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Establishment and Monitoring of a *Pinus greggii* Engelm. ex Parl. Plantation as a Climate Change Mitigation Strategy in Huehuetla, Hidalgo

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Abstract

Climate change, as a global phenomenon, has affected the planet in multiple ways, altering weather patterns and prompting the search for alternatives and strategies for mitigation and adaptation. Forest plantations have emerged as an environmental option due to their potential for CO_2 capture, making it essential to identify tree species that can contribute to this effort. One method for evaluating a species' adaptability to specific climatic conditions is climatic matching. In this study, *Pinus greggii* Engelm. ex Parl. was evaluated for its potential to adapt to the subtropical conditions of Huehuetla, Hidalgo—a region with high potential for restoring degraded lands and supporting fast-growing species. Climatic parameters considered included cardinal temperatures, precipitation range, and altitude, along with tree measurement characteristics: height and basal diameter. The species showed a 50 % adaptation rate to the natural conditions, primarily attributed to altitude, given a 300-meter difference between the planting site and the lower distribution limit of the species. Growth was deemed acceptable, as after 24 months of monitoring and evaluation, the trees reached an average height of 94.6 cm and a basal diameter of 1.6 cm. Individual trees exhibited a diameter at breast height of 1.14 cm, which translated to an average volume of 147.5 cm^3 per tree, equivalent to 61.81 g of stored carbon.

Keywords: Climate homologation, *Pinus greggii*, Engelm. Ex Parl., environmental services.

Introduction

In recent years, forest plantations in Mexico have increased due to the opportunity they represent for enhancing timber production. These plantations are defined as the establishment and management of species on land designated primarily for forest use. As a result, the total area covered by commercial forest plantations (CFP) nationwide has reached 373 127.17 ha, of which timber species account for 85.2%. These plantations are primarily distributed across the states of Veracruz, Tabasco, and Campeche (CONAFOR, 2024; Diario Oficial de la Federación, 2024). In addition, forest plantations play a crucial role in mitigating the effects of climate change. In southern and southeastern Mexico, fast-growing species such as white teak (*Gmelina arborea* Roxb.), teak (*Tectona grandis* L.f.), and eucalyptus (*Eucalyptus* spp.) have been widely used for timber production (Martínez-Zurimendi, 2015). In central Mexico, species from the *Pinus* genus are commonly planted, with *Pinus greggii* Engelm. ex Parl. being one of the most frequently used. This species is particularly valued for its ability to restore eroded soils, as well as its high potential for carbon sequestration, drought tolerance, adaptability to temperature fluctuations, and resistance to certain pests (López et al., 2017; Martínez-Sifuentes et al., 2020; Ortiz et al., 2021; Villegas-Jiménez et al., 2013). According to Carrillo-Castañeda et al. (2024), *P. greggii*, along with *P. pseudostrobus* and *P. devoniana*, demonstrated a high capacity for carbon sequestration when established for the restoration of severely degraded soils in Michoacán.

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Moreover, the increase in atmospheric CO_2 has triggered extreme weather events—such as floods, intense hurricanes, and others—resulting in both human and economic losses worldwide. In response, the Kyoto Protocol of 1997 requires developed countries to reduce their greenhouse gas emissions. It also offers flexible mechanisms, such as the Clean Development Mechanism (CDM), which promotes carbon capture and CO_2 sequestration through forest biomass (IPCC, 2014; Gómez-Guerrero, et al., 2021).

In the municipality of Huehuetla, there have been some attempts to establish small-scale plantations on private land, primarily to improve shade for coffee plantations and to obtain firewood. Arteaga and Castelán (2008) established an agroforestry plantation combining white teak (*Gmelina arborea* Roxb.), teak (*Tectona grandis* L.f.), and pink cedar (*Acrocarpus fraxinifolius* Wight & Arn.) with coffee. Their findings indicated that pink cedar and white teak were the species that adapted best to the site conditions. Huehuetla's altitudinal range spans from 400 to 1 300 meters above sea level and includes three different climate types, providing an opportunity to test various species with different temperature tolerances. According to Medina-Pérez et al. (2023), the Sierra Otomí-Tepehua —which includes the municipalities of Huehuetla, San Bartolo Tutotepec, and Tenango de Doria—is highly vulnerable to extreme hydrometeorological events. These are largely driven by deforestation and the conversion of forest land to agricultural and livestock uses, with landslides caused by heavy rainfall identified as one of the main regional hazards.

