DOI: 10.29298/rmcf.v17i95.1606
Research article

Regeneration dynamics of *Pinus culminicola* Andresen & Beaman var. *culminicola* along an altitudinal gradient of *Cerro El Potosí*

Dinámica de regeneración de *Pinus culminicola* Andresen & Beaman var. *culminicola* en un gradiente altitudinal del Cerro El Potosí

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Fecha de recepción/Reception date: 3 de octubre de 2025.
Fecha de aceptación/Acceptance date: 24 de marzo de 2026.

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Abstract

The *Pinus culminicola* populations of *Cerro El Potosí*, *Nuevo León* state, Mexico, have been drastically reduced by fires, deforestation, and fragmentation, leaving only 30 ha isolated and with a low population density. This study evaluates how soil properties affect the regeneration of *P. culminicola* in *Cerro El Potosí*. The study was conducted in the temperate forest, at three altitudes (3 300, 3 500, and 3 700 masl). The natural regeneration of *P. culminicola* and the physical-chemical properties of the soil were evaluated. The data were analyzed using ANOVA and Tukey, nonparametric tests (Kruskal-Wallis, Mann-Whitney), and Pearson correlations. The results showed that adult individuals had larger diameters and crown areas at 3 700 masl, while seedlings predominated at 3 300 masl. The density of adult trees decreased with altitude, in contrast to that of seedlings. The pH was higher at 3 500 masl, electrical conductivity at 3 700 masl, and both carbon and organic matter increased gradually. In addition, regeneration showed positive correlations with organic matter, carbon, and textural fractions. It was concluded that only *pH* varied with altitude. Seedling growth decreased with increasing altitude, while adult growth increased. Regeneration was positively associated with organic carbon, a key factor for its success.

Keywords: Temperate forest, physical and chemical characteristics, correlation, mensuration parameters, seedlings, soil.

Resumen

Las poblaciones de *Pinus culminicola* del cerro El Potosí, Nuevo León, México, han sido reducidas drásticamente por incendios, deforestación y fragmentación, por lo que apenas permanecen 30 ha aisladas y con una baja densidad poblacional. Este trabajo evalúa cómo las propiedades del suelo afectan la regeneración de dicha especie en el lugar. El estudio se realizó en un bosque templado a tres altitudes (3 300, 3 500 y 3 700 msnm). Se evaluó la regeneración natural de *P. culminicola* y las propiedades físicas y químicas del suelo. Los datos se analizaron mediante ANOVA y *Tukey*, pruebas no paramétricas (*Kruskal-Wallis*, *Mann-Whitney*) y correlaciones de *Pearson*. Los resultados mostraron que los individuos adultos registraron mayores diámetros y áreas de copa a 3 700 msnm, mientras que las plántulas predominaron a 3 300 msnm. La densidad de árboles adultos disminuyó con la altitud, en contraste con la de plántulas. El *pH* fue más alto a 3 500 msnm, la conductividad eléctrica a 3 700 msnm y tanto el carbono, como la materia orgánica aumentaron gradualmente. Además, la regeneración presentó correlaciones positivas con materia orgánica, carbono y fracciones texturales. Se concluyó que solo el *pH* varió con la altitud. El crecimiento de plántulas disminuyó al aumentar la altitud, y en adultos aumentó. La regeneración se asoció positivamente con el carbono orgánico, factor clave para su éxito.

Palabras clave: Bosque templado, características físicas y químicas, correlación, dasometría, plántulas, suelo.

Introduction

Mexico has the greatest diversity of conifer species, harboring four of the six globally recognized families. The *Sierra Madre Oriental* and *Occidental* mountain ranges contain the greatest diversity of the *Pinus* genus, with almost 49 taxa (Gernandt & Pérez-de la Rosa, 2014). Temperate ecosystems support a large number of endemic species, highly susceptible to disturbance (Galicia et al., 2018). Deforestation and land-use change lead to the degradation of these forests, a global problem (Hu et al., 2021). Forests possess the capacity for natural regeneration, an essential process for their preservation and successional dynamics (Ribeiro et al., 2022).

Forest regeneration is conditioned by exposure, humidity (Flores-Rodríguez et al., 2022), altitude (Tovar-Cárdenas et al., 2024), climate, and soil properties (Norden, 2014), among other factors. Therefore, monitoring growth and regeneration is fundamental, as this process is key to ensuring the continuity of species and the stability of plant communities (Patiño-Flores et al., 2022).

