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Research article

Age and diameter jump estimation: a comparison between field and dendrochronological procedures

Estimación de edad y tiempo de paso: comparación entre método de campo y dendrocronológico

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Abstract

The aerial biomass in temperate forests of Mexico is determined in the field, where age and radial growth are important variables involved in this process; however, its determination is usually inaccurate. The objective of this study was to compare the age estimated by eye ring counting (field method) in comparison to the age determined by dendrochronological techniques for two pine species, *Pinus arizonica* (Pa), and *Pinus cembroides* (Pc). A systematic sampling design was used to select 25 Pa and 17 Pc trees in the municipality of *Riva Palacio*, *Chihuahua* state. Trees were felled and cross-sections obtained at different heights along the stem. Age of each cross-section was determined by the field method and alternatively by dendrochronological techniques. The average difference in years for cross-sections of Pa was 16 years (*SD*=6.9) and 100 years for Pc (*SD*=73.4). In terms of diameter jump age for the last 5.0 cm, the results indicated an annual radial growth rate of 0.25 cm year^{-1} and 0.12 cm year^{-1} for Pa and Pc, respectively. The "*t*" test for the estimated ages showed significant difference (*p*<0.01) among age estimation methods and species. Age determination with the field method for different diameter-size classes is inaccurate and overestimate aboveground biomass, particularly for slow-growing species such as *Pinus cembroides*.

Key words: Aboveground biomass, forest biometry, dendrochronology, age, radial increment, diameter jump age.

Resumen

La estimación de biomasa aérea en bosques templados de coníferas en México se realiza a partir de mediciones en campo, en las cuales la edad es una variable importante; sin embargo, su determinación generalmente es imprecisa. El objetivo del presente estudio fue comparar la edad estimada y tiempo de paso (*TP*) mediante conteo directo de los anillos de crecimiento en campo, *versus* la obtenida con técnicas dendrocronológicas para dos especies de pino: *Pinus arizonica* (Pa) y *Pinus cembroides* (Pc). Se realizó un muestreo sistemático en un bosque de coníferas en el municipio Riva Palacio, Chihuahua, en el que se derribaron 25 y 17 árboles de Pa y Pc, respectivamente. Para determinar la edad de los individuos de ambas especies, los incrementos anuales se estimaron con el método tradicional de lectura directa en cortes transversales y alternativamente con técnicas dendrocronológicas. La diferencia promedio en el número de años con el método de campo y el dendrocronológico fue de 16 años para Pa (*SD*=6.9) y de 100 años para Pc (*SD*=73.4). Con respecto al *TP*, los resultados indican que en Pa, el incremento radial fue de 0.25 cm año^{-1}, mientras que para Pc de 0.12 cm año^{-1}. La prueba de comparación de medias para la edad mostró diferencia significativa (p<0.01) entre métodos y especies. El método de campo subestima la edad y *TP* entre categorías diamétricas, lo que implica una sobreestimación de la biomasa aérea, en particular para especies de lento crecimiento como *Pinus cembroides*.

Palabras clave: Biomasa aérea, biometría forestal, dendrocronología, edad, incremento radial, tiempo de paso.

Introduction

Forests are important for the economic development of any country, since they generate material benefits (wood, resins, etc.) as well as non-material benefits (ecosystem services), and they create a food security network and the provision of economic resources (Jones et al., 2019; *Organización de las Naciones Unidas para la Alimentación y la Agricultura* [*ONUAA*], 2018). The economic value of forests is generally reflected in the production of wood and this can be determined by using tools such as forest biometry, whose aim is to estimate volume and wood production. Therefore, an accurate assessment of volumetric stocks together with annual increases is important to plan sustainable forest use.

Traditionally, forest resources in Mexico have been evaluated through forest inventories, by measuring variables of interest for forest modeling. However, in general, there is limited quality control, such as age, which is a key variable for calculating aboveground biomass, passage times, increments and, at large, for good sustainable forest management (NOM-152-SEMARNAT-2023, 2023). The age of the trees provides essential information about the structural attributes of the forest and the dynamics of growth and yield; in addition, it allows the construction of various forestry parameters such as site indices or yield tables (Álvarez et al., 2004; Hernández-Ramos et al., 2022; Hu et al., 2020).

