SEEFOR SOUTH-EAST EUROPEAN FORESTRY

OPEN ACCESS
ISSN 1847-6481
eISSN 1849-0891

ORIGINAL SCIENTIFIC PAPER

DOI: https://doi.org/10.15177/seefor.23-23

Forest Structure of *Pinus ayacahuite* in Southern Mexico: A Non-Parametric Analysis

Karla Mayté Pérez-Vásquez[1], Wenceslao Santiago-García[2,*], Gregorio Ángeles-Pérez[3], Faustino Ruiz-Aquino[2], Elías Santiago-García[4]

(1) Universidad de la Sierra Juárez, Ingeniería Forestal, Avenida Universidad s/n, 68725, Ixtlán de Juárez, Oaxaca, México; **(2)** Universidad de la Sierra Juárez, División de Estudios de Postgrado-Instituto de Estudios Ambientales, Avenida Universidad s/n, 68725 Ixtlán de Juárez, Oaxaca, Mexico; **(3)** Ciencias Forestales, Colegio de Postgraduados, Campus Montecillo, Carretera México-Texcoco km 36.5, 32910 Montecillo, Texcoco, Mexico; **(4)** Dirección Técnica Forestal de la Comunidad de Ixtlán de Juárez, Oaxaca, Carretera Oaxaca-Tuxtepec s/n, 68725 Ixtlán de Juárez, Oaxaca, Mexico

*** Correspondence:** e-mail: wsantiago@unsij.edu.mx

Citation: Pérez-Vásquez KM, Santiago-García W, Ángeles-Pérez G, Ruiz-Aquino F, Santiago-García E, 2023. Forest Structure of *Pinus ayacahuite* in Southern Mexico: A Non-Parametric Analysis. *South-east Eur for* 14(2): 149-157. https://doi.org/10.15177/seefor.23-23.

Received: 13 Sep 2023; **Revised:** 12 Dec 2023; **Accepted:** 13 Dec 2023; **Published online:** 24 Dec 2023

ABSTRACT

Spatial structure refers to the horizontal and vertical arrangement of individual trees, and the most accurate way to describe it within a community is to characterize tree strata in terms of their dimensions. The aim of this study was to determine the horizontal and vertical structure of pure stands of *Pinus ayacahuite* Ehrenb. ex Schltdl., in forests of southern Mexico. Forest measurement data from 24 sample plots were used. For analysis of the horizontal structure, diameters within a range of 0.20 cm to 77 cm were used, while for the vertical structure, heights were from 0.09 m to 40.9 m. Non-parametric histograms and Kernel density methods were used in the analysis, and Fisher and Marron multimodality tests were performed. The homogeneity of the forest stands was determined by the coefficient of homogeneity, and the vertical and horizontal structures were described using the stratification proposed by Pretzsch. The results indicate that the horizontal structure corresponds to a diameter distribution with a reversed "J" shape in 79.2% of the sample plots, while 91.8% of the sites were classified as irregular with coefficients of homogeneity of 1.0 to 3.0. In the vertical structure, it was observed that the lower stratum predominated in 75% of the plots, while 25% had a higher concentration of individuals in the middle stratum. The upper stratum had accumulation percentages ranging from 1.3% to 33.3% but did not predominate in any of the plots. According to the multimodality tests, 50% of the plots present multimodality in the horizontal structure, while in the vertical structure this condition is present in 38% of the plots. Knowledge of the spatial structure of *Pinus ayacahuite* forest stands is essential to define silvicultural strategies that ensure the sustainable functioning of the ecosystem in terms of yield continuity and conservation.

Keywords: *Pinus ayacahuite*; tree stratum; non-parametric methods; irregular forest stands

INTRODUCTION

A managed forest is a biological system that undergoes constant change due to natural processes and applied silvicultural activities (García 1988). Silviculture is a tool for sustainable management of species. Silvicultural practices modify the diversity of forest stands, as well as the spatial mixture of trees, natural regeneration, and size distribution (Del Río et al. 2003, Gadow et al. 2012). In addition to silvicultural treatments, factors such as competition for resources, patterns of regeneration, mortality, differential growth, topographic and climatic variations, soil quality, and interactions between species cause variations in the distribution of tree sizes in forests (Coomes and Allen 2007).

