Modulus of elasticity in standing trees of Pinus montezumae Lamb., using non-destructive testing

Xuxan Alyn Rosas Ramos
Chapingo Autonomous University
Ma. Amparo Máxima Borja de la Rosa
mborjad@chapingo.mx
Chapingo Autonomous University
Roberto Machuca Velasco
Chapingo Autonomous University
Alejandro Corona Ambriz
Chapingo Autonomous University
Liliana Cuapio Hernández
Chapingo Autonomous University

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Abstract

Non-destructive testing applied to the study of the mechanical properties of wood in standing trees has grown significantly in recent years due to the implementation of non-invasive techniques and technologies that do not require the felling of trees for their evaluation. Therefore, the objective of this study was to evaluate the dynamic modulus of elasticity and structural wood quality in standing trees of *Pinus montezumae* Lamb. An acoustic method was used by measuring the ultrasound time of flight for seventy trees with an average age of 74 years, the sensors were placed oppositely at 1.30 m for the transverse section, while for the longitudinal sections the sensors were placed alternately every 2 m. It was found that for *P. montezumae* Lamb, the dynamic modulus of elasticity for the 0–2 m and 2–4 m longitudinal sections at 12% moisture content was 6149.1 and 7039.1 MPa, respectively. Statistically significant differences were also found for the longitudinal dynamic modulus of elasticity (p-value < 0.05). It is concluded that for the study area, the high longitudinal section (2–4 m) allows obtaining structural wood of higher quality compared to the low section (0–2 m).

1 Introduction

The study of the mechanical properties of wood is generally carried out through the application of traditional techniques, most of which conduct to the total or partial destruction of the materials under study (Chavesta et al. 2019). Depending on the damage that these methods or techniques cause to the materials, they are grouped into 1. Non-destructive testing (NDT), 2. Semi-destructive testing (SDT), and 3. Destructive testing (DT) (López et al. 2023).

The non-destructive evaluation applied to the analysis of wood properties emerged due to the growing need to solve practical problems through tests that do not compromise the integrity of individuals. This approach enables the study of the physical and mechanical properties of both standing trees and other wood products without affecting their structure or compromising their final use capacity. Consequently, this type of assessment has proven to be useful and beneficial, especially for the forestry industry (Bucur 2005; Uzcategui et al. 2023; Yang et al. 2002).

Within non-destructive testing (NDT), acoustic or ultrasound tests are commonly used tools to assess the physical and mechanical properties of standing wood, primarily for determining the modulus of elasticity (Schimleck et al. 2019).

Wood subjected to loads exhibits a behavior known as viscoelastic. This means that, upon the application of a load below the elastic limit, it will deform, losing this deformation when the applied load ceases (Vignote and Martínez 2006). The relationship between the applied stress and the resulting deformation is known as the modulus of elasticity (Oxford University Press 1998).

The modulus of elasticity (MOE), also known as strength of wood, is one of the most important mechanical properties and is the most used indicator of wood's capacity to resist bending and support loads (Amishev and Murphy 2008). In wood, two types of elasticity modulus can be determined: static (MOEe) and dynamic (MOEd). The dynamic modulus is an intensive magnitude that represents the amount of elastic energy that a volume of wood can store (Sotomayor and Villaseñor 2016).

For the assessment of the dynamic modulus of elasticity, devices are used to facilitate the travel of acoustic waves through the wood and record the time or velocity of transit of these waves. This, combined with the density of the wood, allows its determination (Soto et al. 2012).

Several authors have studied the use of non-destructive methods based on the transmission of acoustic waves to determine the mechanical properties of wood. In Mexico, notable research has been conducted by Sotomayor Castellanos on the use of non-destructive methods for the mechanical characterization of wood through trans-verse vibrations, static bending, stress waves, and ultrasound (Sotomayor 2014; Sotomayor and Ramírez 2015; Sotomayor et al. 2021; Macedo and Sotomayor 2021).

However, for *Pinus montezumae* Lamb., there are currently no studies addressing the investigation of wood properties, such as the modulus of elasticity, in standing trees through non-destructive testing with ultrasound techniques. Therefore, the objective of this study was to assess the dynamic modulus of elasticity and wood quality for structural use in *P. montezumae* Lamb. trees from a temperate forest located in Milpa Alta, Mexico City, using an acoustic method.