Growth and yield models of commercial forest species have been developed in Mexico (Santiago-García et al., 2020; Tamarit-Urias et al., 2019). However, in many of these models, reliability with respect to basic parameters such as tree age is unknown, which impacts the propagation of errors and, therefore, leads to an overestimation of volumetric stocks.

Growth models applied in forest management are based on physiological processes for decision-making; therefore, it is important to consider the impact that climatic variables may have on the physiological performance of species, particularly due to climate change (Correa-Díaz et al., 2023).

Traditionally, forest inventories collect information on mensuration variables, such as base diameter and stand age. This is used to estimate productivity indicators, such as transition time (*TP*), referred to as the number of years required for the tree to move from one diameter category to the next higher one (Klepac, 1983).

In forest biometry, stem analyses are used to evaluate the past growth of a set of trees and to infer the future growth of the forest. Through this analysis, the growth stages of a stand are evaluated in terms of diameter and height to estimate the *TP* (Imaña & Encinas, 2008). In this sense, dendrochronology as a tool to determine the age of a tree can not only improve the reliability of such analyses, but also allows the development of sustainable use models that accurately reflect the ecological and climatic conditions that have affected tree growth over time (Upadhyay & Tripathi, 2019).

In Mexico, 49 taxa of the *Pinus* L. genus are distributed in several ecological conditions (Gernandt & Pérez-de la Rosa, 2014). Given its importance in forest production, it is one of the most studied genera for this purpose (Sánchez-González, 2008). The Pinaceae involved in the present study were *Pinus arizonica* Engelm. (Pa) and *Pinus cembroides* Zucc. (Pc). In Pa, the coloration of the sapwood and heartwood make it a highly valued wood (Pérez-Olvera & Dávalos-Sotelo, 2016); while Pc is considered one of the best options for reforesting the arid and semi-arid regions of the country (Zárate-Castrejón et al., 2021).

This research aimed to compare the age estimation of *P. arizonica* and *P. cembroides* through direct counting in the field (Field Method; MC), with respect to the use of dendrochronological techniques (Dendrochronological Method; MD) and to analyze the technical implications that the estimation of age and passage time have on the forest management of both species.

The working hypothesis suggests that the field method, compared to the dendrochronological method, overestimates annual growth rates by not considering microrings or missing rings in the Annual radial growth of the tree.

Materials and Methods

Study area

The study site is located between 28°25'02” and 29°17'02” N, and 106°17'45” and 106°54'45” W (Figure 1), in an altitude range of 1 600 to 2 800 m. Annual precipitation and mean annual temperature vary from 400 to 600 mm and from 10 °C to 18 °C, respectively (*Instituto Nacional de Estadística, Geografía e Informática* [INEGI], 2010). The dominant climates of the area are semi-dry temperate and semi-dry cold or semi-cold, covering 82.1 % and 10.0 % of the municipal surface, respectively. The dominant soil classes are Leptosol (46.2 %), Luvisol (30.1 %) and Phaeozem (14.4 %) (INEGI, 2010).