In this context, vegetation promotes microbial activity and fosters trophic relationships that enrich soil dynamics and quality. Thus, analyzing soil properties, such as cation exchange capacity, organic matter, calcium, nitrogen, pH, and sand-to-clay ratios, is crucial for determining soil quality (García-Gallegos et al., 2023). It is recognized that the physical, chemical, and biological properties of soils change with altitude (Kamal et al., 2023). Consequently, the natural regeneration of species could be related to soil properties and influence seedling germination and establishment.

Such is the case of *Cerro El Potosí*, a Protected Natural Area (PNA) that harbors a high diversity of conifer species, among which *Pinus culminicola* Andresen & Beaman var. *culminicola* stands out. This species is endemic and listed as endangered in NOM-059-SEMARNAT-2010 (Secretaría de Medio Ambiente y Recursos Naturales [Semarnat], 2010). However, the distribution area of *P. culminicola* has been affected by disturbances of anthropogenic and natural origin, such as fires, deforestation, fragmentation, livestock grazing, and land-use change, this has reduced its distribution area to approximately 30 ha and caused the loss of nearly 40 % of its populations, currently keeping them in isolated conditions (Estrada-Castillón et al., 2014). Furthermore, a low population density has currently been recorded, consisting mostly of mature individuals (Tovar-Cárdenas et al., 2024).

Therefore, the objective of this study was to analyze the effect of soil physicochemical properties on the natural regeneration of *Pinus culminicola* var. *culminicola* along an east-facing altitudinal gradient on *Cerro El Potosí* in *Galeana*, *Nuevo León* state, Mexico.

Materials and Methods

Study area

The study was conducted in the temperate forest of the *Cerro El Potosí* Protected Natural Area in the state of *Nuevo León*, Mexico, which is part of the *Sierra Madre Oriental* mountain range (Figure 1). The altitudinal range of this mountain varies between 2 000 and 3 721 masl (Instituto Nacional de Estadística, Geografía e Informática [INEGI], 1986). The summit climates are classified as cold and extremely cold (García-Arévalo & González-Elizondo, 1991). The average temperature ranges from 7 to 14 °C, with minimums that can reach -3 °C (Instituto Mexicano de Tecnología del Agua [IMTA], 2016). The soil is a Lithosol or Protorendzina type, shallow (1-5 cm), and composed of limestone, with a high organic matter content and a slightly alkaline pH (7.5) (Rzedowski, 2006).

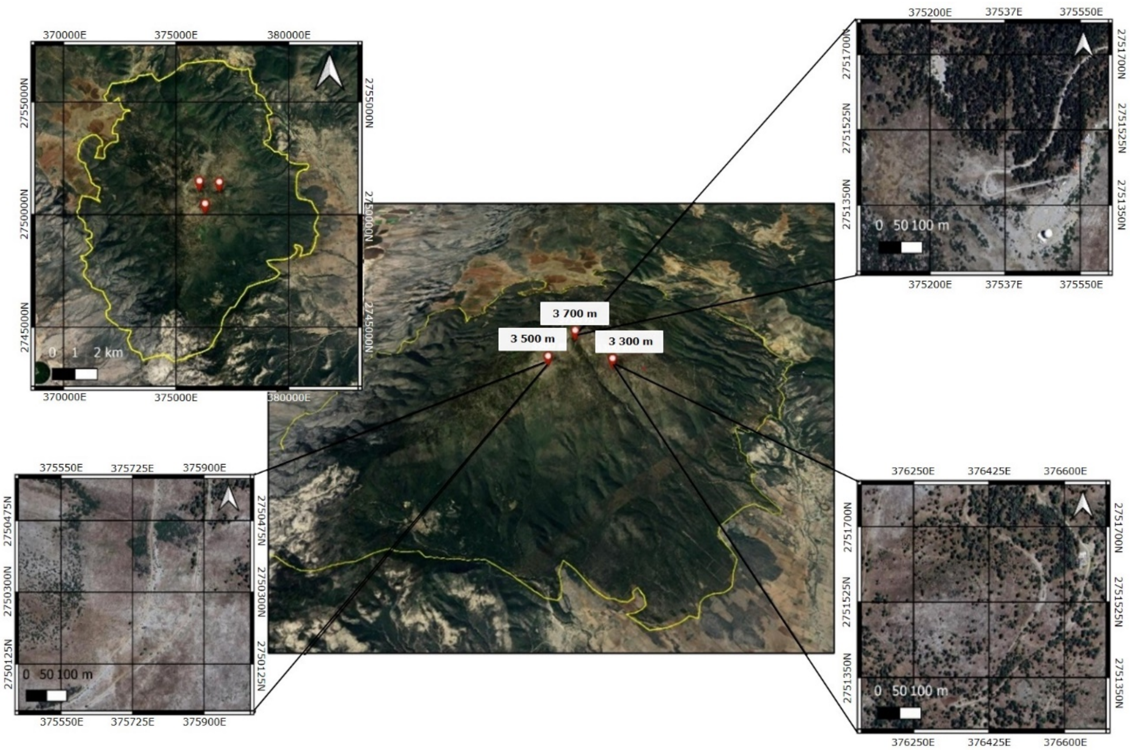


Figure 1. Study area and sampling sites in the *Cerro El Potosí* Protected Natural Area, *Nuevo León*, Mexico.

