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Effects of Thinning on the Diversity, Composition, and Spatial Structure in a Mixed Temperate Forest

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ABSTRACT

Objective: To evaluate the effects of silvicultural thinning on tree diversity and stand structure in a temperate mixed forest.

Design/methodology/approach: Data were collected in a 1 ha research plot. Five scenarios were evaluated through computer simulations: no thinning (T1), thinning with removal of 25% of basal area (Gha^{-1}), (T2), thinning with removal of 25% of Gha^{-1} (T3), thinning with removal of 45% of Gha^{-1} (T4), and thinning with removal of 70% of Gha^{-1} (T5). The importance value index, alpha diversity, Pretzsch's A index and structural complexity index were estimated. A spatial distribution analysis was performed using the pair-correlation function $g(r)$.

Results: *Pinus douglasiana* and *Quercus resinosa* were the species of highest ecological value. Due to the removal effect, no significant changes in tree diversity were observed in the applied thinning scenarios. However, as thinning became more intense, at least one species (*Quercus candicans*) was lost. Thinning from below affected the oaks and thinning from above affected the pine species, which is also reflected in the spatial distribution of the remaining trees.

Limitations on study/implications: The analysis is static; therefore, it is recommended that a long-term study be conducted under varying ecological conditions.

Findings/conclusions: The effect of thinning on forest diversity, composition and structure depends on the type of thinning, condition of the structure, initial composition and intensity of removal. Thinning of less than 25% of the basal area, in the immediacy, allows timber harvesting without generating changes in the diversity, structure and composition of the temperate mixed forest under study.

Keywords: Simulations, pair-correlation function, structural complexity, silviculture, importance value index.

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INTRODUCTION

The configuration of forest canopy, shaped by natural succession and human intervention, constitutes a fundamental indicator of forest ecosystem functioning at different temporal and spatial scales (Gough *et al.*, 2022). Among silvicultural practices, thinning is an important and widely used activity in forest management (Franklin *et al.*, 2007). It involves the reduction of tree density through the selective removal of trees in relatively dense canopies (Liu *et al.*, 2019). This action redistributes available resources, improves nutrient availability, promotes the growth of remaining trees, and can create suitable conditions for species of commercial, ecological, or cultural importance (Smith *et al.*, 1996; Latterini *et al.*, 2023).

In addition to generating intermediate income from timber harvesting, thinning enhances pest control and fire prevention by promoting a more complex and diverse forest structure (Liu *et al.*, 2019; Latterini *et al.*, 2023). It also supports natural regeneration and emulates the effect of natural disturbances (Rubio-Camacho *et al.*, 2023), creating stand structures and spatial patterns that strengthen ecosystem resilience (Stephens *et al.*, 2008).

To study the effects of thinning, indices for characterizing the stand structure and species composition have been used (Gadow *et al.*, 2012; Prodan *et al.*, 1997). These indices comprise three main elements: 1) species composition, 2) dimensional diversity, and 3) spatial structure (Aguirre *et al.*, 2003; Gadow *et al.*, 2012; Pommerening, 2002). Utilizing these indices provides a detailed overview of the current state of forest stands and can be used to evaluate the effects of natural and anthropogenic disturbances on vegetation (Latterini *et al.*, 2023; Rubio-Camacho *et al.*, 2023). Furthermore, they are related to central ecosystem processes, including primary production, water use efficiency, and biogeochemical cycling rates (Gough *et al.*, 2022).

Through diversity indices, some studies in Mexico have demonstrated that silvicultural practices modify the stand structure and species diversity (Pérez-López *et al.*, 2020; Silva-González *et al.*, 2021; Soto Cervantes *et al.*, 2021). However, few studies assess the spatial structure of residual trees, and previous research is highly specific to certain species and regions. Therefore, it is necessary to expand knowledge to other species and forest areas in the country.