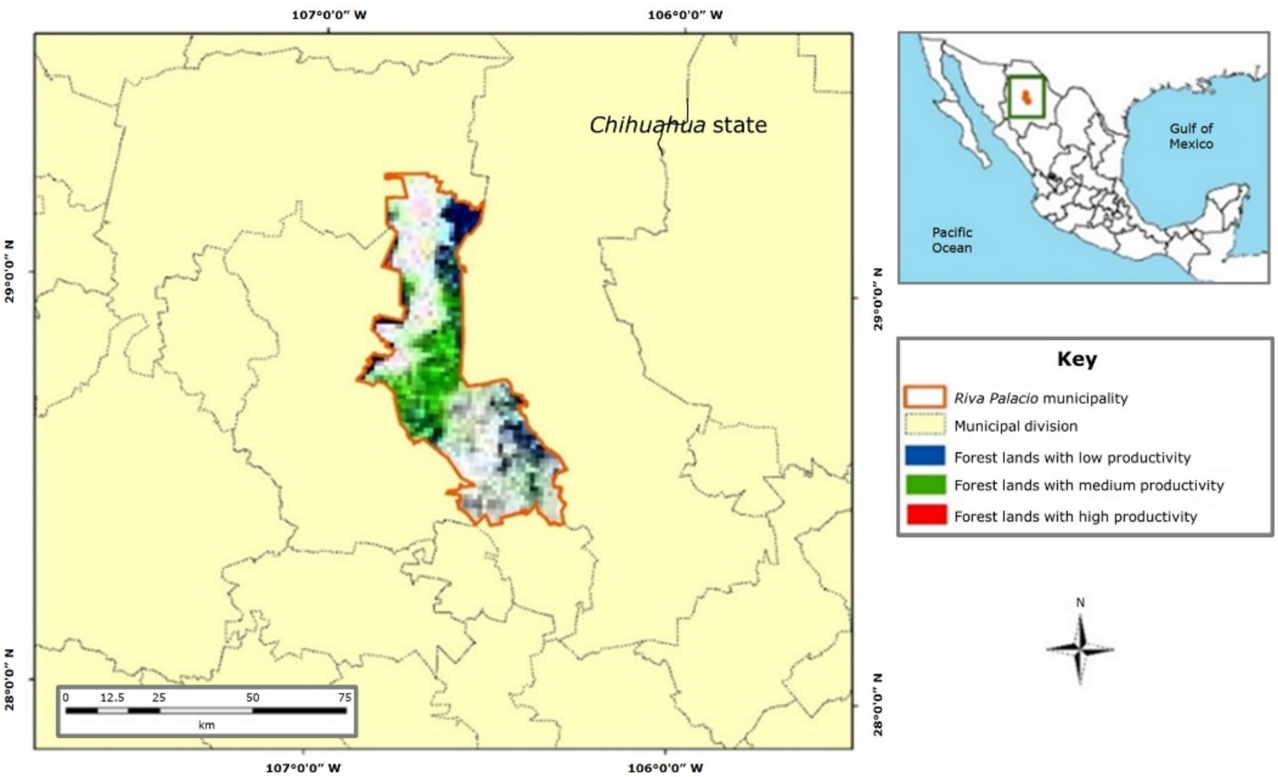

Figure 1. Geographic location of the study area, *Riva Palacio* municipality, state of *Chihuahua*, Mexico.

Sample collection

25 Pa and 17 Pc individuals were selected in an open stand of mixed coniferous forest, based on the diameter classes existing by species and representative of each of them. The selected trees were felled, to subsequently obtain cross sections of 5.0 cm thickness. The first cut was at 0.30 m from ground level, the next at normal diameter (1.30 m) and then at different lengths along the stem. For example, for Pa, the spacings were at 2.6 m, since the selected individuals had a diameter ≥20 cm, while for Pc the subsequent cuts were made at 1.30 m, due to a smaller diameter (≤20 cm).

Field method

The MC consisted of a direct count in the field to obtain information on diameter and age growth, carried out according to the methodology described by Quiñonez et al. (2015). This process consists of locating four radii in each cross section, from which the center is marked and a count of visible rings is made from the center to the bark; the total number of rings is divided into 10-year age categories to define groups of rings and the fraction is taken as residual. Based on the above, the residuals from the center to the bark are counted and the rings are subsequently divided into groups of two. Because the count of annual increments (growth rings) was made in the total of each of the radii (from the center to the bark), the growth of the last 2.5 cm was not counted, in such a way that the age of the tree was based only on the total count of growth.

Dendrochronological method

The MD considered the cross sections previously used in the field phase. A wedge-shaped portion of wood was obtained from each cross section, including the center of the tree (core), which was progressively polished with sandpaper in a sequence from coarse to fine (260, 360, 600, 1 200), in order to highlight the tree rings. Each wedge was dated from the pith to the bark using a stereoscopic microscope with a 10X resolution (Stokes & Smiley, 1996). Subsequently, the width of the rings was measured with a Velmex® measuring system with a precision of 0.001 mm (Robinson & Evans, 1980).

The quality of the dating was evaluated with the COFECHA software, whose critical correlation for an adequate dating must be greater than 0.328 (p<0.01) (Grissino-Mayer, 2001). The database was standardized with the ARSTAN program to generate ring width indices and compare the interannual behavior between both species, based on the Pearson correlation coefficient (Cook, 1987).