The structure of a forest ecosystem refers to the spatial distribution of the main tree characteristics, and the distribution of species by dimension classes is of special importance (Gadow and Hui 1998, Aguirre et al. 2009, Li et al. 2014). The importance of characterizing and quantitatively measuring the structure of forest stands lies in the fact that it provides an understanding of how the ecosystem functions. This is a fundamental aspect that must be considered to understand productivity and make decisions within sustainable forest management (Jiménez et al. 2001, Aguirre et al. 2003, Araujo et al. 2008).

Spatial structure refers to the horizontal and vertical arrangement of individual trees, and the most appropriate and precise way to describe it within a community is to characterize tree strata from the viewpoint of their dimensions (Gadow and Hui 2001). The most used variables to represent the spatial structure of a forest stand are the heights and diameters of the individuals present in it (Corral-Rivas et al. 2019, Guzmán et al. 2019). Horizontal structure is often evaluated in terms of diameter, although basal area or canopy cover can also be used. The vertical structure is assessed using the heights of the trees that constitute the specific study area (Moret et al. 2008). The methods for describing spatial structure can be parametric or non-parametric, of these methods, density functions, such as frequency histograms and Kernel estimators, are outstanding because of their simplicity and ease of interpretation (Pogoda et al. 2020).

In the Sierra Norte region of Oaxaca, in southern Mexico, studies of diversity and structural composition have been conducted to characterize mixed forest stands and *Pinus patula* Schltdl. *et* Cham. (Castellanos et al. 2008, Castellanos-Bolaños et al. 2010, Vásquez-Cortez et al. 2018, Martin et al. 2021). However, it is important to understand quantitative aspects of the dynamics of other species that hold economic, ecological, and social value within forest management. The aim of this study was to determine the horizontal and vertical structure of *Pinus ayacahuite* Ehrenb. ex Schltdl. stands, considering the diameter and height of the individuals as analysis variables.

MATERIALS AND METHODS

The study was conducted in the communal forests of Ixtlán de Juárez, Oaxaca, southern Mexico. This area is geographically located between the coordinates of 17°23'0.50''–17°23'0.58'' N and 96°28'45''–96°28'53'' W. The region falls within the physiographic province known as the Northern Oaxaca Mountain System (Figure 1). The predominant type of vegetation in this region corresponds to pine-oak forests, which were described as heterogeneous by Castellanos-Bolaños et al. (2010). The natural distribution area of *Pinus ayacahuite*, where the study took place, spans an altitudinal range of 2,600 m to 3,100 m and covers an area of 962.85 hectares. The predominant climates are temperate sub-humid with summer rains and temperate humid with summer rains (STF 2015).

In the establishment of the sampling plots, sub-stands were selected without the presence of forest pests, diseases, traces of fires, or any other disturbances. They were pure stands, meaning that the dominant species was *Pinus ayacahuite*. The sampling plots were squares of 400 m^2 each, divided into four quadrants of 10 m × 10 m, and numbered clockwise. Each plot was established facing north and had five control points: one at each vertex and one in the center. All living trees found within the sampling plot were labeled, starting with the tree closest to the center and continuing until reaching the furthest tree.

The forest variables measured in the field and used for analysis of the structure were the following: diameter at breast height of all the individuals (D, cm) measured with a Haglöf Sweden® tree caliper; diameter at the base (DB, cm) of individuals that did not reach a height of 1.30 m, using a Scala® vernier caliper; total height (H, m) of a representative sample of trees, which included individuals of all diameter classes, obtained with a digital clinometer (Haglöf Sweden®); and the height of the individuals whose diameter at the base was measured with a professional Pretul® flexometer.

With the data obtained, the following stand variables were determined: number of trees per hectare (N ha^{-1}); basal area per hectare (BA, m^2·ha^{-1}) derived from the individual basal area, which was obtained with the expression $BA=\frac{\pi}{40000}\times D^2$; mean height and diameter of