The use of experimental plots and the simulation of silvicultural practices in forest management offers multiple benefits, such as the validation and adjustment of management techniques before field application, providing crucial experimental control for the study of complex ecological interactions. These practices serve as essential platforms for decision-making by foresters. Additionally, thinning facilitates the anticipation and adaptation of forest management strategies to the effects of climate change, enables the testing of ecological restoration methods, and maximizes carbon sequestration.

The objective of this study is to analyze the immediate effects of thinning on forest composition and structure at the stand level. The research questions are: 1) How does thinning affect species diversity and composition? 2) What is the relationship between thinning types and structural complexity? and 3) Do different thinning methods generate heterogeneous spatial patterns? These questions are addressed through simulations of various thinning types with variable intensities. A mixed temperate forest dominated by *Pinus douglasiana* Martínez and *Quercus resinosa* Liebm., located in a protected natural area in the state of Jalisco, serves as a case study.

MATERIALS AND METHODS

Study Area

This study was conducted in the forests of the "Sierra de Quila" Flora and Fauna Protection Reserve, Jalisco, Mexico. The reserve is located in west-central Mexico at coordinates 20° 14.65' N to 20° 21.67' N and −103° 56.79' W to −104° 7.98' W. The area spans an altitudinal range from 1350 to 2550 meters above the sea level (INEGI, 2013). The vegetation is a mixed temperate forest, with representative species including *Pinus douglasiana* Martínez, *Pinus devoniana* Lindley, *Quercus resinosa* Liebm., and *Quercus obtusata* Bonpl (CONANP, 2000) (Figure 1).

Data Collection

The data were collected from a permanent research plot (100×100 m, 1 ha). Plot corners were delineated with 2 cm precision using a Ruide Total Station RTS-833 and georeferenced with a Topcon GR-5 Global Navigation Satellite System (GNSS). The plot was referenced to the Universal Transverse Mercator, Zone 13 North (UTM 13N) with central coordinates at 599,773.81 X and 2'245,771.62 Y (Figure 1). The plot was divided into 25 subplots using a Sokkisha TM10E theodolite (20×20 m, 0.40 ha), where trees with a diameter at breast height (d, cm) of 7.5 cm or greater were inventoried. The collected variables included: tree species, tree diameter (d, cm), total tree height (h, m), and crown diameter (dc, m). Additionally, using a total station, the spatial distribution of each tree (x and y coordinates) was obtained.

Simulation of Silvicultural Scenarios

The thinning scenarios evaluated were as follows: T1) no removal, T2) thinning from below with removal of 25% of total basal area (Gha^{-1}) ($d \leq 25$ cm), T3) thinning from above with removal of 25% of Gha^{-1} ($d \geq 30$ cm), T4) thinning from above with removal of 45% of Gha^{-1} ($d \geq 30$ cm), and T5) thinning from above with removal of 70% of Gha^{-1} ($d \geq 30$ cm). The cutting scenarios do not incorporate a temporal component, and only

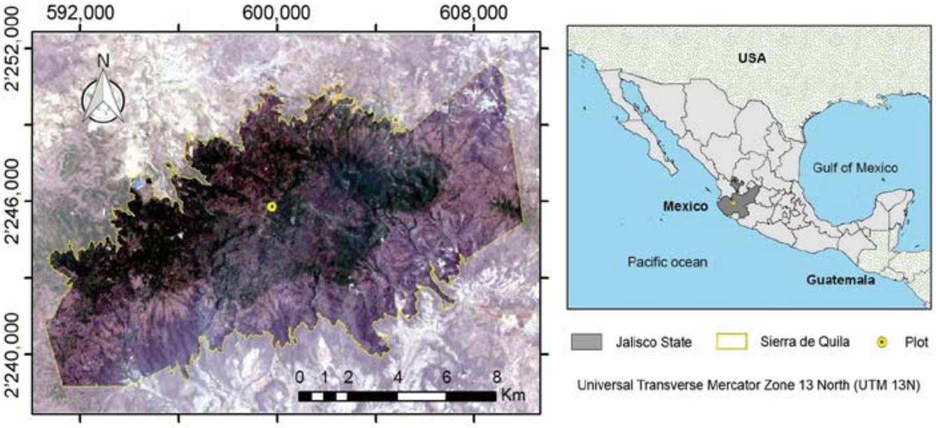


Figure 1. Location of the study area within the "Sierra de Quila" Flora and Fauna Protection Reserve, Jalisco, Mexico.