Comparison of counting methods and passage time

To determine the differences between methods (MC and MD), a comparison of the years counted by each of them was made. Subsequently, the average difference in ages in the total number of cross sections per tree was calculated and the standard deviation for the counting differences between both methods was determined. The statistical difference between the methods used to estimate age with the MC and MD was determined based on the mean and variance. Finally, a comparison test of means was applied with the "*t*" statistic to determine whether the difference in the age estimation showed significance ($p<0.05$). To calculate these data, the age of the samples obtained at 1.3 m height was used.

The determination of the passage time considered the last 5.0 cm of the stem increment in diameter classes of 5.0 cm. For the MC it consisted of the field count of the number of rings present in each radial increment. Similarly, the MD considered the number of rings present in the same portion of the stem, with the difference that these were dated to the year of their formation. The annual increment was obtained from the result of the quotient, dividing the 5.0 cm by the number of years determined by each counting method.

To know the age-height relationship, the ages obtained with the MC were compared with those obtained with the MD. The heights in question were 0.3 m, 1.3 m and subsequently every 2.6 m and 1.3 m for Pa and Pc, respectively.

Results

Quality of dating by dendrochronological method

The dendrochronological parameters that determine the quality of dating indicated that the growths of the Pa and Pc species were correctly dated to the actual year of their formation (Table 1).

Table 1. Dendrochronological parameters according to the COFECHA program, which define the quality of dating of the species *Pinus arizonica* Engelm. and *P. cembroides* Zucc.

Specie	*IS*	*SD*	*SM*	*APO*
Pa	0.69	1.09	0.40	0.54
Pc	0.63	0.40	0.44	0.51

Pa = *Pinus arizonica* Engelm.; Pc = *Pinus cembroides* Zucc.; IS = Intercorrelation between series (it must be greater than 0.328, $p<0.01$); *SD* = Standard deviation; *SM* = Mean sensitivity; *APO* = First-order autocorrelation.

The correlation between dendrochronological series of Ring width index of Pa and Pc was 0.744 ($p<0.01$) for the common period from 1852 to 2014, a result that corroborates correct dating (Figure 2).

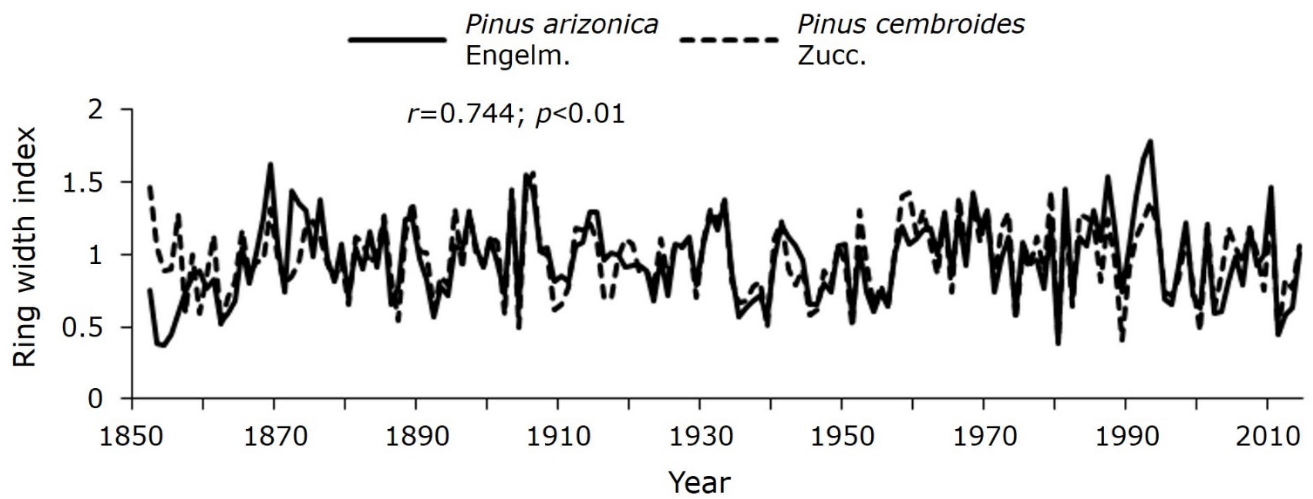

Figure 2. Total ring index dendrochronological series of the species *Pinus arizonica* Engelm. and *P. cembroides* Zucc.