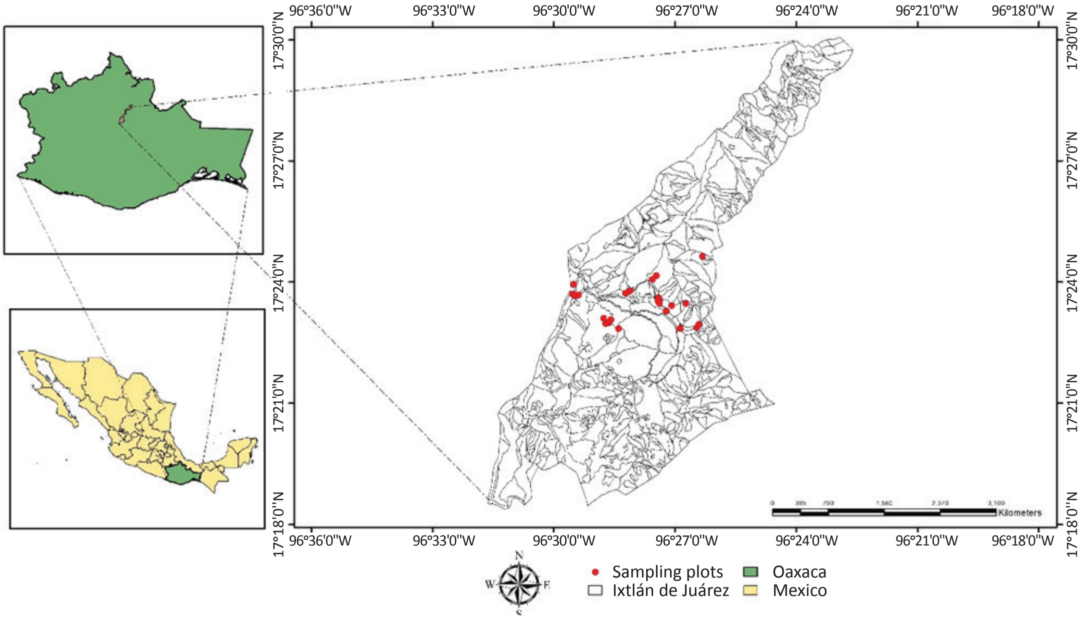

Figure 1. Geographic location of the study area and the sampling plots.

the dominant trees (HD, m; DD, m); and finally, quadratic mean diameter (Dq, cm) $Dq=\sqrt{\frac{40000}{\pi}\times\frac{BA}{N}}$ using the formula (Santiago-García et al. 2013, Pérez-López et al. 2019).

To estimate the heights that were not measured in the field, different documented models for the species were used: *Abies guatemalensis* Rehder, *Alnus acuminata* Kunth, *Arbutus xalapensis* Kunth, *Clethra lanata* M. Martens & Galeotti, *Litsea glaucescens* Kunth, *Pinus ayacahuite*, *P. douglasiana* Martínez, *P. oaxacana* Mirov, *P. patula*, *P. pseudostrobus* Lindl., *P. rudis* Endl, *Quercus* spp., *Clethra mexicana* DC. and other broadleaf species present in the sampling plots (STF 2015, López-Villegas et al. 2017, Santiago-García et al. 2020).

To determine the horizontal structure, the diameters at breast height and diameters at the base were used, and for the vertical structure, the heights observed in the field and those estimated with the height-diameter models were used (Table 1).

In the analysis, histograms and Kernel plots were created for distributions of diameters and heights per sampling unit and for the totality of the data. Pooled and unpooled data by diameter class were used. The statistical programs used were SAS® 9.4 (SAS Institute Inc. 2017) for histograms and Kernel of the grouped data (using the UNIVARIATE and KDE procedures) and RStudio® (R Core Team 2019) for Kernel graphs on non-grouped data (using the DENSITYPLOT function).

To determine the homogeneity of the stands, the homogeneity coefficient (CH) was used, which represents the percentage relationship between the number of trees and the volume, both stratified by diameter classes (De Camino 1976). Authors such as Corral et al. (2005) and Solís et al. (2006) demonstrated that the coefficient of homogeneity can be estimated with equal precision when using the basal area; therefore, due to the number of species present in the plots, this variable was chosen as a volume surrogate for the calculation of CH, through the following expression (Equation 1):

$$CH=\frac{\sum_{i=1}^{n} SN\%}{\sum_{i=1}^{n} SN\% - SBA\%} \qquad (1)$$

where CH is the coefficient of homogeneity; n is the number of diameter classes; SN% is the sum of the percentages of the number of trees up to diameter class i; and SBA% is the sum of the percentages of the basal area up to diameter class *i*.

The description of the vertical and horizontal structures includes the stratification proposed by Pretzsch (1996), which consists of three strata: stratum I, or superior, with heights and diameters ranging from 80% to 100% of the maximum values of the site; stratum II, or middle, ranging from 50% to 80%; and stratum III, or lower, ranging from 0% to 50%. Furthermore, we analyzed the number of modes for the distribution of heights and diameters using the Fisher and Marron multimodality test with the statistical software RStudio® (R Core Team 2019), under the hypothesis that the height and diameter distribution in the plot is unimodal.

