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Research article

Soil fertility and growth of *Pinus patula* Schiede *ex* Schltdl. & Cham. in two commercial forest plantations

Fertilidad del suelo y crecimiento de *Pinus patula* Schiede *ex* Schltdl. & Cham., en dos plantaciones forestales comerciales

René García Martínez[1]*, Maricruz Tenorio Calixto[1], Juan Carlos Montoya Jiménez[1], Luis Alberto León Bañuelos[2], Marlín Pérez Suárez[3]

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[1]Tecnológico Nacional de México, Tecnológico de Estudios Superiores Valle de Bravo, División de Ingeniería Forestal. México.

[2]Tecnológico Nacional de México, Tecnológico de Estudios Superiores Valle de Bravo, División de Ingeniería en Sistemas Computacionales. México.

[3]Instituto de Ciencias Agropecuarias y Rurales (ICAR), Universidad Autónoma del Estado de México (UAEMex). México.

*Autor para correspondencia; correo-e: rene.gm@vbravo.tecnm.mx
*Corresponding author; e-mail: rene.gm@vbravo.tecnm.mx

Abstract

The productivity of commercial forest plantations largely depends on soil fertility and stand density. The objective of this study was to compare soil properties and their influence on tree growth, as well as to develop site-specific height–diameter models for two 18-year-old *Pinus patula* plantations. The tree variables that were measured included diameter at breast height and total height, and the basal area, tree biomass and tree carbon stock were calculated. Soil fertility was characterized through chemical analyses of the 0-30 cm soil layer. Fourteen height–diameter models were fitted. Trees in Plantation A reached greater height, whereas those in Plantation B exhibited larger diameter, basal area, and carbon stock per tree. However, aboveground carbon stocks at the stand level were similar (75.6 Mg ha^{-1} in A and 73.7 Mg ha^{-1} in B). Soil in Plantation B contained higher levels of *SOM*, *N*, *Ca*, *Mg*, and greater *CEC*, which was reflected in higher *SOC* storage. The height-diameter models showed relatively low coefficients of determination (R^2=0.25-0.34); however, model MT1 achieved the best overall fit and normally distributed residuals. In conclusion, soil fertility and stand density were key factors determining productivity and carbon storage. Nevertheless, additional variables should be incorporated into height-diameter modeling to improve their predictive accuracy at the local scale.

Keywords: Carbon stock, carbon capture, tree density, soil fertility, allometric modeling, forest soils.

Resumen

La productividad de las plantaciones forestales comerciales depende en gran medida de la fertilidad del suelo y la densidad arbórea. El objetivo de esta investigación fue comparar las características edáficas y su influencia en el desarrollo del arbolado, además de generar modelos altura-diámetro específicos en dos plantaciones de 18 años *de Pinus patula*. De cada ejemplar se midieron el diámetro normal y la altura, y se calcularon el área basal, la biomasa y el carbono arbóreo. Para caracterizar la fertilidad del suelo se determinaron las propiedades químicas en el perfil 0-30 cm. Finalmente, se ajustaron 14 modelos altura-diámetro. Los árboles de la Plantación A fueron superiores en altura y los de la Plantación B en diámetro, área basal y carbono por árbol, aunque a nivel de superficie, el almacén de carbono aéreo fue similar (75.6 Mg ha^{-1} en A y 73.7 Mg ha^{-1} en B). El suelo de la Plantación B registró altos niveles de *MOS*, *N*, *Ca*, *Mg* y *CIC*, lo que se reflejó en un mayor almacén de *COS*. Los modelos altura-diámetro resultaron con coeficientes de determinación bajos (R^2=0.25-0.34); el modelo MT1 presentó el mejor ajuste global y residuales con distribución normal. En conclusión, la fertilidad del suelo y densidad de plantación determinaron la productividad y almacenamiento de carbono. Sin embargo, en la modelación altura-diámetro aún es necesario incorporar variables adicionales para mejorar su capacidad predictiva a escala local.

Palabras clave: Almacén de carbono, captura de carbono, densidad arbórea, fertilidad edáfica, modelación alométrica, suelos forestales.