static data are analyzed. The criteria used for basal area removal in the iterations were: a) removal of individuals proportionally to basal area, with a maximum variation of 3%, b) residual tree distribution to protect soil conditions, and c) random elimination of trees.

Data Analysis

Before and after applying the iterations, the plot was characterized through stand structure indicators. To analyze the effects of thinning on tree diversity, composition, and structure, the following indices were considered: Species Importance Value Index (IVI), alpha diversity, Pretzsch's A index, and Enhanced Structural Complexity Index (ESCI). The IVI is an index used to rank the dominance of each species in mixed stands (Zarco-Espinosa *et al.*, 2010). The IVI per tree species was calculated by its abundance (number of individuals), dominance (based on crown cover area), and frequency (the number of plots were the species is present), and is presented in percentage values. Alpha diversity estimates species richness using the species richness index (S) and community structure through dominance by the Simpson's diversity index (λ) and evenness by the Shannon-Wiener index (H') (Moreno, 2001; Magurran & McGill, 2011). The A index (Pretzsch, 2009) evaluates the vertical distribution of species in a particular stand or forest. The ESCI allows a comparison of the surface area generated by connecting the tree-top of adjacent trees to form triangles with the total area covered by these projected triangles on a plane (Beckschäfer *et al.*, 2013) (Table 1).

To study the effects of thinning on spatial distribution, the pair correlation function $g(r)$ (Stoyan & Stoyan, 1994) was used. This function is the derivative of Ripley's K function (Ripley, 1977), and is described as: $g(r) = K'(r)/(2\pi r)$, where $K(r)$ is the average number of points within a circle of radius r from an arbitrary point, divided by the point pattern intensity (Stoyan & Stoyan, 1994; Wiegand & Moloney, 2014). The K function is:

$$K(r) = \frac{A}{n(n-1)} \sum_{i=1}^{n} \sum_{j\neq 1}^{n} l_{ij}(r) e_{ij}(r)$$

Where: A is the area, l_{ij} is the count function at the specific distance (r) from the reference point, and $e_{ij}(r)$ is the edge correction factor.

For all summary statistics used in this study, isotropic correction was applied (Ripley, 1977; Stoyan & Stoyan, 1994). When $g(r)=1$, it means that the points are randomly distributed at that distance. If $g(r)>1$, it indicates that the points are clustered at that distance, and if $g(r)<1$, it means that the points are regularly distributed. To address statistical significance ($\alpha=0.05$), significance bands were generated using Monte Carlo simulations based on 199 replications of a homogeneous Poisson process, which generate random data to serve as the null model. The bands were created using the fifth highest and the fifth lowest values from these simulations.

The analyses conducted in this study were performed using R 4.1.2 (R Core Team, 2021). Specific functions were created in this language for the development of thinning

Table 1. Species Diversity Indices. Where: S represents the number of tree species; p_i is the proportion of the i-th species; ln stands for natural logarithm; Z denotes the number of vertical zones and p_{ij} is the proportion of the i-th species in each j-th vertical zone, estimated by the equation $p_{ij} = n_{i,j}/N$, where $n_{i,j}$ is the number of records of the same species (i) in zone (j) and N=total number of recorded trees.