In light of these considerations, the current approach to forest plantations should be strategic, aiming to mitigate the effects of climate change—particularly through CO_2 capture, which is part of the payment for environmental services scheme (FAO, 2022; UNDP, 2023). This represents a local action with global impact. Consequently, there is a clear need to establish forest plantations and conserve natural forests. In the case of Huehuetla, Hidalgo, *Pinus greggii* appears to be a promising species, as it is well-suited to the municipality's natural conditions due to its subtropical characteristics (Perry, 1991; Ramírez-Herrera et al., 2005; Martínez-Sifuentes et al., 2020). Furthermore, Ortiz et al. (2021) recommend using *P. greggii* provenances from northern and central Mexico, where the species is endemic. Its genetic plasticity allows it to thrive on eroded soils, making it highly valuable for watershed protection and the restoration of degraded areas. Additionally, it exhibits rapid growth in such environments.

This implies the use of methodologies that address the degree of species adaptation to environments different from their natural distribution, such as climatic matching. In this sense, species distribution is limited by physiological, ecological, and biogeographic factors, which make it difficult to accurately determine a species' distribution area, as it is a dynamic phenomenon (Maciel-Mata, 2015). Climatic matching aims to expand the adaptation range of species from a different place of origin than the one where they are intended to be established, taking into account climatic parameters, with the most relevant being extreme temperatures, absolute minimum temperature, and the seasonal distribution and annual volume of precipitation (Golfari, 1963). Gómez (2021) discusses the concept of ecological matching, which is more complex, as it considers lithological, physiographic, climatic, and soil characteristics that influence the degree of adaptation. Therefore, considering that *P. greggii* is distributed along the mountain range of the Sierra Madre Oriental, where the municipality of Huehuetla, Hidalgo is located, the use of climatic matching will allow for the extension of the local distribution range of this subtropical conifer species.

Thus, the objective of this study was to establish and monitor an experimental plantation of *Pinus greggii* Engelm. ex Parl. in the municipality of Huehuetla, Hidalgo to evaluate initial growth, adaptation potential, and carbon capture.