2 Materials and methods

2.1 Study Area

The study area is located in The Communal Lands of Santa Ana Tlacotenco, Milpa Alta, Mexico City, specifically in the area known as Temetlatitla located between coordinates 19°06' 51.57" N and 98°59' 06.59" W (Fig. 1). The total study area was 35.27 hectares, with an altitudinal range from 3271 to 3348 m above sea level. The main types of vegetation are represented by pine forest and mixed forest (pine-oak) (Rodríguez and López 2006).

2.2 Experimental design

A sampling intensity of 10% was applied, resulting in a sampling area of 3.5 hectares. Once the sampling area was determined, sampling sites were generated by creating a systematic grid with square plots of 0.25 hectares, from which 14 sites were randomly selected (Fig. 1).

The sample size was calculated using the following equation (Lohr 2021):

$$n = \frac{N\sigma^2}{(N-1)\frac{B^2}{4} + \sigma^2}$$

1

where: n = sample size, N = population size, σ2 = sampling variance and B = estimation error.

The calculation of the population size (N) was based on the determination of tree density in the study area (52 trees per hectare), resulting in a population size of 1820 trees. The sample variance was calculated from the measurement of ultrasound flight time for a pre-sample of 20 trees, resulting in a sample variance of 6937.12. The established estimation error was 20 microseconds. The sample size (n) for the study area was 70 trees.

2.3 Time of flight measurement and collecting wood samples

The flight time was measured using the portable instrument Fakopp Microsecond Timer® for 5 randomly selected trees at each sampling site, with an average age of 74 years. Data collection took place from March to June 2023, and flight time measurements were taken in both the transverse and longitudinal axes of the trees. The measurement in the transverse axis was performed by placing the sensors oppositely at a height of 1.30 m, taking three repetitions with the device. The measurement in the longitudinal axis was conducted for two height sections, the first leaving 20 cm from the base of the tree to 2 m, and the second from 2 m to 4 m, placing the sensors alternately and taking three repetitions with the device.

Additionally, increment cores were extracted using the Haglöf® incremental borer or Pressler borer with an inner diameter of 12 mm for 3 trees out of the 5 previously selected, obtaining a total of 42 increment cores. Likewise, measurements of dendrometric variables, including diameter at breast height, total height, and height of the first branch, were carried out.

2.4 Determination of ultrasonic velocity, wood density and dynamic modulus of elasticity

The ultrasonic velocity (Vus) was calculated based on the distance between the sensors and the flight time.

The determination of wood density at 12% moisture content was carried out based on the estimation of anhydrous density (ρ_0). For this purpose, the increment cores were sectioned every 5 growth rings, and then they were dried in a Memmert® UN110 oven at a temperature of 103 ± 1°C until reaching a constant weight. Subsequently, the sections were weighed on an analytical balance with a precision of 0.01, and the anhydrous volume was determined by water displacement method (Archimedes' principle) (Valencia and Vargas 1997). The anhydrous density (ρ_0) was obtained as the ratio of weight to anhydrous volume.

Based on the anhydrous density data, the determination of wood density at 12% moisture content was calculated using the following equation (Kollmann, 1959).

$$\rho_{12} = \rho_0 \frac{1 + 0.12}{1 + 0.84 * \rho_0 * 0.12}$$

2

where: ρ_{12} = wood density at 12% moisture content and ρ_0 = anhydrous density (kg m^{-3}).

Dynamic modulus of elasticity for the cross-sectional and longitudinal sections was calculated using the following equation (Ettelaei et al. 2019).

$$E_{us} = \rho_{12} V_{us}^2$$

3

Where: E_{us}= dynamic modulus of elasticity (N m^{-2}), ρ_{12} = wood density at 12% moisture content (kg m^{-3}) and V_{us}= ultrasonic velocity (m s^{-1}).

2.5 Transformation of elasticity modulus at 12% moisture content

The adjustment of density at 12% moisture content was carried out for the longitudinal section from 2 to 4 m, considering data from a study on *Pinus sylvestris* regarding the variation of wood density with tree height (Gutiérrez-Oliva et al. 1997). Based on this study, a 4.3% decrease in density was determined for the longitudinal section from 2 to 4 m compared to the longitudinal density from 0 to 2 m.

The obtaining of the elasticity modules at 12% moisture content was carried out by transforming the ultrasound velocities in the green state using the graph of ultrasound velocity as a function of moisture content for *Pinus douglasiana* wood (Sotomayor 2015). Additionally, a linear regression model predicting the ultrasonic wave velocity with Fakopp from measurements with Sylvatest, as well as the average velocity recorded by Sylvatest for the longitudinal section of three pine species (*Pinus sylvestris, Pinus pinaster*, and *Pinus radiata*), was considered (Acuña et al. 2007). With this data, a theoretical graphical model was generated for the ultrasound velocity for *P. montezumae* Lamb., accepting the same trend as Sotomayor (2015) from 0% humidity to the maximum wood moisture obtained from the formula of Kollmann (1959). From this wood, an increase of 1718 m s^{-1} in ultrasound velocity from the green state to 12% wood moisture was obtained.