RESULTS AND DISCUSSION

In 79.2% of the plots, a diameter distribution in the form of an inverted "J" or negative exponential was found. In these plots, a greater proportion of individuals with small diameters can be observed; this proportion decreases as the size of the diameter increases (Figure 2a and Figure 2b). Although 20.8% of the remaining plots exhibited a regular distribution, a slight displacement of data towards smaller diameter categories can be observed, resulting in a left-sided distribution (Figure 2c). Gadow et al. (2007) mention that inverted J-shaped curves are typical of diameter distributions of irregular forest stands.

The general irregularity of *Pinus ayacahuite* stands was observed when comparing the 24 sampling plots in Kernel density graphs and a histogram generated from the diameters of all the individuals inventoried (Figure 2). Through graphic analysis, it was possible to determine that the highest densities of individuals were concentrated in diameter classes smaller than 25 cm, with modes ranging from 0.9 cm to 23 cm in the sampling units.

Because of the left-sided asymmetry observed in 79.2% of the plots, we can assume that the *Pinus ayacahuite* stands have a high level of regeneration. Ramirez et al. (2019) characterized the stand structure of a community near Ixtlán de Juárez and found an inverted "J"- shape of the diameter distribution, describing the stands as mature growing systems. It is necessary to consider that the age and size of the trees are not always closely related; this happens more frequently in tolerant species, such as *P. ayacahuite*, which has slower growth than other species of the genus *Pinus* in the study area and incorporates more individuals in lower diameter classes due to the good survival capacity in young stages, leading to the development of an irregular-type structure (Newton 2007, Soto et al. 2010). Restrepo et al. (2012) mention that this structure is the best guarantee of survival in the forest community because taller trees are eliminated and replaced without difficulty by smaller and presumably younger ones.

The horizontal characterization made with histograms and Kernel density graphs confirms the heterogeneity of the

Table 1. Descriptive statistics of data used to determine the horizontal and vertical structure of *Pinus ayacahuite* stands**.**

Variable	n	Mean	Minimum	Maximum	Standard deviation
D	1162	19.610	0.20	77.0	14.706
DB	157	0.842	0.20	2.8	0.526
H	1319	13.204	0.09	40.9	9.142

n - number of trees; D - diameter at breast height (cm); DB - diameter at the base (cm); H - total height (m).