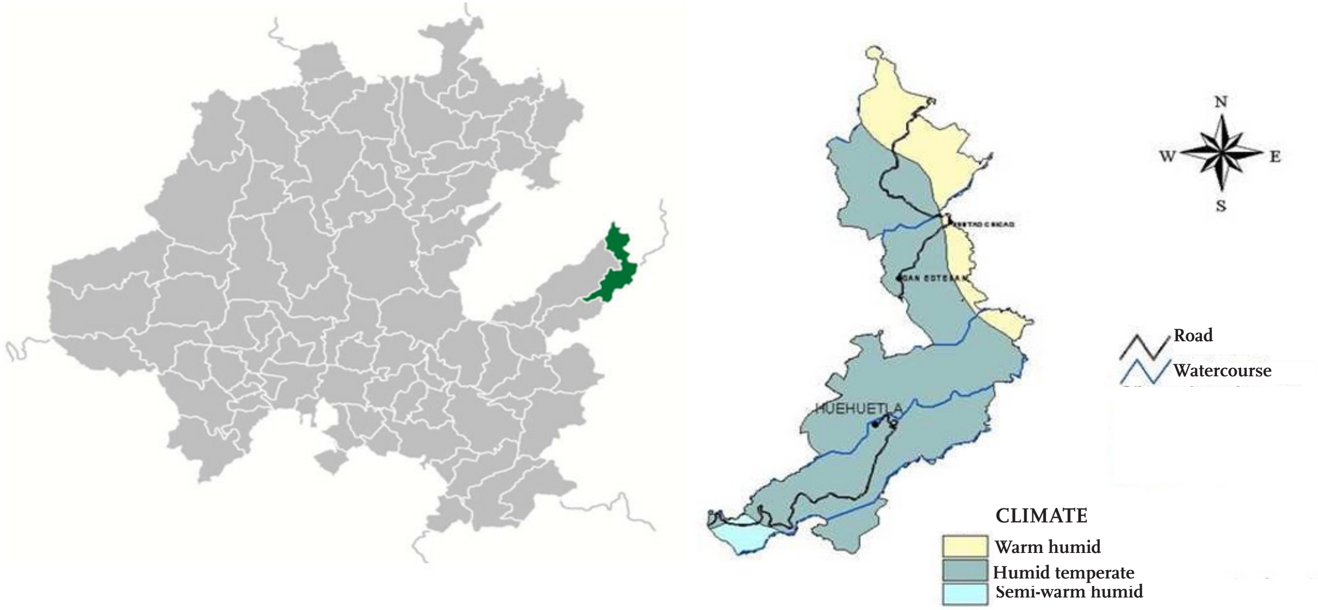
Materials and Methods

Study Area Description

The municipality of Huehuetla is located between 20° 23' and 20° 41' N and 97° 59' to 98° 10' W, situated in the northwestern and eastern part of the state of Hidalgo. It is part of the Tuxpan-Nautla region, within the coffee-growing area known as Otomí-Tepehua. According to García (2004), Huehuetla has three climate types: humid warm (Am) with summer rainfall, characterized by a short dry season during the cooler half of the year, yet with sufficient total annual precipitation to keep the soil moist year-round. This climate is intermediate between Af and Aw, resembling the former in total rainfall and the latter in annual distribution. The highest precipitation occurs in summer and part of autumn, when tropical cyclones affecting Mexico are most frequent, significantly increasing rainfall in this region. Other climate types present include humid sub-warm (ACf) with year-round rainfall, and humid temperate (Cm) with heavy rainfall during the summer. The average annual temperature ranges from 16 °C to 22 °C, with an average annual precipitation of 2 400 mm and elevation ranging from 400 to 1 300 meters above sea level. According to INEGI (2010), the predominant soil types are Umbrisol (56.95 %), Luvisol (36.2 %), Leptosol (4.32 %), and Phaeozem (2.33 %), with vegetation consisting of tropical rainforest and cloud forest. The plantation was established on Umbrisol soils, which, according to FAO (2025), are characterized by a dark layer rich in organic matter but with acidic pH (below 5.5) and low fertility. Figure 1 shows the location map of the municipality and the distribution of climate types.

Plantation Establishment

A total of 200 pine seedlings were planted, with an average height of 85 cm and a basal diameter of 8 mm, after



Source: Government of the State of Hidalgo (2010). Compilation based on INEGI data.

Figure 1. Location of the municipality of Huehuetla, Hidalgo, and climate.

having been grown in a nursery for two years. The site was prepared manually using the common pit system, since the slope of the terrain did not allow mechanization. Pits measuring 40 x 40 x 40 cm were dug to create favorable conditions for root establishment and to increase survival chances. The spacing between plants was 2.5 x 2.5 m in a square grid design. The plantation was established in June 2022 under a humid sub-warm climate. The seedlings originated from Estado de México.

Climatic matching

As a tool to assess adaptability to specific regions with particular climatic conditions, climatic matching was carried out using the FAO (1981) methodology, which considers the climatic variables of a species' place of origin in relation to the site where it will be introduced. Initially, the thermal profile of *Pinus greggii* was obtained. Then, the temperature data for the municipality of Huehuetla, reported by the National Meteorological Service, were evaluated and adjusted using the Regional Thermal Gradient for the planting site. The following climatic parameters were considered: minimum, optimal, and maximum temperatures, precipitation range, and altitude—for both the species and the plantation site.

The climatic requirements used for *P. greggii* included an altitudinal range of 1 400 to 2 600 meters above sea level, vital cardinal temperatures from 12 to 20 °C, with an optimal range of 16.8 to 17.5 °C, and extreme or lethal cardinal temperatures of 45 °C and -9 °C. Precipitation range between 640 and 1 370 mm, although it may extend from 500 to 2 900 mm (Dvorak et al., 1996; Ramírez-Herrera et al., 2005; Muñoz et al., 2012; Rodríguez et al., 2013). However, Martínez-Sifuentes et al. (2020) reported an average annual temperature of 25.4 °C in the distribution area in the Sierra Madre Oriental.

For the case of the municipality of Huehuetla, the thermal range considered was 14.0 to 32.5 °C, with an annual precipitation of 2 400 mm. The specific elevation of the planting site was 1 100 meters above sea level.

Evaluation and Monitoring

A total of four evaluations of survival and growth were conducted following the planting date, one every six months (December 2022, June 2023, December 2023, and June 2024). Tree measurement characteristics considered were height, basal diameter, and diameter at breast height (DBH). In the fourth evaluation, some trees reached or exceeded a height of 1.30 meters; for these, volume was calculated using the following formula:

$$V = \frac{\pi}{4} * d^2 * A * Cm$$

Where:

V = total tree volumen in cm^3

d = diameter at breast height (cm)

A = total tree height (cm)

Cm= form factor or morphic coefficient. This coefficient is used to correct the overestimation of tree volume that results from calculating it as a perfect cylinder. A value of 0.65 was used for conifers.