2.6 Statistical analysis

The data analysis was performed using the R statistical package (R Core Team 2023). Descriptive statistics were obtained for the variable's height, diameter at breast height, density at 12% moisture content, ultrasound velocity, and elasticity modulus in the green state and at 12% moisture content.

The Lilliefors normality test (Kolmogorov-Smirnov) was applied to the longitudinal elasticity modules at 12% moisture content, which showed a non-normal distribution (p-value < 0.05).

To test the equality of variances of the longitudinal elasticity modules from 0 to 2 m and from 2 to 4 m at 12% moisture content, the Levene test was applied, demonstrating homoscedasticity of variances (p-value > 0.05).

To detect statistically significant differences between the elasticity modulus for the two longitudinal sections at 12% moisture content, the robust method of Wilcoxon Signed-Rank for non-normal and homoscedastic paired samples was applied.

The comparative analysis of elasticity modulus between sampling sites for the two longitudinal sections consisted of applying the non-parametric Kruskal-Wallis test with a significance level α of 0.05 and the Post Hoc Kruskal-Wallis test with Bonferroni correction, due to the non-compliance with normality for all sampling sites through the Shapiro-Wilk test (p-value < 0.05), and compliance with homoscedasticity for all sites through the Levene test (p-value > 0.05).

Grading structural timber was carried out for the two longitudinal sections through the elasticity modulus at 12% moisture content, for which three categories were established: 1. Unsuitable for structural use for values below 6000 MPa, 2. Structural B for values between 6000 to 8000 MPa, and 3. Structural A for modulus greater than 8000 MPa, considering the specified values for the average elasticity modulus for coniferous species established in the Complementary Technical Standards for the Design and Construction of Wood Structures (Mexico City Government, 2017).

3 Results and discussion

3.1 Descriptive analysis

The results of silvicultural measurements (total height, height of the first branch, and diameter at breast height) are presented, as well as ultrasound test results for standing trees in the green state (Table 1) and at 12% moisture content (Table 2).

Table 1
Descriptive statistics for height, diameter at breast height, density, ultrasound velocity and dynamic modulus of elasticity in green state

	H (m)	HR (m)	D (cm)	ρ_{12} (kg m^{-3})	$V_{us}T$ (m s^{-1})	$V_{us}L1$ (m s^{-1})	$V_{us}L2$ (m s^{-1})	$E_{us}T$ (MPa)	$E_{us}L1$ (MPa)	$E_{us}L2$ (MPa)
n	70	70	70	70	70	70	70	70	70	70
Min.	21.1	6.0	44.1	506.0	1251.0	683.9	965.4	912.7	285.1	518.1
Max.	36.0	24.0	91.6	628.0	1894.0	2010.7	3036.4	2092.9	2523.4	5084.2
μ	28.5	15.1	67.9	571.7	1581.6	1533.8	1847.8	1442.9	1402.3	1960.2
σ	2.9	4.2	10.4	32.6	144.7	320.6	445.7	279.5	519.9	961.4
CV	10.2	28.0	15.4	5.7	9.1	20.9	24.1	19.3	37.0	49.0

where: H: height, HR: height of the first branch, D: diameter at breast height, ρ_{12}: density at 12% moisture content, $V_{us}T$: transversal ultrasound velocity, $V_{us}L1$: longitudinal ultrasound velocity from 0–2 m, $V_{us}L2$: longitudinal ultrasound velocity from 2–4 m, $E_{us}T$: transversal modulus of elasticity, $E_{us}L1$: longitudinal modulus of elasticity from 0–2 m, $E_{us}L2$: longitudinal modulus of elasticity from 2–4 m, MPa: megapascals, μ: arithmetic mean, σ: standard deviation, CV: coefficient of variation (%).