Index	Expression
Species richness (S)	Number of species
Simpson's diversity (λ)	$\lambda = \sum p_i^2$
Shannon's entropy (H')	$H' = -\sum_{i=1}^{S} p_i * \ln(p_i)$
Species vertical distribution (A)	$A = -\sum_{i=1}^{S}\sum_{j=1}^{Z} p_{ij} * \ln p_{ij}$

simulations, and custom codes were generated for the estimation of diversity and structural indices. For the spatial analysis, the SPATSTAT library was used (Baddeley *et al.*, 2015).

RESULTS AND DISCUSSION

The experimental plot contained 2 genera and 6 species: *Pinus douglasiana* Martínez, *P. lumholtzii* Rob. & Fern., *P. oocarpa* Shiede, *Quercus resinosa* Liebm., *Q. candicans* Née, and *Q. coccolobifolia* Trel. In the initial state of the stand, a density of 573 trees per hectare and a basal area of 27.8 m^2 per hectare were recorded. The most abundant species were *Quercus resinosa* and *Pinus douglasiana* (Table 2).

Table 2. Forest stand variables of thinning scenarios in a mixed temperate forest in Jalisco, Mexico. Where: Gha^{-1} is the basal area per hectare, Vha^{-1} is the volume per hectare, Nha^{-1} stands for the number of trees per hectare, $d_{1.3}$ is the diameter at breast height, h is the total height, and T_i is the iteration or evaluated scenarios.

Variable	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5
	Pinus					***Quercus***				
Gha^{-1}	21.0	19.1	14.1	9.6	3.1	6.8	2.1	6.3	6.0	5.4
Vha^{-1}	284.5	268.8	184.5	118.7	27.7	69.4	26.7	62.6	58.6	50.1
Nha^{-1}	216.0	128.0	178.0	151.0	107.0	357.0	30.0	352.0	350.0	343.0
$d_{1.3}$ mean	31.2	41.8	27.9	24.9	17.9	14.2	28.7	13.9	13.7	13.3
$d_{1.3}$ sd	16.3	12.3	15.3	13.9	6.9	6.5	9.6	6.0	5.5	4.8
$d_{1.3}$ min	7.6	25.5	7.6	7.6	7.6	6.4	6.4	6.4	6.4	6.4
$d_{1.3}$ max	78.0	78.0	73.2	71.6	29.9	50.9	50.9	50.9	39.8	28.7
h mean	19.6	24.5	18.3	16.9	13.9	12.8	19.4	12.6	12.6	12.3
h sd	7.4	4.6	7.3	6.9	5.2	4.6	7.0	4.4	4.4	4.0
h min	4.5	14.7	4.5	4.5	4.5	4.2	5.2	4.2	4.2	4.2
h max	40.1	40.1	37.3	36.5	26.2	32.9	32.9	32.9	32.9	24.5
h dom	25.5	25.5	23.9	20.6	14.5	18.1	19.4	17.7	17.6	16.1

T1: No removal, T2: Thinning from below (T2), removal of 25% of basal area (Gha^{-1}), T3: Thinning from above (T3), removal of 25% of Gha^{-1}, T4: Thinning from above (T4), removal of 45% of Gha^{-1}, and T5: Thinning from above (T5), removal of 70% of Gha^{-1}.

The changes in the statistics of tree diameter ($d_{1.3}$) and height (h) before and after applying the different thinning scenarios showed a decrease in these metrics as the intensity of thinning increased. The basal area (Gha^{-1}) showed a similar pattern, fluctuating from 21 to 3.1 m^2 for *Pinus* and 6.8 to 2.1 m^2 for *Quercus*. The highest volume (Vha^{-1}) removed was for scenario T5 (276.1 m^3 ha^{-1}) and T4 (175.14 m^3 ha^{-1}). Scenario T2 had the least impact on Gha^{-1} (58.44 m^2 ha^{-1}) and Vha^{-1} (58.44 m^3 ha^{-1}), but it removed the highest number of trees per hectare. By targeting understory trees with $d \leq 25$ cm, T2 primarily affected young oaks, which are shade-tolerant and typically found in higher density below the main canopy. In contrast, scenario T5 primarily affected pine trees, leading to reductions in all stand indicators (Table 2).

