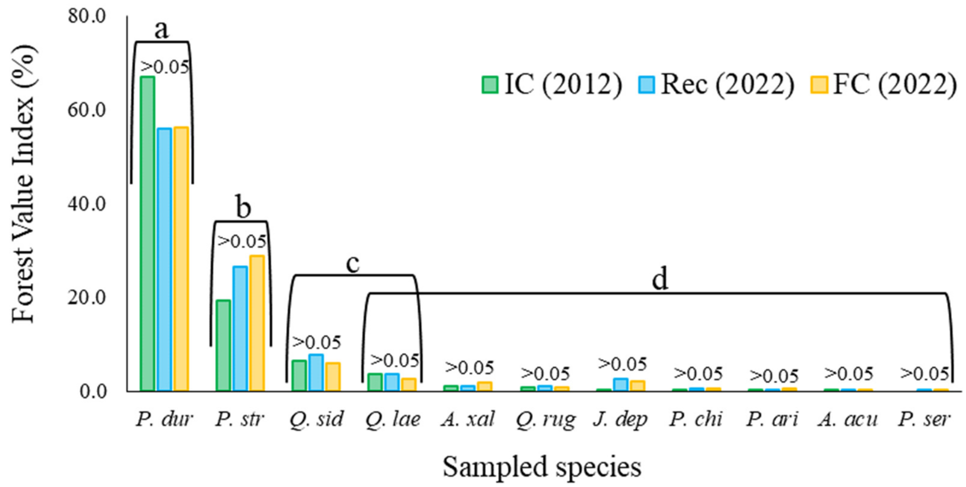

Figure 5. Groups of uniform productive values for the Forest Value Index. *Groups with the same letter represent non-significant differences

Where: IC (2012): Initial Condition; Rec (2022): Recruitment; FC (2022): Final Condition; *P. dur*: *Pinus durangensis* Martínez.; *P. ari*: *Pinus arizonica* Engelm.; *P. lei*: *Pinus leiophylla* Schiede ex Schltdl. & Cham.; *P. str*: *Pinus strobiformis* Engelm; *J. dep*: *Juniperus deppeana* Steud.; *Q. sid*: *Quercus sideroxyla* Bonpl.; *Q. lae*: *Quercus laeta* Liebm.; *Q. rug*: *Quercus rugos*a Née; *A. xal*: *Arbutus xalapensis* Kunth; *A. acu*: *Alnus acuminata* Kunth; *P. ser*: *Prunus serotina* Ehrh.

Finaly, the fourth group integrated eight species (including *Quercus laeta* Liebm.), this group represents values of less than 10% of forest importance. Taking the results as a reference, the species of greatest productivity is *Pinus durangensis*. Graciano-Avila et al. (2017) indicate that pine-oak forest, the same species is the one with the greatest forest contribution, with values close to 70% of forest importance.

Conclusions

This study combined evidence-based insights with an analysis of the trade-off between structural heterogeneity and stand productivity as a function of time, spatial scale, and silvicultural treatments, while tree growth and species diversity were examined in detail. It was identified that the sustainable management of Pine-Oak forests in northern Mexico does not have a significant effect on the richness, diversity and distribution of the importance of the species. For this reason, we consider that the application of silvicultural treatments of individual selection is an adequate methodology to manage forests and promote ecological conservation. Allows to increase the number of species that define the structure of a forest. Likewise, the importance of continuous monitoring of the dynamics of the stands and the effect of the application of ecologically sustainable forestry treatments is highlighted, in order to develop and apply management strategies based on conservation and its effects on temperate climate forest ecosystems dominated by conifers.

Additionally, it was proved that the separation of means is a useful tool to define groups of ecological and forest importance, in this way it is possible to adequately define the values that species contribute to the richness, diversity and productivity of ecosystems. The analysis carried out has the potential to be replicated and used in forest management programs with ecologically sustainable productive purposes.

Authors' Contributions

Conceptualization, J.R.S.; methodology, J.R.S., S.A.G.G. and V.S.G.M.; validation, S.P.Á., O.A.A.C. and G.Q.B.; formal analysis, J.R.S. and S.A.G.G.; investigation, J.R.S. and V.S.G.M.; resources, J.R.S.; data curation, J.R.S., S.A.G.G. and V.S.G.M.; writing-original draft preparation, J.R.S., S.A.G.G. and S.P.Á.; writing-review and editing, O.A.A.C. and G.Q.B.; supervision, J.R.S. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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