Table 2
Ultrasonic velocities and longitudinal modulus of elasticity at 12% moisture content

	$V_{us}T\_12$ (m s^{-1})	$V_{us}L1\_12$ (m s^{-1})	$V_{us}L2\_12$ (m s^{-1})	$E_{us}T\_12$ (MPa)	$E_{us}L1\_12$ (MPa)	$E_{us}L2\_12$ (MPa)
n	70	70	70	70	70	70
Min.	2969.1	2402.4	2683.8	4886.3	3517.4	3843.6
Max.	3612.3	4285.8	4754.8	7614.2	11019.1	12467.4
μ	3300.0	3262.1	3566.3	6240.1	6149.1	7039.1
σ	144.7	341.2	445.7	667.6	1317.3	1740.4
CV	4.3	10.5	12.5	10.7	21.4	24.7

where: $V_{us}T\_12$: transverse ultrasonic velocity, $V_{us}L1\_12$: longitudinal ultrasonic velocity from 0 to 2 m, $V_{us}L2\_12$: longitudinal ultrasonic velocity from 2 to 4 m, $E_{us}T\_12$: transverse modulus of elasticity, $E_{us}L1\_12$: longitudinal modulus of elasticity from 0 to 2 m, $E_{us}L2\_12$: longitudinal modulus of elasticity from 2 to 4 m, MPa = megapascals, μ = arithmetic mean, σ: standard deviation, CV = coefficient of variation (%).

Results for the study area include an average height of 28.5 m, diameter at breast height of 67.9 cm, and a mean density of 571.7 kg m^{-3} at 12% moisture content for *P. montezumae* Lamb. The modulus of elasticity in the green state was found to be 1442.9 MPa for the transverse section, 1402.3 MPa for the low longitudinal section, and

1960.2 MPa for the high longitudinal section. These modulus with a 12% moisture content, increased to 6240.1 MPa (transverse section), 6149.1 MPa (low longitudinal section) and 7039.1 MPa (high longitudinal section).

It was found that the range of values for the longitudinal dynamic modulus of elasticity at 12% moisture content of *P. montezumae* ranged between 3517 and 11019 MPa for the lower section and between 3843 and 12467 MPa for the upper section, similar to the range obtained for *Pinus elliottii* of 2520 to 11300 MPa with an average of 6350 MPa (Yang et al. 2017), analogous to that obtained in this study, where the average was 6149 and 7039 MPa for the lower and upper sections, respectively.

The average value for the longitudinal modulus of elasticity was 6149 MPa (low section) and 7039 MPa (high section). These values are relatively lower compared to those obtained for pieces of wood from *P. pinaster* and *P. radiata* at 12% moisture content with ME-2 classification according to Standard (UNE 56544) of 9330 MPa and 8990 MPa, respectively (Vega et al. 2019). It also differs from the average of 11420 MPa for pieces of *Pinus nigra* Arnold subsp. salzmannii (Dunal) Franco at 10.6% moisture content (Arriaga et al. 2022). These differences could be attributed, firstly, to the study objects and age, as Vega et al. (2019) used sawn pieces from young trees aged between 15 and 19 years. Secondly, the indirect type of wave transmission method employed by Arriaga et al. (2022) could also contribute to the variations.

Regarding the acoustic wave velocity at 12% moisture content, an average value of 3262 and 3566 m s^{-1} was obtained, slightly lower than the value of 4926 m s^{-1} for *P. nigra* Arnold subsp. salzmannii (Dunal) Franco (Osuna et al. 2021). The difference between the average velocity found by Osuna et al. (2021) and that presented in this article was likely due to the fact that the measurements by this author were conducted on beams of 0.015 x 0.020 x 11 m with transducers placed opposite each other (direct transmission method) at a distance of 11 m, whereas in this study, the transducers were placed 2 m apart on standing timber using a semi-direct wave transmission method. Concerning these differences Arriaga et al. (2022) found that the wave velocity with the Microsecond Timer in direct transmission is higher (4904 m s^{-1}) compared to semi-direct transmission (4604 m s^{-1}).

3.2 Comparative analysis of longitudinal modulus of elasticity among sampling sites

Statistically significant differences were found for the modulus of elasticity at 12% moisture content in the two longitudinal sections (p-value < 0.05) (Fig. 2). Likewise, statistically significant differences were found for the modulus of elasticity at 12% moisture content between sampling sites (p-value < 0.05) for the low longitudinal section of 0–2 m (Table 3 and Table 4) and the high longitudinal section of 2–4 m (Table 5 and Table 6).