P. douglasiana and *Q. resinosa* were identified as the species with the greatest ecological importance across the different thinning scenarios, with no significant changes observed after thinning. In contrast, *Q. candicans* and *P. oocarpa* had the lowest ecological values. Overall, there was an increase in the relative Importance Value Index (IVI) for the most represented species (Table 3).

Species richness prior to thinning was six species, which decreased to five in scenarios T3, T4, and T5 after thinning was simulated (Tables 3-4). In these scenarios, *Q. candicans* was the species that was removed. Despite this reduction in species richness, species diversity did not show apparent changes across the different thinning intensities. However, compared to T1, there was a decrease in the Shannon index (H') as the thinning intensity increased (Table 4).

The structural complexity of the forest stand decreased with increasing thinning intensity, indicating that the ESCI is particularly sensitive to silvicultural interventions. Scenario T2 showed the greatest impact on structural complexity, resulting in a 65% reduction in structural complexity. In contrast, T3 had the least impact, with only a 14% reduction, followed by T4 and T5 with 27% and 46%, respectively (Table 4).

Although silvicultural interventions are often used to regulate species composition and diversity in forest ecosystems (Latterini *et al.*, 2023), the thinning simulated in this study, did not lead to a strong decrease in species composition. Other research have documented that selective extractions can increase tree diversity and species richness over time, particularly when compared to more intensive methods (Torras & Saura, 2008). However, selective cuts may also result in the decline of old trees and negatively impact the establishment of shade-intolerant species (Jardel-Peláez, 2012).

Previous studies have demonstrated that thinning can increase structural complexity, as observed in *Pinus sylvestris* L. (Saarinen *et al.*, 2021). This contrasts with our study, where structural complexity of the stand decreased, which can be explained by the intensity and type of thinning used. Similar results have been reported in mixed pine-oak forests in Durango, Mexico, where low-intensity thinning did not significantly impact diversity and structure (Monárrez *et al.*, 2021; Delgado *et al.*, 2016).

Spatial Attributes

The results of the spatial analysis, including species and genera, illustrate the pattern of tree arrangement and are crucial for understanding forest ecosystems dynamics. Figure 2 shows the spatial distribution of the trees within the experimental plot.

Table 3. Ecological values of tree species by thinning scenario in a mixed temperate forest in Jalisco, Mexico. Where: Gha^{-1} is the Basal area per hectare (m^2), Nha^{-1} the Number of trees per hectare, RA is the Relative abundance (%), RD the Relative dominance (%), RF is the Relative frequency (%), and IVI the Importance value index (%).