Difference between methods with respect to age

The estimation of the average age at different heights indicated that for the first cross section of Pa (0.30 m from the ground), an average difference of 36 years was obtained between both methods (Figure 3). On average, the MC underestimated the real age by 16 years per section, with a standard deviation of 6.9 years and a variation range of 1 to 65 years compared to the MD.

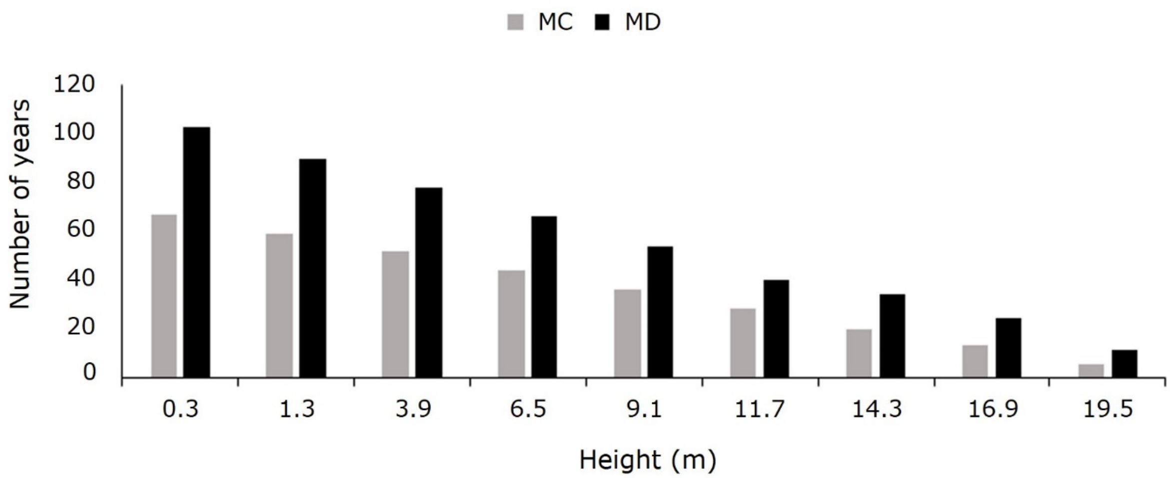

Figure 3. Average years determined with the field method (MC) and the dendrochronological method (MD) in cross sections at different heights for *Pinus arizonica* Engelm.

For Pc, an average difference of 100 years per section was determined between both methods, with a standard deviation of 73.4 years and a variation interval of 3 to 288 years (Figure 4).

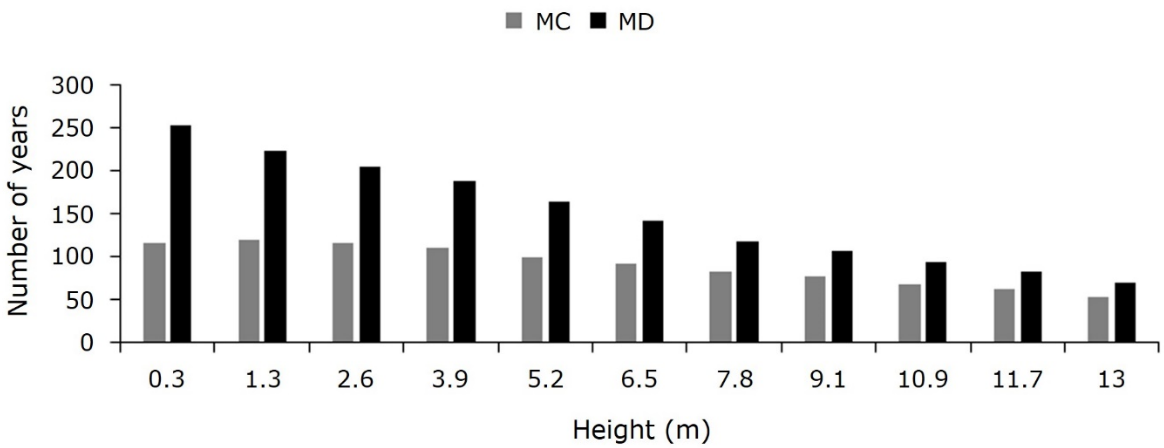

Figure 4. Average years determined with the field method (MC) and the dendrochronological method (MD) in cross sections at different heights for *Pinus cembroides* Zucc.