Table 3
Kruskal-Wallis test for longitudinal elasticity modulus from 0–2 m between sampling sites

	Chi-squared	df	p-value
Kruskal-Wallis test	33.362	13	0.001503

Table 4
Post Hoc Kruskal-Wallis test for longitudinal elasticity modulus from 0–2 m

Sampling sites	Mean	Homogeneous groups
12	7666.216	a
2	7617.344	a
9	6881.312	a
3	6854.530	a
14	6638.324	a
4	6413.293	a
7	5975.890	a
8	5647.917	a
5	6090.770	a
1	5637.146	a
10	5719.278	b
13	5478.509	b
11	4687.694	b
6	4779.514	c

Table 5
Kruskal-Wallis test for longitudinal elasticity modulus from 2–4 m between sampling sites

	Chi-squared	df	p-value
Kruskal-Wallis test	25.818	13	0.01798

Table 6
Post Hoc Kruskal-Wallis test for longitudinal elasticity modulus from 2–4 m

Sampling sites	Mean	Homogeneous groups
5	9696.580	a
9	8187.820	a
12	7487.319	a
14	7634.910	a
11	7420.000	a
8	6810.285	a
2	6738.768	a
13	6549.288	a
3	6645.259	a
10	7140.585	a
1	6414.679	a
7	6272.329	a
4	6107.788	b
6	5442.293	b

Influence of the sampling sites for the longitudinal modulus of elasticity was found, and the reason for these differences could be related to the biophysical characteristics of the sites, such as exposure, tree density, and understory density. Regarding the latter two, some sites showed high grass cover with low tree densities of 32 trees ha-1, while others with tree densities exceeding 80 trees ha-1 had little to no understory cover. Additionally, another factor that could have influenced these differences was the age of the trees. This variable, studied by Gil-Moreno et al. (2023), demonstrated effects on the strength wood, modulus of elasticity, and wood density for *Pinus sylvestris* L.

3.3 Grading structural timber

Results of structural timber grading for the seventy sampled trees (Fig. 3).

It was found that, for the low longitudinal section (0–2 m), 37% of the tree's sampled exhibited timber quality unsuitable for structural use, whereas for the high longitudinal section (2–4 m), the amount of timber unfits for this purpose decreased to 23%. On the other hand, medium quality (Structural B) was equally represented in both longitudinal sections (57% of the trees sampled). Finally, the highest quality (Structural A) was more prevalent in the high longitudinal section of 2–4 m (20% of the trees sampled), while in the low longitudinal section of 0–2 m, it was only observed in 6% of the tree's sampled.

Regarding the combinations of structural timber grading in the 70 sampled individuals (Fig. 4), it was found that 9 trees simultaneously exhibited unsuitable quality in both longitudinal sections, while almost a third of the tree sampled (24 trees) showed medium quality (Structural B) present in both longitudinal sections. In contrast, no individual presented high quality (Structural A) in the two longitudinal sections.

4 Conclusions

Experimentally significant statistical differences were found between the dynamic modulus of elasticity for the two longitudinal sections. Additionally, this longitudinal variation showed that the dynamic modulus of elasticity for the high longitudinal section (2–4 m) was higher than that for the low section (0–2 m).

The sampling sites were found to influence the dynamic modulus of elasticity for both longitudinal sections.

The low longitudinal section (0–2 m) had the highest proportion of timber unsuitable for structural use (37%), and 57% of the trees exhibited a medium quality for structural use in both longitudinal sections.

The highest quality wood for structural use was found in a higher proportion for the high longitudinal section of 2–4 m (20% of the trees), while for the low section of 0–2 m, it was only found in 6% of the trees.

This research examined the potential of this species in the production of wood for structural use. The results show that, overall, the quality and quantity of wood are more suitable for the second log (longitudinal section of 2–4 m) compared to the first log (longitudinal section of 0–2 m) in this study area.

The use of non-destructive tests (ultrasound testing) provides an advantage for evaluating the dynamic modulus of elasticity and for the grading structural timber compared to traditional destructive methods. It is also useful for characterizing timber from species under environmental protection regulations or norms, as well as in areas with logging restrictions or limitations.