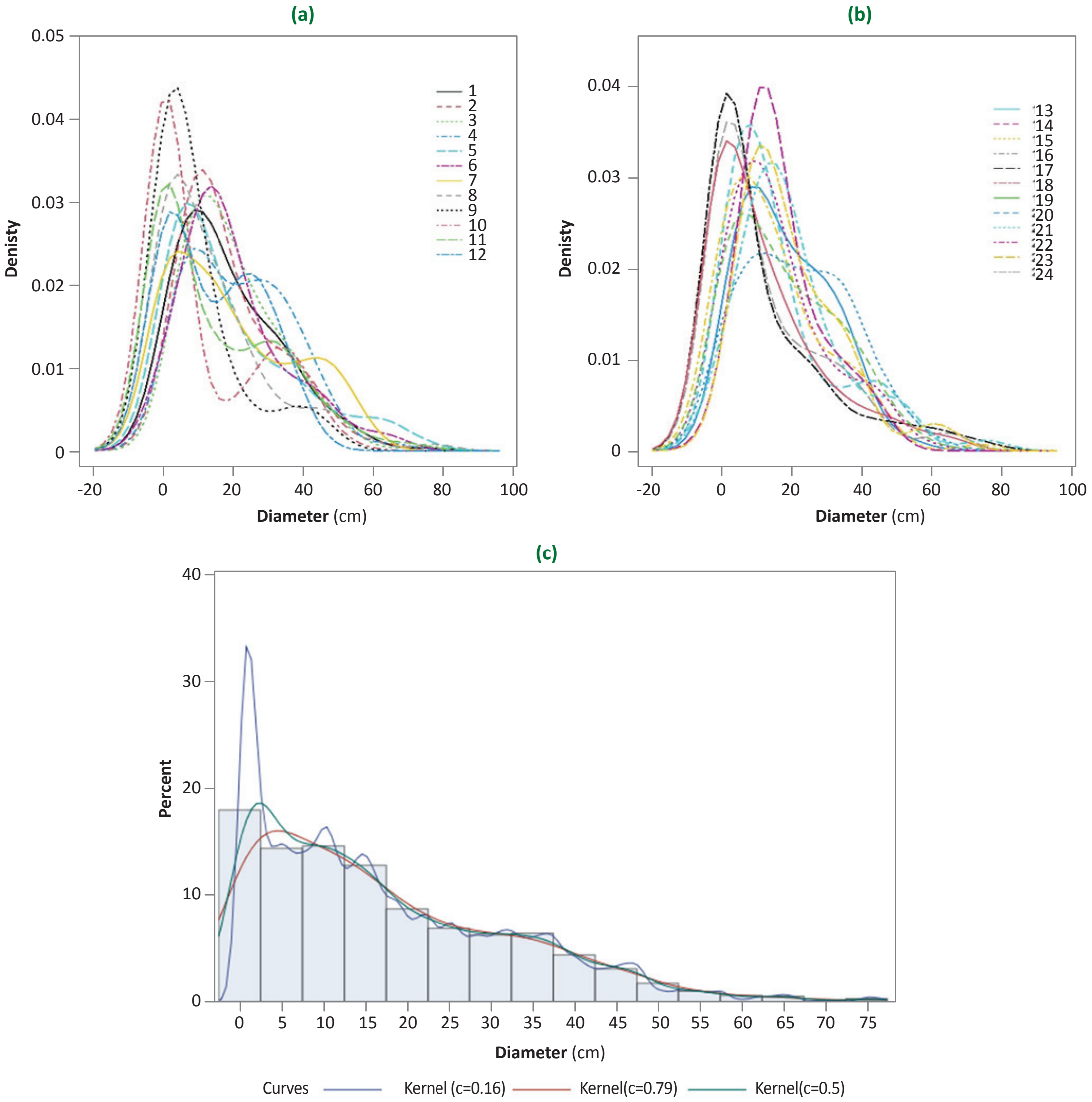

Figure 2. Diameter distributions. **(a)** and **(b)** Diameter distributions of the 24 sampling plots in Kernel density graphs; **(c)** Histogram of the diameter distribution of all the individuals in the 24 sampling plots.

stands of *Pinus ayacahuite*. De Camino (1976) affirms that the coefficient of homogeneity CH varies between one and infinity, with a value of 1.0 indicating complete heterogeneity, and an increase represents an approach towards homogeneity. The CH values obtained fluctuated in the range of 1.51 to 3.55 and were represented with the Lorenz curve, which shows that, as the value of CH decreases, the curve moves further away from the line of maximum homogeneity (Figure 3) (De Camino 1976, Del Río et al. 2003).

Based on the classification established by De Camino (1976), 91.8% of the sites correspond to an irregular forest (CH=1.0-3.0) with values ranging from 1.51 to 2.84. In the transition category (CH=3.1-3.5), only 4.1% of the sites were found with a coefficient of 3.10, and 4.1% were defined as regular forest (CH>3.5) with a value of 3.55.

The stratification for the vertical structure was as follows: the lower stratum (stratum III) predominated in 75% of the plots; the middle stratum (stratum II), present in 25% of the sites, had a concentration of individuals ranging from 41.7% to 57.7%; and the percentages of accumulation in the upper stratum (stratum I) varied from 1.3% to 33.3%, but it did not predominate in any of the plots (Table 2).

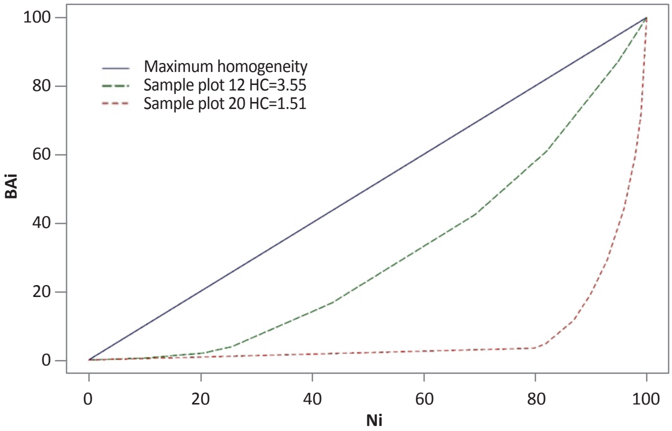

Figure 3. Comparison of the Lorenz curves for the sites with the minimum and maximum values of the coefficient of homogeneity CH. Ni represents the cumulative percentage of the number of trees; and BAi represents the cumulative percentage of basal area.