Passage time, number of rings in the last 5.0 cm

In both counting methods, a difference was noted in the estimated age according to the dominant diameter classes (Table 2). With the MC, it was determined that Pa trees in this region take 10 years on average to pass from one diameter category to the next, with an Average annual increase of 0.5 cm year^{-1}. In contrast, the MD indicated an average of 20 years and an Average annual increase of 0.25 cm $year^{-1}$ to reach the same radial increment.

Table 2. Difference in passage time between the MC and the MD for *Pinus arizonica* Engelm.

CD (cm)	MC (years)	MD (years)
30.0-34.9	12	30
35.0-39.9	12	18
40.0-44.9	10	17
45.0-49.9	12	17
50.0-54.9	10	13
55.0-59.9	6	22
Mean	10	20
SD	5	35
Variance	2	6

CD = Diameter class; MC = Field method; MD = Dendrochronological method; *SD* = Standard deviation.

The *TP* mean determined with the MD for Pc was 39 years for an increase in diameter of 5.0 cm, 68 years standard deviation and 0.12 cm $year^{-1}$ growth rate. This result was different from that obtained with the MC which recorded an average of 16 years, standard deviation of 2 years and a growth rate of 0.31 cm $year^{-1}$ (Table 3).

Table 3. Difference in passage time in the MC and the MD for *Pinus cembroides* Zucc.

CD (cm)	MC (years)	MD (years)
30.0-34.9	15	30

35.0-39.9	17	39
40.0-44.9	17	47
Mean	16	38
SD	2	68
Variance	2	8

CD = Diameter class; MC = Field method; MD = Dendrochronological method; *SD* = Standard deviation.

Analysis of the diameter classes of the cross sections

The analysis suggests that Pa could be harvested once the trees reach 30 cm in diameter in 56 years, according to the MD; while, for a diameter of 40 cm, the same method indicates that 72 years must pass. This is in contrast to the MC, which indicates 43 and 57 years for 30 and 40 cm, respectively; that is, 13 and 15 years of difference for the parameters indicated (Table 4).

Table 4. Age analysis by diameter classes for individuals of *Pinus arizonica* Engelm.

CD (cm)	Frequency	MC (years)	MD (years)	Difference (years)
10.1-15.0	2	21	26	5
15.1-20.0	3	34	42	8
20.1-25.0	8	39	47	8
25.1-30.0	19	32	43	11
30.1-35.0	34	43	56	13
35.1-40.0	41	57	72	15
40.1-45.0	34	68	86	18
45.1-50.0	19	82	99	17
50.1-55.0	6	82	109	27

CD = Diametric class; MC = Field method; MD = Dendrochronological method.

The analysis of the diameter classes of Pc suggests that from the 15.1 to 20.0 cm class (144 years), the trees can be used (Table 5). Because Pc is a long-lived species, there is a minimal difference in volume between one diameter class and a later one.

Table 5. Age analysis by diameter classes for Pc individuals.

CD (cm)	Frequency	MC (years)	MD (years)	Difference (years)
5.1-10.0	14	24	82	58
10.1-15.0	26	34	115	81
15.1-20.0	19	52	144	92
20.1-25.0	23	75	177	42
25.1-30.0	22	93	202	109
30.1-35.0	21	98	228	130
35.1-40.0	9	113	286	173
40.1-45.0	2	107	319	212
45.1-50.0	1	100	388	288

CD = Diametric class; MC = Field method; MD = Dendrochronological method.

Statistical comparison between both methods for estimating age

The data resulting from the comparison between both methods are compiled in tables 5 and 6. On average, the MC underestimates the average age of the trees by more than double for both species (Table 6).