Initial Estimation of Carbon Content in Biomass

The amount of biomass in tree stands, expressed in terms of carbon content, is estimated to be approximately 50 %, regardless of ecosystem type, species, or region (Díaz et al., 2007; Acosta et al., 2009; Ronquillo-Gorgúa, et al., 2022). Similarly, the IPCC (2005) states that the carbon content in a tree is equivalent to 50 % of its biomass. Therefore, the carbon content for young trees is estimated using the following equation:

Biomass x Carbon content = Carbon stock.

Several methods are used to estimate carbon stock; however, all are subject to a certain degree of approximation. According to Portillo et al. (2023), the margin of error in biomass estimation—and therefore in carbon stock—ranges from 53 % to 80 %, regardless of the method used. Consequently, this study employed three estimation methods, including:

1) the method recommended by CONAFOR (Comisión Nacional Forestal), expressed by the following formula:

$$C = V * FD * CC * BEF$$

Where:

C: amount of carbon stored per tree

V: volume in m^3

FD: wood density factor; for conifers, the value is 0.48

CC: carbon content by species; for *P. greggii*, it is 51 %

BEF: biomass expansion factor; the value is 1.3

2) The Acosta et al. (2009) method, expressed with the allometric equation for the determination of biomass obtained for *Pinus patula* Engelm. Ex Parl. and other pine species given by:

$$B = 0.0948 * DN^{2.4079}$$

Where:

B: biomass (kg)

DBH: diameter at breast height (cm)

Multiplying the biomass by 0.50, which means that 50 % of the tree biomass is *C*.

3) The method proposed by the IPCC (2005) recommends multiplying the estimated tree volume by the carbon fraction, which is equivalent to 0.5.

Results and Discussion

The thermal table for *P. greggii* is presented in Table 1. This table made it possible to determine the species' adaptation percentage to the environmental conditions of Huehuetla, specifically at the plantation site, after subtracting the temperature differential (3.4 °C) resulting from the Regional Thermal Gradient.

An adaptation rate of 50 % to the local conditions was observed, which may be attributed to altitude as a natural limiting factor, given the 300-meter difference between the plantation site and the lower altitudinal limit of the species' natural distribution. However, as noted by Gómez (2021), although altitude is part of the physiographic characterization, it may also be influenced by factors such as lithology and soil properties. Similarly, Romahn-Hernández et al. (2020), in a study on the natural distribution of sacred fir (*Abies religiosa* (Kunth) Schltdl. et Cham.), reported high mortality rates among mature trees at the lowest altitudinal range. They also observed lower vigor in both mature and young trees, concluding that altitude is a key factor in the survival of sacred fir and suggesting an upward altitudinal shift in response to climate change.

In terms of temperature, the evaluated area falls within the thermal thresholds reported by Ramírez-Herrera et al. (2005), whose optimal range is between 16 and 18 °C. Regarding precipitation, the annual 2 300 mm recorded in Huehuetla falls within two of the reported ranges for *P. greggii*: 500 to 2 900 mm and 750 to 2 300 mm. Based on these favorable conditions, planting was carried out on June 26 and 27, 2022, when the soil was sufficiently moist following the onset of the rainy season. Initial measurements of the specimens—specifically, height and basal diameter—were taken on June 28, 2022, after having spent two years in the nursery.

The growth performance of the individuals is considered acceptable. After 24 months of monitoring and evaluation, 85 % of the 104 surviving trees exceeded 1.30 m in height. The average height was 1.85 m, with a maximum of 3.45 m (Figure 2). The average diameter at breast height was 1.14 cm, which allowed for an initial volume estimate of 147.5 cm^3. Additionally, the mean basal diameter exceeded 20 mm, with the largest reaching over 50 mm (Figure 3). Table 2 presents the estimated statistics, showing the percentage increase in both height and basal diameter two years after planting, relative to initial measurements.

Regarding survival, a gradual mortality of individuals was observed, with evaluation results showing survival rates of 85.5%, 79.5%, 67.5%, and 51% in the final assessment. Among the main factors contributing to mortality was pest damage, primarily by the stem borer (*Oncideres* spp.), which caused girdling of the stem and restricted sap flow in affected individuals. This was observed only during the first two evaluations. Additionally, mortality was attributed

Table 1. Thermal table generated for *P. greggii* Engelm. ex Parl., based on its cardinal temperatures.