Table 2. Distribution of individuals by stratum and maximum height of each plot.

Sample plot	Maximum height (m)	Stratum I		Stratum II		Stratum III		Total individuals	
		(Nah)	(%)	(Nah)	(%)	(Nah)	(%)	(Nah)	(%)
1	34.90	6	7.8	17	22.1	54	70.1	77	100
2	30.10	6	9.0	17	25.4	44	65.7	67	100
3	30.80	6	13.0	19	41.3	21	45.7	46	100
4	29.26	13	33.3	11	28.2	15	38.5	39	100
5	40.90	8	18.2	8	18.2	28	63.6	44	100
6	36.87	3	5.8	17	32.7	32	61.5	52	100
7	29.13	8	27.6	13	44.8	8	27.6	29	100
8	32.40	8	19.5	16	39.0	17	41.5	41	100
9	34.51	9	14.8	11	18.0	41	67.2	61	100
10	30.10	7	17.5	14	35.0	19	47.5	40	100
11	30.82	12	30.8	19	48.7	8	20.5	39	100
12	28.43	8	20.5	22	56.4	9	23.1	39	100
13	35.80	7	13.2	12	22.6	34	64.2	53	100
14	33.82	2	4.3	9	19.6	35	76.1	46	100
15	36.26	3	6.3	10	20.8	35	72.9	48	100
16	28.00	11	22.9	20	41.7	17	35.4	48	100
17	29.43	3	6.3	20	41.7	25	52.1	48	100
18	27.15	2	4.9	9	22.0	30	73.2	41	100
19	28.68	11	20.4	21	38.9	22	40.7	54	100
20	28.30	4	1.3	7	3.1	213	95.5	224	100
21	29.35	7	17.1	18	43.9	16	39.0	41	100
22	27.33	8	14.0	17	29.8	32	56.1	57	100
23	25.77	7	26.9	15	57.7	4	15.4	26	100
24	28.87	17	28.8	14	23.7	28	47.5	59	100

Nah - number of trees

In addition to the height stratification, Table 3 presents the results of diameter stratification for each measurement plot.

The lower stratum predominated in 95.8% of the plots, reaffirming the high level of individuals in juvenile and regeneration stages, as can be seen in the inverted "J" shaped diameter distribution (Figure 2). In only one plot was the intermediate stratum dominant, with a 53.8% concentration of individuals. Diameter stratification generally coincides with height stratification.

Through the histograms and Kernel density graphs of the vertical structure, we observed that nine sampling plots have more than one mode, which was verified with the Fisher and Marron statistical multimodality test (R Core Team 2019). According to this test, 62% of the sites exhibit a unimodal height distribution (Table 4). It is important to highlight that these unimodal distributions were found only in the lower stratum, indicating sites where regeneration is occurring.

By plotting the heights of all 24 sample plots and comparing their distributions, we can easily discern the data grouping in the lower and middle strata. The presence of individuals taller than 30 m is rarer (Figure 4) because the upper stratum was not predominant in any plot. The number of modes and the asymmetry in the graphs help to identify the strata and allow us to infer whether the stands are in a juvenile or mature state (Gadow et al. 2007).

The abundance of individuals in the lower stratum is attributed to the tolerance of *Pinus ayacahuite*, as the survival rate in juvenile stages is high despite not receiving direct sunlight, which results in slow growth (Valladares et al. 2004). However, with greater light availability, regeneration may be favored, as observed in one sampling site (plot 20), where the concentration of individuals in the lower stratum was higher compared to the rest of the plots. This is attributed to its proximity to a clearcutting stripe.

Table 3. Distribution of individuals by stratum, minimum and maximum diameter of each plot.