Scenario	Species	Nha^{-1}	Gha^{-1}	RA	RD	RF	IVI
No removal (T1)	*P. douglasiana*	164	17	28.6	61.2	30.4	40.1
	Q. resinosa	309	5.4	53.9	19.4	30.4	34.6
	P. lumholtzii	45	3.6	7.9	13	20.3	13.7
	Q. coccolobifolia	47	1.2	8.2	4.3	15.2	9.2
	P. oocarpa	7	0.4	1.2	1.4	2.5	1.7
	Q. candicans	1	0.2	0.2	0.7	1.3	0.7
	Total	573	27.8	100	100	100	100
Thinning from below (T2) 25% removal of the Gha^{-1}	*P. douglasiana*	91	15.5	57.6	73	40	56.9
	Q. resinosa	34	3.3	21.5	15.6	23.3	20.1
	P. lumholtzii	20	1.3	12.7	6.1	23.3	14
	Q. coccolobifolia	9	0.7	5.7	3.1	8.3	5.7
	P. oocarpa	3	0.3	1.9	1.3	3.3	2.2
	Q. candicans	1	0.2	0.6	1	1.7	1.1
	Total	158	21.2	100	100	100	100
Thinning from above (T3) 25% removal of the Gha^{-1}	*Q. resinosa*	306	5.2	58.2	25.5	31.6	38.4
	P. douglasiana	132	11.2	25.1	55.2	31.6	37.3
	P. lumholtzii	38	2.8	7.2	13.8	18.4	13.1
	Q. coccolobifolia	44	0.8	8.4	4.2	15.8	9.4
	P. oocarpa	6	0.3	1.1	1.3	2.6	1.7
	Total	526	20.2	100	100	100	100
Thinning from above (T4) 45% removal of the Gha^{-1}	*Q. resinosa*	306	5.1	61	33.4	32.4	42.3
	P. douglasiana	113	6.7	22.5	43.7	31.1	32.4
	P. lumholtzii	31	2.1	6.2	13.9	17.6	12.5
	Q. coccolobifolia	46	1.1	9.2	7.3	16.2	10.9
	P. oocarpa	6	0.3	1.2	1.7	2.7	1.9
	Total	502	15.4	100	100	100	100
Thinning from above (T5) 70% removal of the Gha^{-1}	*Q. resinosa*	301	4.7	66.9	55.4	34.8	52.4
	P. douglasiana	82	2	18.2	24.3	30.4	24.3
	Q. coccolobifolia	42	0.7	9.3	8.2	15.9	11.1
	P. lumholtzii	21	0.9	4.7	10.9	15.9	10.5
	P. oocarpa	4	0.1	0.9	1.2	2.9	1.7
	Total	450	8.4	100	100	100	100

Table 4. Structure and diversity values of the residual tree stand by treatment. Where: Nha^{-1} is the number of trees per hectare and ESCI is the Enhanced Structural Complexity Index.

Scenario	**Stand structure**		**Diversity**			
			Richness	**Dominance**	**Evenness**	**Structure**
	Nha^{-1}	**ESCI**	**Species Richness (S)**	**Simpson's diversity (λ)**	**Shannon's entropy (H')**	**A Pretzsch**
T1	573	7.9	6	0.39	1.16	1.65
T2	158	2.8	6	0.40	1.18	1.82
T3	526	6.8	6	0.41	1.12	1.54
T4	502	5.8	5	0.44	1.07	1.65
T5	450	4.3	5	0.49	0.99	1.78

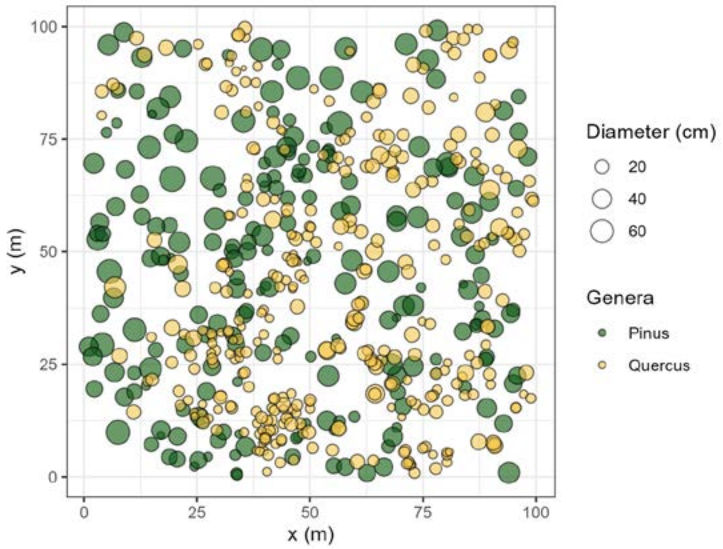
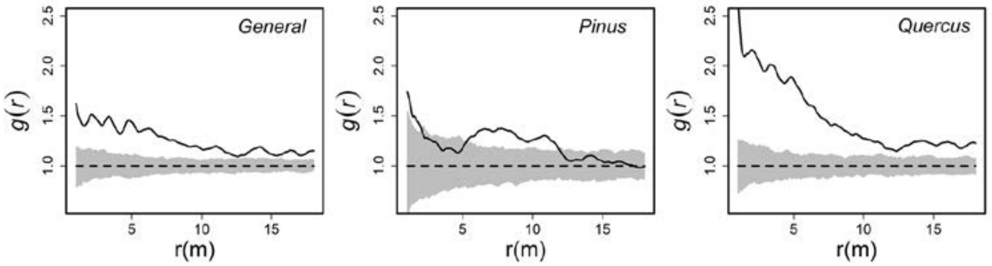