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Figures

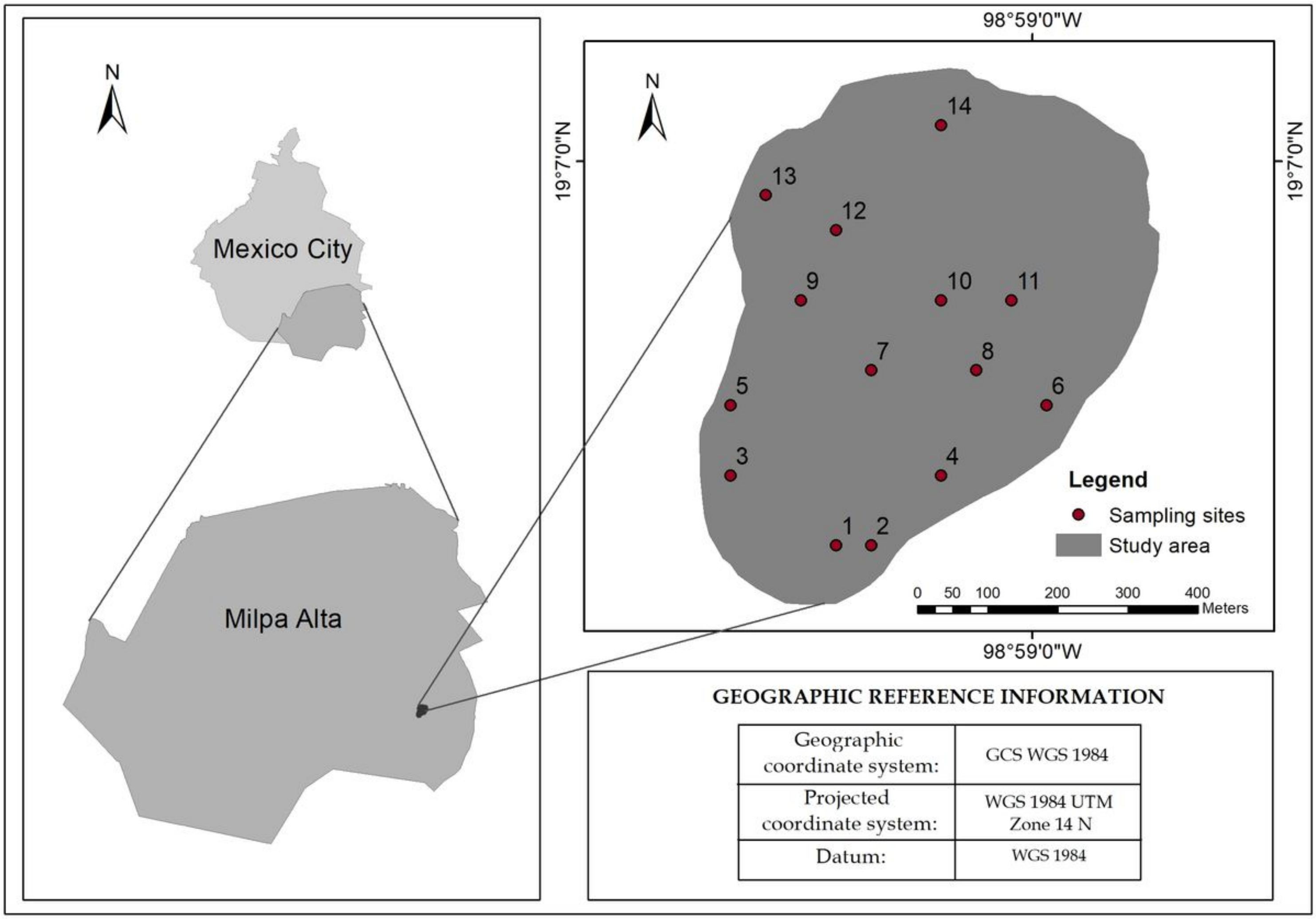

Figure 1

Location of the study area in Milpa Alta, Mexico City.