Sampling sites

The selection of sampling sites on *Cerro El Potosí* was based on data obtained by Tovar-Cárdenas et al. (2024). Three altitude levels were defined (3 300, 3 500, and 3 700 masl). At each level, four 400 m^2 circular plots were established to evaluate the natural regeneration of *P. culminicola* and the physicochemical properties of the soil (Figure 1). For the regeneration analysis, the diameter of *P. culminicola* var. *culminicola* individuals was recorded (using a model W606PM Lufkin® diameter tape), as well as the height and crown area measured from North to South and from East to West (using a model FCN Truper® 10 m measuring tape). Only specimens with a diameter of 7.5 cm or less were considered, according to the methodology established by the National Forest

Commission (Comisión Nacional Forestal [Conafor], 2018). To categorize the levels of natural regeneration, the methodology of Chauhan et al. (2008) was used, which classifies them into three categories: good, fair, and poor. Regeneration was considered good when the density of young trees was greater than that of adults. If both densities were equal or similar, it was classified as fair, while if the density of young trees was less than that of adults, it was categorized as poor. The Natural Regeneration Index (*NRI*) was also calculated according to the methodology proposed by Acosta et al. (2006), whose expression is as follows:

$$RNr = \frac{(ArRN + FrRN + CTrRN)}{3}$$

Where:

RNr = Relative natural regeneration

ArRN = Relative abundance of natural regeneration

FrRN = Relative frequency of natural regeneration

CTrRN = Relative size category of natural regeneration

Relative abundance was calculated from the number of individuals of each species in relation to the total number of individuals, expressed as a percentage. Relative frequency was obtained by dividing the number of sites where each species appeared by the total number of sampled sites.

For the physicochemical analysis of the soil, five subsamples (0-10 cm deep) were collected from each sampling site using a soil rake (model T-2000 Truper®). These were mixed to obtain a composite sample of 1 000 g of soil (Cantú-Silva et al., 2018). The samples (n=12) were sent to the Soil and Forest Nutrition Laboratory of the *Facultad de Ciencias Forestales* of the *Universidad Autónoma de Nuevo León* (Graduate School of Forest Sciences at the Autonomous University of *Nuevo León*), where they were subjected to a drying process at room temperature, sieved through a 0.2 mm mesh, and finally prepared for chemical analysis.

The assessed variables were: organic matter (*OM*) and organic carbon (*OC*) content, determined using the modified Walkley-Black method (Woerner-Petran, 1989). Soil *pH* and texture were determined according to NOM-021-RECNAT-2000 (Semarnat, 2002), using method AS-23 and procedure AS-09 (Bouyoucos hydrometric method), respectively. Electrical conductivity (*EC*) was determined using the rapid method in a 1:5 soil-water suspension (Woerner-Petran, 1989). *pH* and *EC* were estimated using a model 542 Corning® combination *pH* and conductivity meter. Bulk density (*BD*) was calculated using the cylinder method (Woerner-Petran, 1989).

Data analysis

The Levene and Shapiro-Wilk tests for homogeneity of variances were applied to verify the normality of data for all variables. For data that met the assumptions of normality and homogeneity (*pH*, electrical conductivity, bulk density, organic carbon, organic matter, texture: sand, silt, and clay), analysis of variance (ANOVA) and Tukey's test ($p<0.05$) were used. For variables that did not meet the aforementioned assumptions (stem diameter, height, and crown area), the Kruskal-Wallis and Mann-Whitney tests were used. Finally, Pearson correlations between soil variables and *P. culminicola* var. *culminicola* regeneration were determined at each altitude level. The analyses were performed using the statistical software Past4 version 4.7 (Hammer et al., 2001).

Results

Mensuration Parameters

At 3 700 masl, adult trees exhibited greater crown area and diameter, while the greatest tree height was recorded at 3 500 masl but without significant differences (*p*<0.05). In seedlings, crown area, height, and diameter were greater at 3 300 masl (*p*<0.01) (Table 1).