Table 6. Descriptive statistics of age (mean and variance), when comparing the MC *versus* the MD for the two species under study.

Species	Average MC (years)	Average MD (years)	Variance MC ($years^2$)	Variance MD ($years^2$)
Pa	90.2	210.6	942.126	3 805.083
Pc	89.8	206.1	753.360	4 984.295

Pa = *Pinus arizonica* Engelm.; Pc = *Pinus cembroides* Zucc.; MC = Field method; MD = Dendrochronological method.

The statistical results suggest a significant difference between both counting methods ($p<0.01$) (Table 7).

Table 7. Statistics of the test for comparison of paired means between counting methods, applied to each species.

Species	Critical *t*-value (two tails)	Degrees of freedom	*t*-statistic	Two-tailed statistic *P* (*T*<=*t*)
Pa (MC *vs.* MD)	2.0106	48	-8.7322	0.000002
Pc (MC *vs.* MD)	2.0930	19	-6.1661	0.000006

Pa = *Pinus arizonica* Engelm.; Pc = *Pinus cembroides* Zucc.; MC = Field method; MD = Dendrochronological method

Discussion

The number of annual rings in a cross section can be accurately determined by dendrochronological analysis, unlike the field method which generally underestimates the number of rings present, particularly in the outer part where the rings are compressed (Alteyrac et al., 2005).

The main advantage of dendrochronological dating is that it allows to accurately identify the limits of annual growth and, therefore, provides a correct dating of the number of growths in a radial increment (Fritts, 1976; Schweingruber, 1996). In contrast, the estimation of the number of rings with the MC leads to errors derived from a poor definition of the limits of annual growth, as is the case of Pc where the rings are difficult to discern visually, so they must be viewed microscopically.

The exact dating of rings facilitates the analysis of a large number of ecological processes over a variable time span (Santiago-García et al., 2020). For the taxa analyzed, the difference for *TP* between the two methods was greater than 10 years for both species (Table 1 and 2). The difference in means highlighted that the age estimation showed less discrepancy between methods at a tree height later than 7.8 m in Pc (Figure 3).

The age of the rotation detected for Pc was 144 years (Table 4), which shows some coincidence with slow-growing species such as *Pinus strobiformis* Engelm., *P. lumholtzii* B. L. Rob. & Fernald and *P. leiophylla* Schiede *ex* Schltdl. & Cham. present in mixed forests of the *Sierra Madre Occidental* (Hernández et al., 2020).

The use of dendrochronological techniques can strengthen sustainable management programs for species in the process of harvesting, since it allows increasing the certainty in cutting rotations. In this way, the precision in counting the growth rings and the Annual radial increment must be considered in decision making, through the correct estimation of the *TP*; although it should be noted that the methodology involves a longer time in processing the samples, requires trained personnel for dating, in addition to the infrastructure required for this purpose. The problem can be solved if the process is carried out in specialized centers with the equipment and personnel trained in this type of analysis.

Conclusions

Despite the widespread belief that estimating age by direct counting of rings in the field is reliable, the results of this study show that direct counting leads to significant biases with implications for the projection of variables such as volume, passage time or available aboveground biomass.

Overestimating annual increment with the Field Method (MC) favors the reduction of cutting shifts and consequently overexploiting the resource.

The Dendrochronological Method (MD) provides accurate estimates of age and passage times; however, despite the fact that it requires some specialization for its application, it should be favored over MC, particularly for planning sustainable management of forest resources.

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Conflict of interest

The authors declare that they have no conflict of interest. Doctors Arian Correa Díaz and Gerónimo Quiñonez Barraza, section editors of the *Revista Mexicana de Ciencias Forestales*, declare that they have not participated in the editorial process of this manuscript

Contribution by author

José Villanueva Díaz: conceptualization, writing and analysis of information; Emilia Raquel Pérez Evangelista: dating of samples, writing and dendrochronological analysis; Arian Correa-Díaz: data analysis, review and correction of the manuscript; Luis Ubaldo Castruita Esparza: location of study sites and sampling; Julián Cerano Paredes: analysis of dendrochronological information; Gerónimo Quiñonez Barraza: methodology and analysis of information; Aldo Rafael Martínez Sifuentes: data analysis and correction of the manuscript.

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