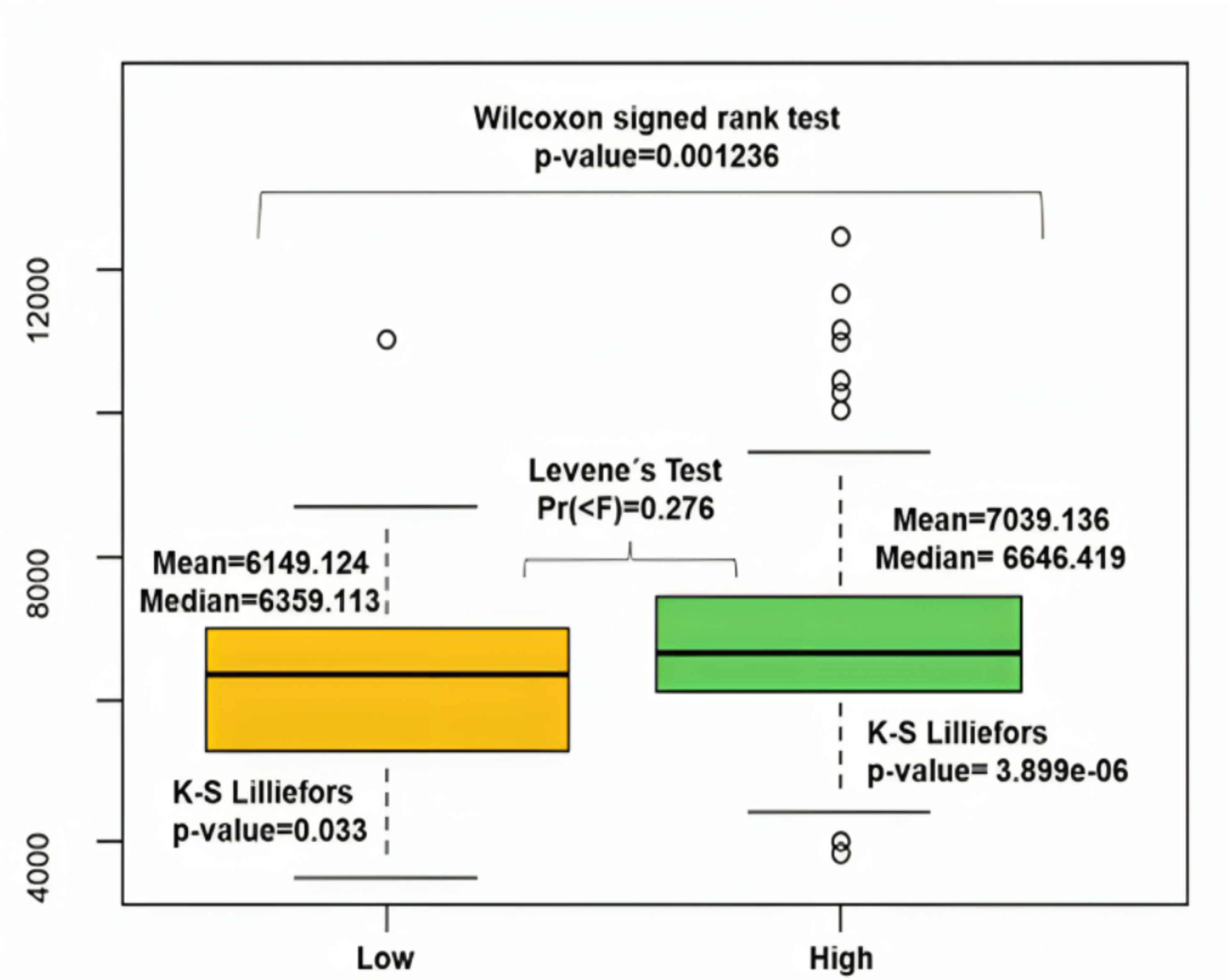

Figure 2

Results of the normality test, equality of variances test, and comparative test of longitudinal elasticity modulus