Sample plot	Maximum diameter (cm)	Minimum diameter (cm)	Stratum I		Stratum II		Stratum III		Total individuals	
			(Nah)	(%)	(Nah)	(%)	(Nah)	(%)	(Nah)	(%)
1	57.6	1.6	2	2.6	13	16.9	62	80.5	77	100
2	47.8	1.4	6	9.0	8	11.9	53	79.1	67	100
3	75	4.5	1	2.2	4	8.7	41	89.1	46	100
4	65.5	1.1	1	2.6	12	30.8	26	66.7	39	100
5	74.8	0.2	5	11.4	5	11.4	34	77.3	44	100
6	66.8	5.6	3	5.8	4	7.7	45	86.5	52	100
7	57.2	5.0	7	24.1	6	20.7	16	55.2	29	100
8	77.0	5.0	1	2.4	7	17.1	33	80.5	41	100
9	48.0	1.6	8	13.1	7	11.5	46	75.4	61	100
10	51.7	0.4	4	10.0	14	35.0	22	55.0	40	100
11	57.5	0.8	3	7.7	16	41.0	20	51.3	39	100
12	41.5	3.0	7	17.9	21	53.8	11	28.2	39	100
13	60.5	0.3	6	11.3	10	18.9	37	69.8	53	100
14	76.0	6.2	1	2.2	2	4.3	43	93.5	46	100
15	64.1	1.5	3	6.3	7	14.6	38	79.2	48	100
16	55.0	3.5	1	2.1	12	25.0	35	72.9	48	100
17	51.0	0.4	3	6.3	10	20.8	35	72.9	48	100
18	54.0	4.1	2	4.9	5	12.2	34	82.9	41	100
19	58.7	0.6	3	5.6	13	24.1	38	70.4	54	100
20	70.0	0.2	1	0.4	3	1.3	220	98.2	224	100
21	52.9	3.6	4	9.8	12	29.3	25	61.0	41	100
22	53.2	1.7	2	3.5	11	19.3	44	77.2	57	100
23	52.3	8.3	3	11.5	8	30.8	15	57.7	26	100
24	50.7	3.4	6	10.2	14	23.7	39	66.1	59	100

Nah - number of trees

Table 4. Multimodality in horizontal and vertical structures of the 24 sample plots.

Variable	Number of plots with multimodal distribution	Proportion
Diameter	12	50%
Height	9	38%

Terborgh (1985) points out that forests have multiple vertical strata, which vary in number depending on the latitude of the stand's location, as this determines the angle of penetration of the sun's rays into the understory. According to Parker (1997), the light demand of the species is the reason they are arranged in different positions along the vertical profile of the forest since light intensity decreases as it penetrates towards the lower levels of the canopy. In this way, species that demand more light are positioned in higher canopies, while more shade-tolerant species tend to be positioned at lower heights within the forest (Donoso 1993, Parker and Brown 2000).

Oyarzún et al. (2019) state that vertical heterogeneity corresponds to the degree of dispersion of trees at different canopy heights and determined that, in forests with a temperate climate, functionally tolerant species such as *Amomyrtus luma* and *Myrceugenia planipes* are distributed in the lower canopy with a bimodal distribution, a description that coincides with the characteristics of the species and the vertical structure described in this research.

The graphs of the vertical structure exhibit behavior similar to those of the horizontal structure, demonstrating the efficiency of calculating heights from allometric models that facilitate the data collection phase, as suggested by Gadow et al. (2007).

The structural characterization of *Pinus ayacahuite* allows planning silvicultural treatments to control stand dynamics and achieve objectives of forest management. It is important to consider regeneration and incorporation into different diameter classes to ensure the permanence of the species and continuous yields while protecting the canopy in accord with its tolerance and light demand. The structure of the forest stand is crucial for promoting biodiversity, regulating the water cycle, storing carbon, and resisting disturbances, as well as for providing forest products and services. Therefore, managing, and conserving forests while considering their structure is essential to guarantee their health and sustainable functioning.