Introduction

Commercial forest plantations (CFPs) have become an important strategy to meet the growing demand for timber and other forest products and contribute to reducing pressure on natural woods (Comisión Nacional Forestal [Conafor], 2015; García-Cuevas et al., 2022; Muñoz-Flores et al., 2021) and mitigating the effects of climate change by establishing fast-growing native or introduced species (García-Cuevas et al., 2022; Muñoz-Flores et al., 2021). However, the productivity of these systems depends on site quality, which is related to climatic, edaphic (García-Martínez et al., 2024), and silvicultural management factors. In particular, the physical and chemical properties of the soil play a fundamental role, as they can directly influence nutrient availability, moisture retention, and soil biological activity. Factors that influence vegetation development (Lal, 2004; Weil & Brady, 2017). For example, in forests of

Pinus arizonica Engelm. and *Pinus engelmannii* Carrière, a soil depth >43 cm indicated better site quality (Martínez-Salvador et al., 2013).

Several studies have shown that differences in soil fertility can translate into significant variations in tree growth, even under similar climatic conditions. In plantations of *Tectona grandis* L. f. established under comparable hydroclimatic conditions, tree growth was directly related to soil quality (Salcedo-Pérez et al., 2019). In a similar way, research on *Pinus cooperi* C. E. Blanco has shown that trees established in sites with better soil conditions (nutrients and moisture) exhibited higher radial growth rates (82.5 % latewood proportion), with wider growth rings (Pompa-García & Domínguez-Calleros, 2015).

On the other hand, tree density influences tree growth dynamics. In a previous study by Qiao et al. (2024) in poplar (*Populus tomentosa* Carrière) plantations, they concluded that low and medium densities favored tree growth and high soil nutrient levels.

In Mexico, *Pinus patula* Schiede *ex* Schltdl. & Cham. is one of the most widely used subtropical species in reforestation programs and forestry projects due to its rapid growth and wood quality (Aparicio-Rentería et al., 2014). However, in the central region of the country, survival rates in plantations for this species barely reach 44 % (Torres-Rojo, 2021). Therefore, reliable information on the quality of forest areas where plantations are established is essential, especially with fast-growing species like the one of interest, because there is a strong relationship between environmental variables and yields (García-Aguilar et al., 2017).

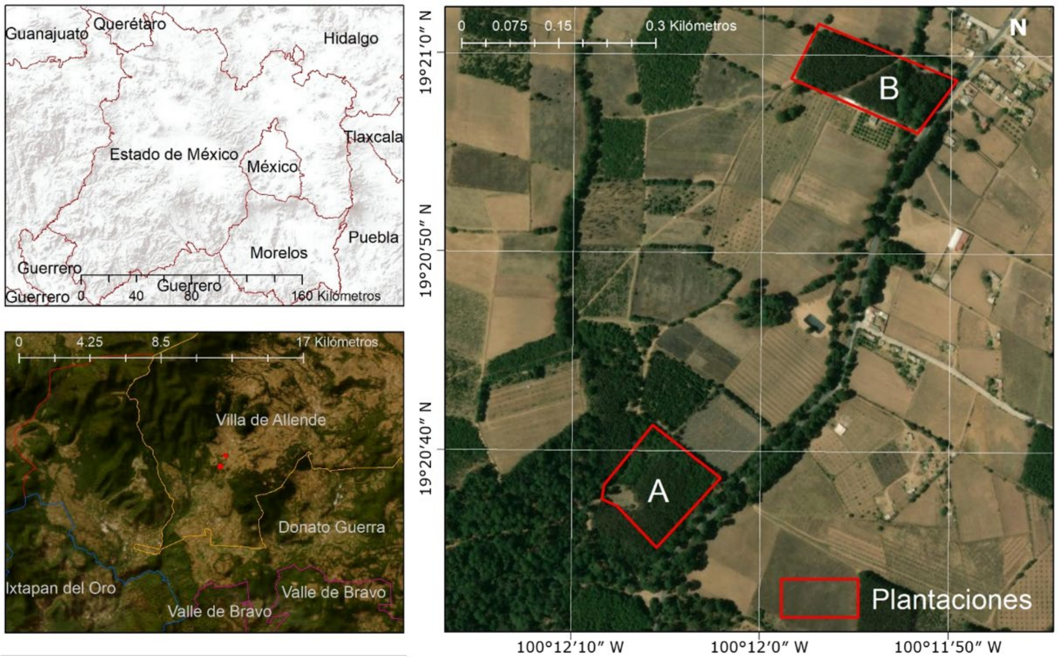
Another key aspect is the development of biometric tools that allow for the accurate description of tree growth and the estimation of structural variables relevant to forestry planning. Among these, height-diameter models are a fundamental component of forest inventories because they allow for the estimation of tree height from normal diameter using allometric models, thus optimizing field measurement processes (Santiago-García et al., 2017). Although important, the accuracy of the equations can vary and depends on site conditions and stand structure, so it is necessary to develop specific models for each region and planted species. For example, Monárrez-González et al. (2024) developed equations that provide reliable and accurate estimates to determine stem volume and total tree volume of the species *Pinus ayacahuite* Ehrenb. *ex* Schltdl., *P. leiophylla* Schiede *ex* Schltdl. & Cham., *P. hartwegii* Lindl., *P. montezumae* Lamb., *P. patula*, *P. pseudostrobus* Lindl., *P. teocote* Schied. *ex* Schltdl. & Cham., *Abies religiosa* (Kunth) Schltdl. & Cham. and *Quercus* sp. in temperate forests of the state of *Puebla*, Mexico.