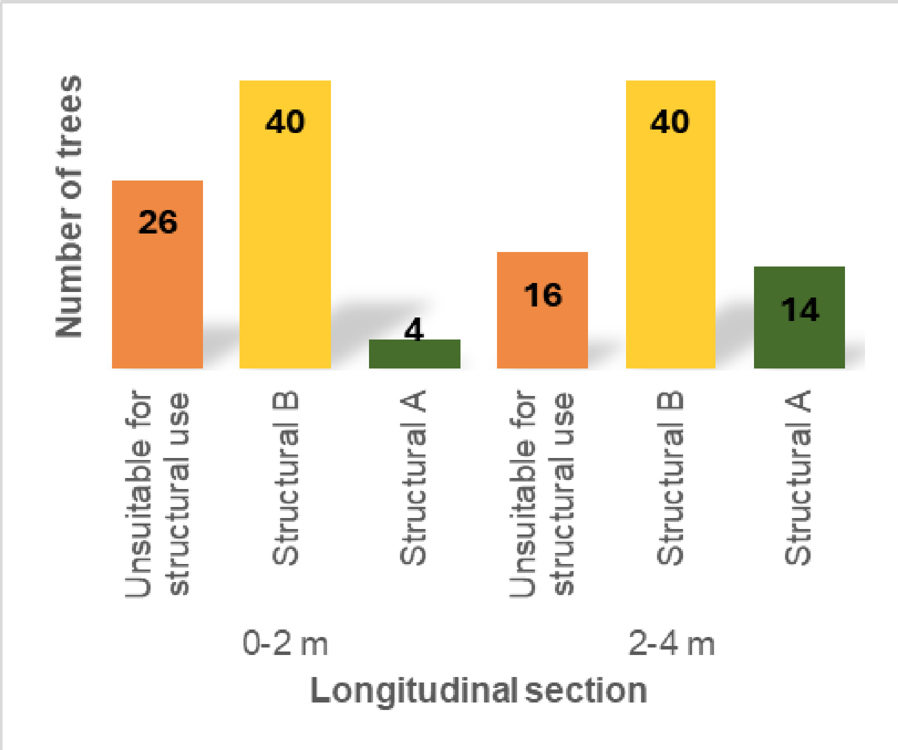

Figure 3

Results for the grading structural timber

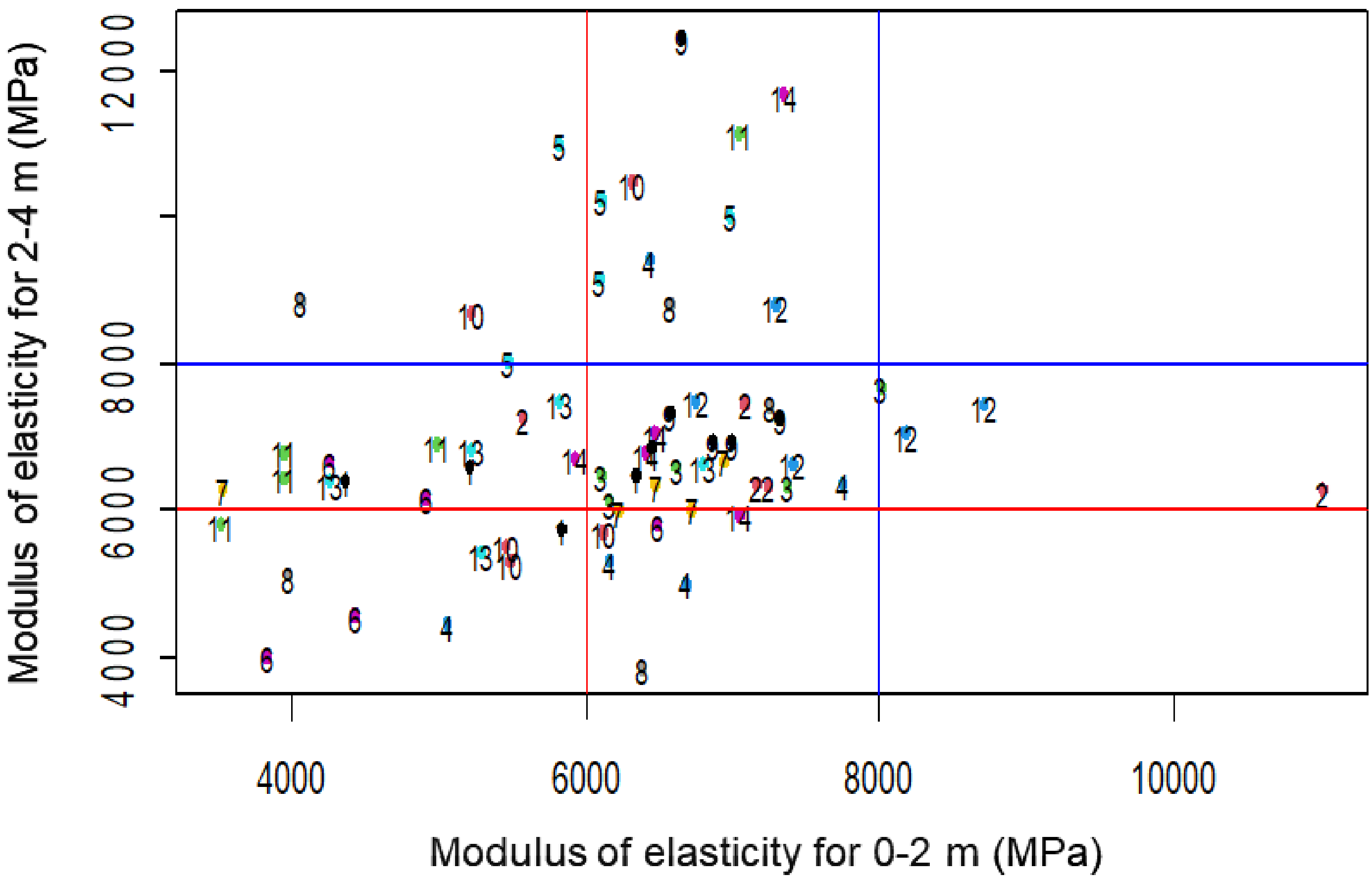

Figure 4

Scatter plot depicting the grading of structural timber by sampling sites for the longitudinal sections