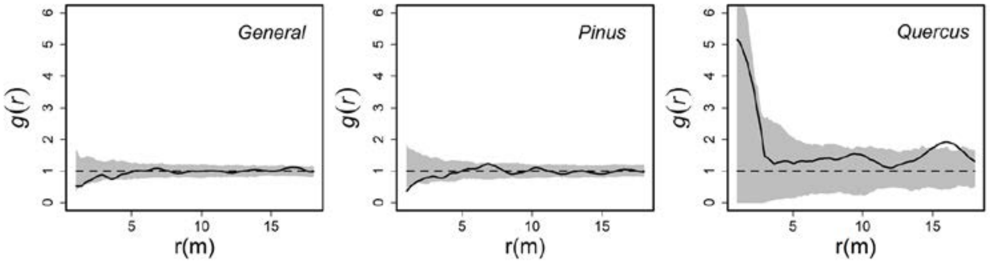
Figure 2. Spatial distribution of trees in the experimental plot. The circles represent the scale of the tree diameter and the colors indicate the genus.

The effects of thinning on spatial distribution varied according to the type and intensity of the intervention. Thinning from below (T2) significantly impacted the spatial distribution of oaks, leading to a random distribution at various scales (Figure 3b). In contrast, thinning from above had a more pronounced effect on the spatial distribution of pines (Figure 3c and Figure 3d). When analyzing all species collectively, thinning did not show significant effects. Scenario T1 resulted in a clustered distribution at different scales (Figure 3a), a pattern that was repeated in treatments T3-T5. However, T2 had a randomizing effect on the overall distribution, as the distribution of residual trees did not differ significantly from a random distribution or CSR (Figure 3b).

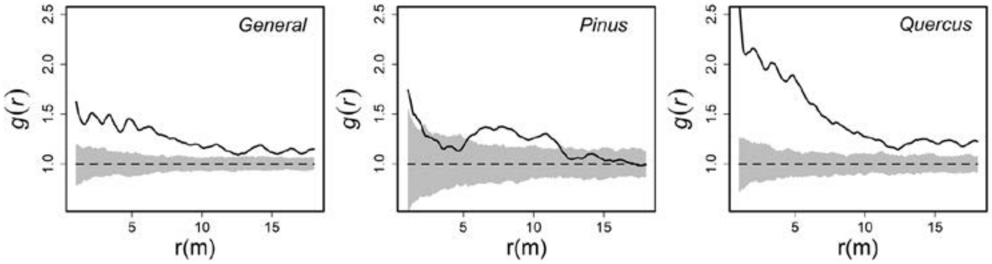
The impact of thinning on *Pinus* species was variable depending on the treatment applied. Specifically, T1 showed a clustered distribution between 4 and 9 meters, a trend that was repeated in treatment T3 and intensified in T4, increasing the clustering in the scale of 1 to 13 meters. Conversely, treatments T2 and T5 exhibited a randomizing effect, although T5 still displayed a slight clustering at a small scale of 7 to 9 meters (Figure 3e). In