Although many studies exist on soil fertility, productivity and height-diameter modeling in forest species, few works simultaneously integrate soil characterization, tree growth and the assessment of biometric models in commercial plantations of *P. patula* established under conditions in central Mexico. Therefore, the objective of this research was to compare soil characteristics and their relationship to tree growth, as well as to adjust height-diameter models for two commercial *P. patula* plantations established in *Villa de Allende*, State of Mexico, Mexico.

Materials and methods

Study area

The study was conducted in two commercial *P. patula* plantations located in *San Jerónimo Totoltepec*, *Villa de Allende*, State of Mexico, Mexico. The predominant climate is temperate subhumid, with an average annual temperature of 18.8 °C and annual rainfall of 1 000 mm (Instituto Nacional de Estadística, Geografía e Informática [INEGI], 2008). The soil is Andosol (INEGI, 1978) derived from volcanic ash (Meza-Pérez & Geissert-Kientz, 2006). The commercial plantations are located at the following coordinates: Plantation A (19°20’40” N and 100°12’05” W) and Plantation B (19°20’59” N and 100°11’53” W) (Figure 1). The average altitude in the area is 2 470 m.



Kilómetros = Kilometers. *Plantaciones* = Plantations. *Querétaro* = State of *Querétaro*; *Hidalgo* = State of *Hidalgo*; *Guanajuato* = State of *Guanajuato*; *Tlaxcala* = State of *Tlaxcala*; *Estado de México* = State of Mexico; *México* = Mexico City; *Puebla* = State of *Puebla*; *Morelos* = State of *Morelos*; *Guerrero* = State of *Guerrero*. *Villa de Allende* = *Villa de Allende* municipality; *Donato Guerra* = *Donato Guerra* municipality; *Ixtapan del Oro* = *Ixtapan del Oro* municipality; *Valle de Bravo* = *Valle de Bravo* municipality.

Figure 1. Geolocation of *Pinus patula* Schiede *ex* Schltdl. & Cham. plantations in *Villa de Allende*, State of Mexico, Mexico.

In 2024, when the field data were collected, the plantations were 18 years old. Plantation A covers 1 ha and has 1 100 trees ha^{-1}. Plantation B covers 1.6 ha and has 703 trees ha^{-1}.

Tree measurement

In each plantation, 10 circular sites of 450 m^2 (radius=12 m) were randomly established to measure the characteristics of all living trees without structural damage. Normal diameter (cm) was measured at a height of 1.3 m using a model Mantax Blue Haglöf® calipers, and total height was measured with a model Vertex Laser Geo Haglöf® hypsometer, according to the procedures described by West (2015). Basal area (cm^2) was calculated from the diameter data.

Total biomass was calculated using the following allometric equation (Castellanos et al., 1996):

$$Biomass(kg) = exp(-1.8621) \times DN^{2.27675} \qquad (1)$$

Where:

DN = Normal diameter (cm)

Carbon stock per tree was calculated using a conversion factor of 0.50 to convert biomass to carbon equivalents (Petersson et al., 2012).