Temperature range (°C)			Value
	Above 25.2		0
23.5		25.1	1
21.8		23.4	2
20.1		21.7	3
18.4		20.0	4
16.7	17.5	18.3	5
15.0		16.6	4
13.3		14.9	3
11.6		13.2	2
9.9		11.5	1
	Below 9.8		0

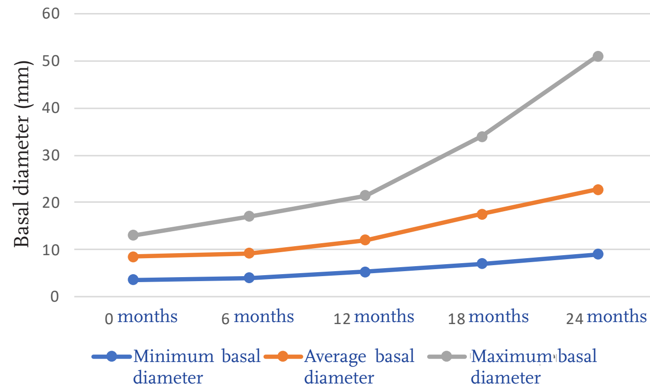


Figure 3. Basal diameter growth of *P. greggii* Engelm. ex Parl. in Huehuetla, Hidalgo.

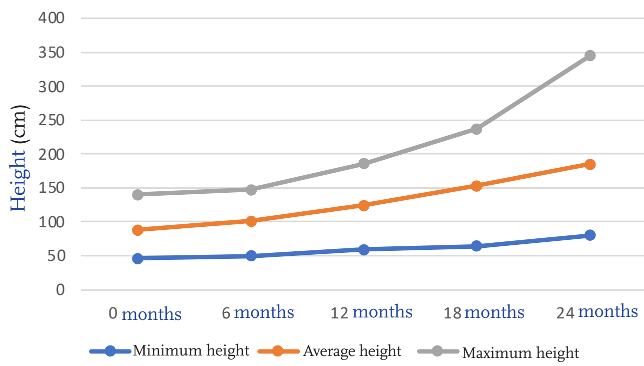


Figure 2. Height growth of *P. greggii* Engelm. ex Parl. in Huehuetla, Hidalgo.

to the exceptional and extreme drought that occurred in 2024, particularly during March, April, and May. This drought was driven by anticyclonic systems that caused heatwaves, resulting in hot to very hot conditions and a lack of rainfall. The drought affected 32 municipalities in the state of Hidalgo and nearly the entire national territory (CONAGUA-SMN, 2024). Despite these challenges, the survival percentage remained higher than the national average for reforestation efforts (36 %), although it fell short of the 80 % threshold required by the Comisión Nacional Forestal during the first year (Vázquez-Cisneros et al., 2018).

Ortiz et al. (2021) tested 13 provenances from northern and central Mexico on eroded soils in the Mixteca region of Oaxaca, finding high adaptability. Based on these results, the provenance from Estado de México was selected. Similarly, Flores et al. (2014) recommend the use of any provenance due to their strong performance, particularly as *P. greggii* is native to the Sierra Madre Oriental, including the state of Hidalgo (Domínguez-Calleros et al., 2017). Hernández-Martínez et al. (2007) also note that *P. greggii* Engelm. var. *australis* grows naturally in the municipality of Tenango de Doria, Hidalgo, which borders Huehuetla, thus potentially extending the species' adaptation range.

P. greggii has been used for its rapid growth and potential in programs aimed at the restoration of degraded soils and carbon sequestration. López et al. (2017) estimated the amount of carbon stored in soils associated with *P. greggii* and *P. oaxacana*, finding high levels of carbon both in the soil and leaflitter, and recommended their use on soils under extreme erosion conditions. Similarly, Muñoz et al. (2012) evaluated the survival and growth of *P. greggii* during the initial growth stage, finding that after six years, individuals exceeded five meters in height with a survival rate of 60 %.

In this context, the initial merchantable volume of pines was 1.475 x $10^{4}\cdot m^{3}$ obtained after 24 months of monitoring. When expressed as carbon, this corresponds to 46.94 g per tree using the CONAFOR method. Using

Table 2. Estimated statistics for height and basal diameter variables.