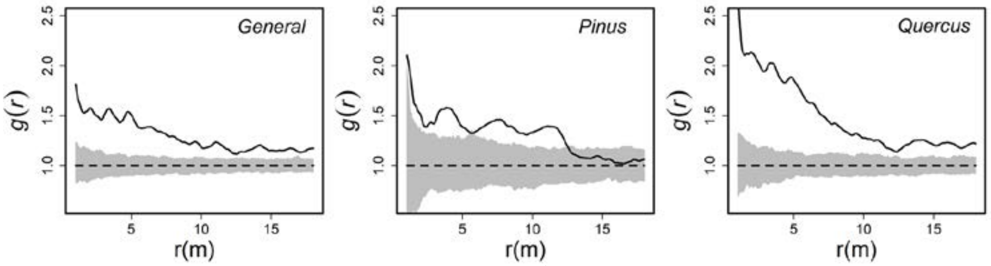
(**a**) T1 Original plot. No removal scenario.



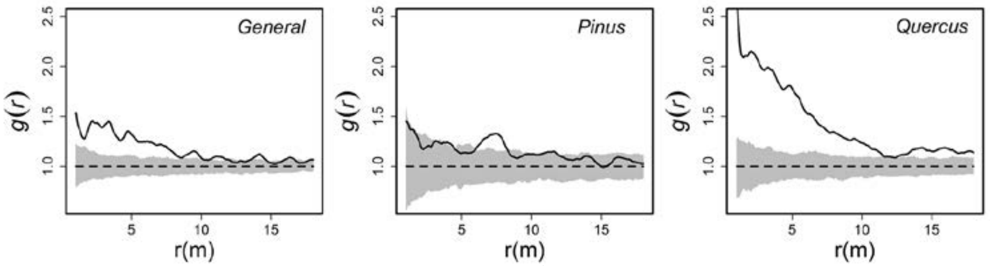
(**b**) T2 Thinning from below with removal of all trees with diameter <=25 cm.



(**c**) T3 Thinning from above, 25% removal of the Gha^{-1} (trees with diameter >=30 cm).



(**d**) T4 Thinning from above, 45% removal of the Gha^{-1} (trees with diameter >=30 cm).



(**e**) T5 Thinning from above, 70% removal of the Gha^{-1} (trees with diameter >=30 cm).

Figure 3. Spatial distribution by management scenario, where: $g(r)$ is the pair correlation function (with $g(r)=1$ indicating a random distribution, $g(r)>1$ a clustered distribution, and $g(r)<1$ indicating a regular distribution) and r denotes distance in meters.

the no-thinning scenario (T1), *Quercus* trees were clustered at all scales of analysis (0-18 m) (Figure 3a). This aggregated distribution was observed in most treatments, except for T2 (Figure 3b), where a random distribution was noted at most scales of analysis. This finding aligns with the observed effects of T2 on pines and on the overall species distribution.

In Mexico, studies have documented that forests undergoing silvicultural interventions often exhibit random distribution patterns (Corral *et al.*, 2005). Similar findings were observed in our study; for instance, T2 influenced the spatial structure of *Quercus* and *Pinus*, resulting in a random distribution of residual trees. Graciano *et al.* (2020), found that trees in five *Pinus durangensis* forest associations displayed a random distribution and high heterogeneity, which were attributed to the species composition and the management practices applied.

CONCLUSIONS

In this study, silvicultural treatments were simulated to evaluate their impact on the structure and composition of species in a temperate forest. It was concluded that the effect of thinning on the residual stand's structure depends on factors such as the type of thinning (thinning from above or from below), the initial condition of the stand, its composition, and the intensity of removal. To optimize outcomes and develop management prescriptions that balance wood production with the conservation of diversity, composition, and stand structure, it is essential to consider the ecological conditions of the study areas as well as the types of removal scenarios or silvicultural practices. Implementing silvicultural simulations in experimental research plots supports the sustainable management of forests, by allowing for the emulation of both natural and anthropogenic disturbances, which is crucial for effective forest management.

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