Soil chemical analysis

At each plantation, 10 soil samples were collected at a depth of 0 to 30 cm. Sampling was performed using a stainless-steel auger (model HA 6510 SPECTRUM®) with a 2 cm diameter (Acosta-Mireles et al., 2009). The samples were placed in plastic bags and transported to the Soil Fertility and Environmental Chemistry Laboratory at the *Montecillo* Campus Graduate Studies School (*Colegio de Postgraduados*), for analysis.

pH was measured in a 2:1 water-to-soil suspension (Weil & Brady, 2017) using a model GroLine Combo Hanna® portable meter. Soil organic matter (*SOM*) and soil organic carbon (SOC) were quantified using the Walkley-Black method (Sleutel et al., 2007). Nitrogen (N) was determined via the semi-micro-Kjeldahl technique (Sáez-Plaza et al., 2013), and phosphorus (*P*) was determined using the Olsen method (Food and Agriculture Organization of the United Nations [FAO], 2021). Exchangeable cations (K^+, Ca^{2+}, Mg^{2+} and Na^{1+}) were extracted with ammonium acetate (J. T. Baker®, México) (Havlin et al., 2017), and quantification was performed using atomic absorption spectrophotometry (model SpectrAA 220 Varian®). Data interpretation was based on information published in NOM-021-RECNAT-2000 (Secretaría del Medio Ambiente y Recursos Naturales [Semarnat], 2002) and data published in various documents (Binkley & Fisher, 2013; Havlin et al., 2017; Osman, 2013; Porta-Casanellas et al., 2019; Weil & Brady, 2017).

Soil bulk density for the 0-30 cm depth was determined by relating the mass of the dry soil (dried in an ICB® 18 L oven at 105 °C for 24 hours) to the volume of the auger used to extract the sample (Osman, 2013). The bulk density was 1.0 Mg m^{-3} for Plantation A and 1.1 Mg m^{-3} for Plantation B. This information was used to calculate the soil *C* stock using the following formula (Acosta-Mireles et al., 2009):

$$Carbon\ (Mg\ ha^{-1}) = A \times SD \times BD \times \frac{SOC}{100} \qquad (2)$$

Where:

A = Land area (10 000 m^2)

SD = Sampling depth (0.3 m)

BD = Soil bulk density

SOC = Soil organic carbon concentration (%)

Soil and tree data analysis

Differences between plantations regarding tree variables (height, diameter, basal area, and carbon) and soil variables (*SOM*, *N*, *P*, *K*, *Ca*, *Mg*, *Na*, *pH*, electrical conductivity [*EC*], and *C* storage) were evaluated using an independent-samples Student's *t*-test with Welch's correction (Uramoto et al., 2025). The analysis was performed using R software, version 4.5.2 (R Core Team, 2025).

Height-diameter models

To estimate height from diameter at a specific site, 13 nonlinear models and one quadratic model—widely used in studies of allometric relationships—were fitted (Table 1).

Table 1. Functions for modeling total height based on normal diameter for *Pinus patula* Schiede *ex* Schltdl. & Cham.

Model	Equation	Reference
MC	$h = \beta_0 \left[1 - e^{-\beta_1 d}\right]^{\beta_2}$	Clutter et al. (1983)
MT1	$h = \beta_0 \left[1 - e^{-\beta_1 d^{\beta_2}}\right]$	Temesgen et al. (2014)
MT2	$h = e^{\left(\beta_0 + \frac{\beta_1}{d + \beta_2}\right)}$	
MC1	$h = \beta_0 \, e^{(-\beta_1 d^{-\beta_2})}$	Castillo-Gallegos et al. (2018)
MC2	$h = \dfrac{d^{\beta_0}}{\beta_1 + \beta_2 d^{\beta_0}}$	
MC3	$h = \dfrac{\beta_0 d}{\beta_1 + d}$	
MC4	$h = \dfrac{\beta_0}{1 + {\beta_1}^{-1} d^{-\beta_2}}$	
MC5	$h = \beta_0 \left(1 + \dfrac{1}{d}\right)^{-\beta_1}$	
MC6	$h = \beta_0 \left(-\ln\left(\dfrac{1}{d}\right)\right)^{\beta_1}$	
MC7	$h = \left(\beta_0 + \dfrac{\beta_1}{d}\right)^{-\beta_2}$	
MS	$h = \beta_0 \, d^{(\beta_1 + \beta_2 d)}$	Sharma (2009)
MG1	$h = \beta_0 + \beta_1 d + \beta_2 d^2$	García-Cuevas et al. (2017)
MG2	$h = \beta_0 \, e^{\beta_1 \left(\frac{1}{d}\right)}$	
MG3	$h = e^{\beta_0 + \beta_1 \ln(d)}$	

h = Total height; *d* = Normal diameter; βi = Parameters of the model. Table modifies from Guerra-De la Cruz et al. (2019).

Data from 113 trees were used for Plantation A, and data from 86 trees were used for Plantation B. The models were selected from the study by Guerra-De la Cruz et al. (2019) and fitted using R software (R Core Team, 2025) with the gslnls package (Chau, 2025).