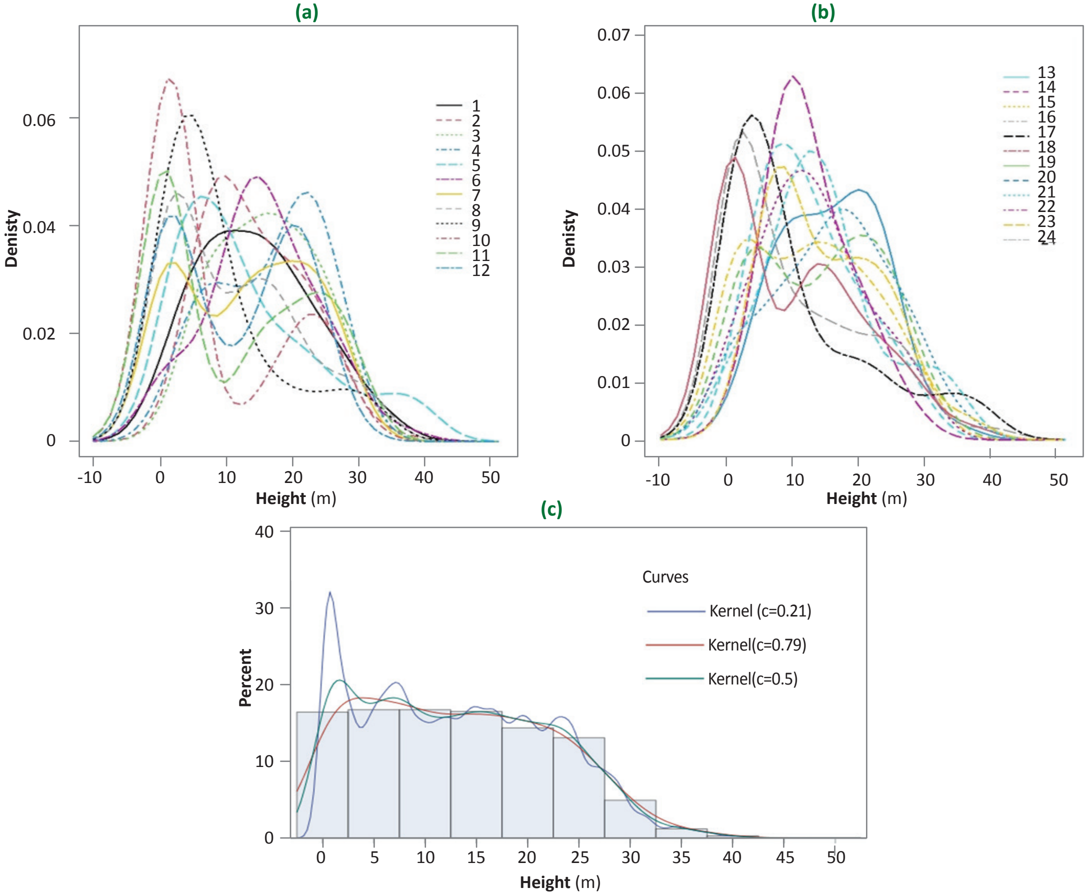

Figure 4. Height distributions: **(a)** and **(b)** Comparison of Kernel density graphs of the heights of the 24 plots; **(c)** Histogram of heights of all individuals.

CONCLUSIONS

The horizontal structure of *Pinus ayacahuite* stands exhibited a reversed "J"-shape in 79.2% of the sampling plots. Therefore, these forest stands can be described as irregular, with a greater number of individuals in lower diameter classes, which decreases as diameter increases. Based on the homogeneity coefficients obtained and following the classification established by De Camino, *Pinus ayacahuite* stands were defined as heterogeneous and irregular, with values ranging from 1.51 to 3.55. In 75% of the sampling plots, the vertical structure showed a higher concentration of trees in the lower stratum, while in the remaining 25%, individuals in the middle stratum predominated. Individuals taller than 30 meters were few; thus, the upper stratum had concentrations that varied from 1.3% to 33.3%. For both the horizontal and vertical structure, the concentration of individuals in lower classes resulted in positive asymmetry, indicating that *Pinus ayacahuite* exhibits a characteristic behavior of a species with a tolerant temperament, especially in the early stages of growth. This data grouping also demonstrates that this species has high potential for regeneration and incorporation of individuals into different diameter classes, resulting in an irregular structure. Frequency histograms and Kernel density graphs are non-parametric methods that provide an alternative for describing spatial structure. They offer advantages such as speed and ease of data interpretation. These tools highlighted the strong relationship between the diameters and heights of the individuals because the data distribution was similar. The results documented in this study regarding the horizontal and vertical structure, contribute to our understanding of size distribution and stratification of the species *Pinus ayacahuite* in southern Mexican forests. This knowledge is relevant for decision-making to achieve sustainable forestry management.

Author Contributions

WSG conceived and designed the research, KMPV, WSG and ESG carried out the field measurements, KMPV and WSG processed the data and performed the statistical analysis, GAP, FRA and ESG supervised the research and helped to draft the manuscript, KMPV, WSG, GAP, FRA and ESG wrote, reviewed, and edited the manuscript. All authors read and approved the final manuscript.

Funding

This research received no external funding.

Acknowledgments

We are infinitely grateful to the community of Ixtlán de Juárez and the forestry technical team for the facilities granted to carry out this study.

Conflicts of Interest

The authors declare no conflict of interest.

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