Parameter	Variables					
	Initial height (cm)	Initial basal diameter (mm)	Height at 24 months (cm)	Basal diameter at 24 months (mm)	Height increase (%)	Basal diameter increase (%)
Minimum value	46	3.6	80	9	53.96	85.71
Mean value	90.1	6.9	184.7	22.7	68.85	106.75
Maximum value	140	11.3	345	51	84.53	127.45
Range	94	7.7	265	42	95.26	138.03
Standard deviation	19.689	1.612	52.134	8.046		

the method by Acosta et al. (2009), the estimated carbon content was 64.98 g, and according to the IPCC (2005) method, 73.5 g were obtained. From these results, an average of 61.81 g of carbon stored in the aboveground biomass of each tree was calculated, representing 226.84 g of CO_2 removed from the atmosphere. This conversion considers the molecular weight ratio between CO_2 (44) and carbon (12) (Jiménez et al., 2013; Robledo, 2015; Jáuregui et al., 2022). Furthermore, Pacheco et al. (2007) highlighted the importance of *P. greggii* for carbon capture, reporting a storage potential of 17.9 $t \cdot ha^{-1}$ during the first six years, equivalent to 65 $t \cdot ha^{-1}$ of accumulated carbon dioxide. These findings support the classification of this species as having high carbon sequestration potential. The variations in carbon storage estimates are attributed to the use of indirect methods, which calculate tree biomass using allometric equations or mathematical models based on regression analyses involving tree variables such as diameter at breast height (measured at 1.30 m), commercial (hc)and total height (ht), diameter growth, basal area, and wood specific gravity. Alternatively, estimates can be derived from stem volume, dry weight, and an expansion factor to calculate total tree weight. The "average tree" technique is also used, which assumes that the average-sized tree contains an average quantity of biomass (Fonseca et al., 2013; Fonseca-González, 2017).

Moreover, tropical species have also been used due to their important environmental role, as tropical forests can capture more than 40 $t \cdot ha^{-1}$ of CO_2 per year, equivalent to 2.3 to 10 t of carbon (Robledo, 2015). Aguirre et al. (2018) estimated that in an Andean forest in Ecuador, one hectare can capture 42.29 $t \cdot ha^{-1}$ of carbon accumulated in the tree, shrub, herbaceous, and necromass strata; when considering only the tree stratum, the value was 26.56 $t \cdot ha^{-1}$. Similarly, Seppänen (2002) reported that in southeastern Mexico, high-yield eucalyptus plantations (40 $m^3 \cdot ha \cdot yr$) can sequester between 320 and 610 $t \cdot ha^{-1}$ of CO_2 over a seven-year period, equivalent to 91 to 175 $t \cdot ha^{-1}$ of carbon. As early as 2007, the Ibero-American Network on Environmental Physics and Chemistry published several works on carbon capture in terrestrial ecosystems across Ibero-America, highlighting the growing need to evaluate this environmental service in economic terms (Gallardo, 2007).

The underlying principle is that forest ecosystems can capture significant amounts of greenhouse gases (GHGs), especially CO_2. For this reason, there has been increasing interest in recent decades in enhancing carbon stocks in vegetation through forest conservation, reforestation, and related strategies. Many studies have demonstrated the capacity of forest species to store carbon in their biomass (Rodríguez et al., 2016; Ronquillo-Gorgúa et al., 2022). This capacity has led to the development of payment schemes for environmental services related to carbon capture, contributing to forest conservation, soil recovery in deforested areas, and the restoration of degraded ecosystems.

Conclusions

After 24 months of plantation establishment, the increase in height has been greater than 90 cm, while basal diameter has increased more than 1.5 cm, and diameter at breast height exceeded 1 cm. After 12 months, 28% of the trees had surpassed the minimum height of 1.30 m required to measure diameter at breast height (DBH), reaching 85% by the final measurement. This growth has resulted in an initial volume that, when quantified as carbon stored per tree, exceeds 60 g.

The contribution of this species to mitigating climate change may be significant, as reforestation and afforestation efforts are a priority strategy for capturing excess atmospheric carbon dioxide while simultaneously promoting the conservation of native forests.

Local climate matchin is expected to expand the distribution range of *P. greggii*, since regional temperatures fall within the species' thermal tolerance. This makes it a promising candidate for reforesting unproductive or degraded lands requiring conversion to forest use.

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