To evaluate and compare the goodness-of-fit of the nonlinear and quadratic models, six statistical criteria were examined:

(1) Sum of squared errors (*SSE*)

(2) Mean squared error (*MSE*)

(3) Root mean squared error (*RMSE*)

(4) Coefficient of determination (R^2)

(5) Corrected Akaike information criterion (*AICc*)

(6) Bayesian information criterion (*BIC*)

Finally, each statistical criterion was assigned a rank from 1 to 14 (1=Best fit and 14=Worst fit); the ranks obtained across the criteria were summed for each model to yield a final score (FS), with the model achieving the lowest final score representing the best fit.

Results and Discussion

Characteristics of the soil

The *SOC* stock (Mg ha^{-1}) showed a significant difference (p<0.05) between the plantations. The mean values were 92.2±8.5 and 124.4±10.8 for Plantation A and Plantation B, respectively.

The amount of *C* incorporated into the soil depends on carbon fluxes within the ecosystem, particularly the incorporation of carbon derived from leaf litter (Liao et al., 2010). In plantations of various forest species in central Mexico, *SOC* ranged from 85.8 to 118.8 Mg ha^{-1} (García-Martínez et al., 2024). In temperate forests of state of *Durango*, Mexico, the average is 112.2 Mg ha^{-1} (Vargas-Larreta et al., 2023). Meanwhile, in managed *Abies religiosa* forests in the State of Mexico, the *SOC* stock was 129.1 Mg ha^{-1} (Martínez-Campos et al., 2025), and in pine-oak forests within the Monarch Butterfly Reserve in the State of Mexico, it is 103 Mg ha^{-1} (Pérez-Ramírez et al., 2013).

Chemical properties differed between the plantations (Table 2). Soil fertility in Plantation B was characterized by higher contents of *SOM*, *N*, *Ca*, and *Mg*. These variables are key determinants of growth and productivity in forest ecosystems, as *SOM* regulates nutrient availability, moisture retention capacity, and soil microbial activity (Lal, 2004; Six et al., 2002).

Table 2. Soil fertility assessment in two commercial *Pinus patula* Schiede *ex* Schltdl. & Cham. forest plantations located in *Villa de Allende*, State of Mexico, Mexico.

Variable	Plantation A	Diagnosis	Plantation B	Diagnosis
SOM (%)	5.3±0.7 b	Low	6.5±0.9 a	Medium
N (%)	19±3.8 b	Low	22±4.4 a	Medium
P (ppm)	8.0±2.4 a	Medium	5.5±1.7 b	Medium
K (meq 100g^{-1})	0.40±0.08 a	Medium	0.4±0.07 a	Medium
Ca (meq 100g^{-1})	3.9±0.6 b	Low	4.7±0.7 a	Medium
Mg (meq 100g^{-1})	0.4±0.06 b	Very low	0.6±0.09 a	Low
Na (meq 100g^{-1})	0.1±0.04 b	Salt free	0.3±0.12 a	Low
CEC (meq 100 g^{-1})	4.81±0.61 b	Very low	6.0±0.12 a	Low
pH	6.2±0.18 a	Moderately acidic	6.4±0.19 a	Moderately acidic
EC (mS cm^{-1})	0.06±0.02 a	Salt free	0.05±0.01 a	Salt free

Means followed by different letters in the same row indicate a significant difference (p<0.05) according to Student's *t*-test.

In particular, the higher *N* content in Plantation B could explain the superior basal area accumulation, given that this nutrient is often limiting for the growth of *Pinus* species due to its direct influence on woody biomass production (Prescott, 2002; Vitousek & Howarth, 1991). The better *P* level in Plantation A is linked to its suitability for forestry, whereas Plantation B had historically been used for agriculture, which depleted the available nutrient. Low soil *P* levels have been observed in forest plantations established on former agricultural plots (García-Martínez et al., 2024). High cation exchange capacity (*CEC*) and the availability of *Ca* and *Mg* promote root development and nutrient uptake efficiency (Weil & Brady, 2017). The soil conditions of this plantation account for the superior radial growth and *C* storage per tree. Diameter and basal area are highly sensitive to soil fertility and serve as the primary predictors of aboveground tree carbon (Balderas-Torres & Lovett, 2013; Chave et al., 2014).

Tree characteristics

The greater average tree height recorded in Plantation A (Table 3) was associated with high stand density, which increased competition for light and promoted apical growth. In forest plantations older than 20 years, high densities have been shown to positively affect height growth (Kremer et al., 2025). This occurs because, in dense stands, trees prioritize stem elongation to reach the upper canopy (Poorter et al., 2017; Pretzsch & Schütze, 2016).

Table 3. Tree characteristics in two commercial *Pinus patula* Schiede *ex* Schltdl. & Cham. forest plantations located in *Villa de Allende*, State of Mexico, Mexico.

Locality	**Height (m)**	**Diameter (cm)**	**Basal area (cm^2)**	**Carbon (kg árbol^{-1})**
Plantation A	20.8±3.3 a	19±4.4 b	300.8±131 b	68.7±33 b
Plantation B	19.4±3 b	22.8±6 a	434.4±219 a	104.9±60 a

Means with different letters in the same column indicate a significant difference (p<0.05).

In Plantation B, the greater growth in tree diameter and basal area could be explained by reduced competition among individuals and greater resource availability per tree—such as water, nutrients, and growing space. Louw and Scholes (2006) observed positive correlations between Site index (*SI*) and soil properties, indicating that moisture and nutrient availability play a fundamental role in site productivity and foster higher growth rates and timber yields in *P. patula*. For the same species, García-Aguilar et al. (2017) concluded that stands classified as excellent quality ($SI>33$) showed average diameters of 38.5 cm and heights of 34.5 m, whereas in low-quality sites ($SI<24$), the values were 26.0 cm and 22.6 m, respectively. Since timber volume depends primarily on tree diameter and height, these results suggest a higher potential for timber production on better-quality sites.

Regarding planting spacing, tree diameter in *Pinus taeda* L. after 24 years was lower in high-density plantations (Jeton-Cardoso et al., 2013). Consequently, reducing planting density promotes radial stem expansion, thereby increasing basal area and timber volume (Pretzsch & Schütze, 2016).

Plantation density affects biomass growth rates (Avendaño-Yáñez et al., 2019). The amount of *C* stored per tree differs from the amount stored across the plantation as a whole. In the present study, Plantation A stored 36.2 kg less *C* per individual, despite having a higher number of trees per hectare. However, this difference was not reflected in the stored aboveground carbon per unit area, which was 75.6 and 73.7 Mg ha^{-1} for Plantation A and Plantation B, respectively. There is evidence that dense stands tend to maximize height but not necessarily individual biomass (Poorter et al., 2017). Studies on *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* plantations indicate that tree biomass is positively correlated with planting density at early ages (up to 25 years); however, in the long term, planting density (833 to 2 500 trees ha^{-1}) shows no difference regarding biomass accumulation and carbon storage (Marziliano et al., 2015). On the other hand, Kholdaenko et al. (2022) observed in *Picea obovata* Ledeb. that tree-level productivity (stem volume and basal area) was negatively affected by stand density, whereas stand-level productivity was enhanced.

The results of this study suggest that effective silvicultural practices, such as thinning, could promote tree growth, given that such activities are not commonly performed in the study area's forest plantations. In *Pinus taeda* plantations, it has been shown that early thinning (at 17 years) significantly improves biomass accumulation and carbon sequestration and storage compared to late thinning (at 32 years) or unthinned stands (Tavankar et al., 2025). Finally, forest production systems are key to achieving net-zero CO_2 emission goals; consequently, climate change mitigation is a fundamental priority in a sector traditionally dominated by timber production and biodiversity conservation (Olsson & Johansson, 2025). Therefore, current forest management must balance the economic profitability derived from timber production with CO_2 sequestration (Hiltunen et al., 2021).

Diameter-height models

The 14 fitted models yielded low coefficients of determination, ranging from 0.25 to 0.34 (Table 4); such models typically exhibit this level of variability. Based on the final ranking, the functions with the best fit criteria values were MG1 and MS, with final scores of 5 and 10, respectively; however, the predicted curves for both models were inconsistent with biological tree growth, as the fitted line tended to decline for individuals with larger diameters. In contrast, the MT1 model—despite exhibiting an asymptotic curve—better represented the biology of tree growth. Consequently, the latter model was selected to predict tree height (Figure 2). Residuals for the selected model showed a normal distribution (W=0.9924, p>0.05) (Figure 2). Biological interpretation was considered a criterion complementary to statistical fit.

Table 4. Goodness-of-fit statistics for models analyzed to predict *Pinus patula* Schiede *ex* Schltdl. & Cham. height in two plantations in *Villa de Allende*, State of Mexico, Mexico.

Model	***MSE***	***RMSE***	***R^2***	***AICc***	***BIC***	**FS**
MG1	4.5 (1)	2.13 (1)	0.34 (1)	776.72 (1)	789.29 (1)	5
MS	4.52 (2)	2.14 (2)	0.33 (2)	777.51 (2)	790.08 (2)	10
MT1	4.66 (3)	2.17 (3)	0.31 (3)	782.89 (3)	795.46 (3)	15
MC	4.68 (4)	2.18 (4)	0.31 (4)	783.66 (4)	796.23 (4)	20
MG2	4.82 (10)	2.2 (8)	0.29 (8)	787.05 (7)	796.51 (5)	38
MC5	4.83 (11)	2.21 (11)	0.29 (11)	787.34 (9)	796.8 (6)	48
MC3	4.87 (12)	2.22 (12)	0.28 (12)	788.93 (12)	798.39 (7)	55
MC2	4.75 (5)	2.19 (5)	0.3 (5)	786.26 (5)	798.83 (8)	28
MC4	4.75 (6)	2.19 (6)	0.3 (6)	786.26 (6)	798.83 (9)	33
MC1	4.77 (7)	2.2 (7)	0.3 (7)	787.18 (8)	799.75 (10)	39
MT2	4.8 (8)	2.21 (9)	0.29 (9)	788.23 (10)	800.8 (11)	47
MC7	4.8 (9)	2.21 (10)	0.29 (10)	788.33 (11)	800.9 (12)	52
MC6	5 (13)	2.24 (13)	0.26 (13)	793.38 (13)	802.84 (13)	65
MG3	5.12 (14)	2.27 (14)	0.24 (14)	797.73 (14)	807.19 (14)	70

MSE = Mean squared error; *RMSE* = Root mean squared error; *AICc* = Corrected Akaike information criterion; *BIC* = Bayesian information criterion; FS = Final score.

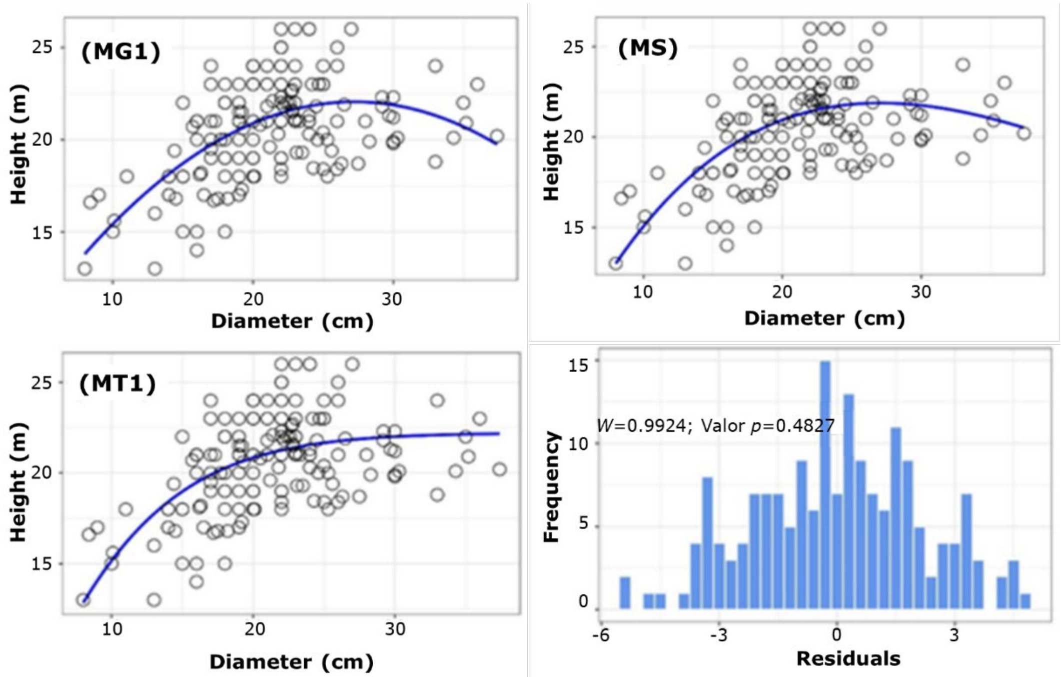


Figure 2. Plot of observed and predicted values (blue line) for the MT1 model fitted to predict *Pinus patula* Schiede *ex* Schltdl. & Cham. height, and a histogram of the selected model's residuals.

Based on the significance values of the fitted model parameters, most were found to be significant; however, five models (MT2, MC1, MC2, MC4, and MC7) did not have statistically significant values for all their parameters (Table 5). The results of this study align with data published by García-Cuevas et al. (2017), who obtained highly significant coefficients; however, they differ regarding R^2 values, as those authors obtained values exceeding 0.90 for allometric relationships in tropical species in the state of *Quintana Roo*. Nevertheless, the lack of significance in certain parameters of models MT2, MC1, MC2, MC4, and MC7 suggests a low explanatory contribution from the independent variable—a situation also documented in height-diameter models, where biological variability and stand structural heterogeneity make it difficult to obtain robust parameters (Quiñónez-Barraza et al., 2012). In particular, modeling total height as a function of diameter often yields lower coefficients of determination and greater residual dispersion compared to diameter or volume models, due to the influence of ecological and competition factors not explicitly included in the equation (García-Cuevas et al., 2017; Quiñónez-Barraza et al., 2012).

Table 5. Values and significance of coefficients for the models analyzed for *Pinus patula* Schiede *ex* Schltdl. & Cham.

Model	b_0	*Pr*(>|*t*|)	b_1	*Pr*(>|*t*|)	b_2	*Pr*(>|*t*|)
MC	22.4307	<0.0001	0.1515	0.0003	1.52138	0.0394
MT1	22.2116	<0.0001	0.0605	<0.0001	1.27810	<0.0001
MT2	3.2303	<0.0001	3.5234	0.0221	-2.42738	0.3536
MC1	23.8586	<0.0001	16.2435	0.3647	1.58630	0.0023
MC2	1.9906	0.0003	2.1244	0.4258	0.04272	<0.0001
MC3	27.3390	<0.0001	6.5510	<0.0001		
MC4	23.4098	<0.0001	0.0201	0.4094	1.99063	0.0004
MC5	26.5416	<0.0001	5.1666	<0.0001		
MC6	9.1117	<0.0001	-0.7402	<0.0001		
MC7	27.3686	0.829	-104.2119	0.8600	-0.97780	0.4800
MS	2.3824	0.0023	0.8763	<0.0001	-0.00754	<0.0001
MG1	5.5012	0.0030	1.2156	<0.0001	-0.02232	<0.0001
MG2	26.3438	<0.0001	-4.8829	<0.0001		
MG3	2.2923	<0.0001	0.2426	<0.0001		

Pr(>|*t*|) = 95 % statistical significance associated with each coefficient in a regression model; b_0, b_1, b_2 = Regression model parameters.

Consequently, although most models demonstrate overall statistical validity, further evaluation is needed regarding additional transformations, the inclusion of complementary dendrometric variables, or even mixed-effects approaches to capture intra- and inter-specific variability at the site; furthermore, the results of the fitted models should be interpreted with caution.

Various allometric models have been developed in Mexico; however, the diversity of species and environmental conditions increases the need to develop new models with lower error rates (Hernández-Ramos et al., 2024), particularly in areas designated for forestry. The resulting equations are applicable to forest inventories, the reconstruction of scenarios following silvicultural interventions or catastrophic natural events (García-Cuevas et al., 2017), and yield prediction prior to the establishment of new forest plantations.

Conclusions

Soil fertility and planting density were the factors that most influenced tree growth and productivity in the studied *Pinus patula* plantations. Trees in Plantation B—characterized by higher levels of *SOM*, *N*, *Ca*, *Mg*, and *CEC*—exhibited greater diameter, basal area, and carbon accumulation; conversely, the higher density of Plantation A favored height growth due to competition for light. Despite differences observed at the individual tree level, carbon storage per hectare was similar across plantations, demonstrating a compensatory effect between density and individual tree growth. The MT1 allometric model proved to be a viable option for estimating height based on diameter. These results highlight the importance of jointly considering edaphic conditions and silvicultural management to optimize timber production and carbon storage in the studied plantations.

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Conflict of interest

The authors declare no conflict of interest.

Contribution by author

René García Martínez: planning and execution of fieldwork and laboratory work, manuscript drafting; Maricruz Tenorio Calixto: execution of fieldwork and laboratory work, geographic data processing; Juan Carlos Montoya Jiménez: statistical data analysis, geographic data processing, manuscript drafting; Luis Alberto León Bañuelos: drafting and revision of the manuscript; Marlín Pérez Suárez: drafting and revision of the manuscript.

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