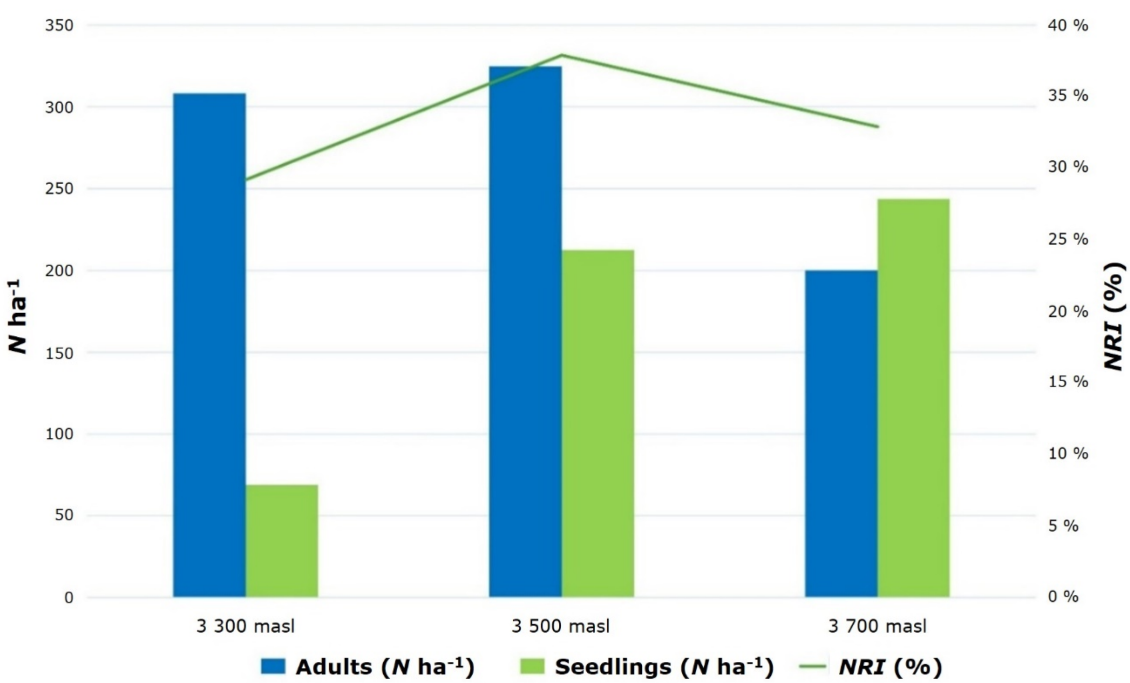
Table 1. Average values of mensuration parameters of adult trees and seedlings by altitude level.

Altitude	Development stage	Mensuration parameters		
		Crown area (cm^2)	Height (cm)	Diameter (cm)
3 300	Adults	62 642.88 a	145.97 a	8.72 b
	Seedlings	1 418.47 e	29.9 e	1.68 e
3 500	Adults	91 044.16 a	178.2 a	11.1 ab
	Seedlings	673.69 e	23.69 e	1.3 e
3 700	Adults	103 976.88 a	155.34 a	13.33 a
	Seedlings	37.51 d	8.76 d	0.39 d

Identical letters indicate similarity between means (adults: a, b, and c; seedlings: d, and e). Different letters only indicate a lack of similarity and should not be interpreted as evidence of significant differences.

Natural regeneration density

The highest density of adult trees and the lowest density of seedlings were recorded at 3 300 masl, with an *NRI* of 29 %, classified as low regeneration. At 3 500 masl, the density of adults decreased and that of seedlings increased, reaching the highest *NRI* (37 %), which is also considered low. At 3 700 masl, the lowest density of adults and the highest density of seedlings were observed with an *NRI* of 32 %, corresponding to regular regeneration (Figure 2).



NRI = Natural Regeneration Index.

Figure 2. Density of adult trees and seedlings of *P. culminicola* var. *culminicola* along an altitude gradient in the *Cerro El Potosí* Protected Natural Area, *Nuevo León*, Mexico.

Physicochemical soil analysis

pH was higher at 3 500 masl, with significant differences compared to the other levels ($p<0.05$). *EC* showed an upward trend with altitude, with no significant differences between levels. The *BD* was greater at 3 500 masl and less at 3 700 masl ($p>0.05$). *OC* and *OM* increased with altitude.

Regarding soil texture, a transition from loam soils (3 300 masl) to silty loam soils was observed at altitudes above 3 500 and 3 700 masl. Silt content increased slightly with altitude, while clay content decreased. The percentage of sand showed little variation (31.79 and 33.56 %) (Figure 3).

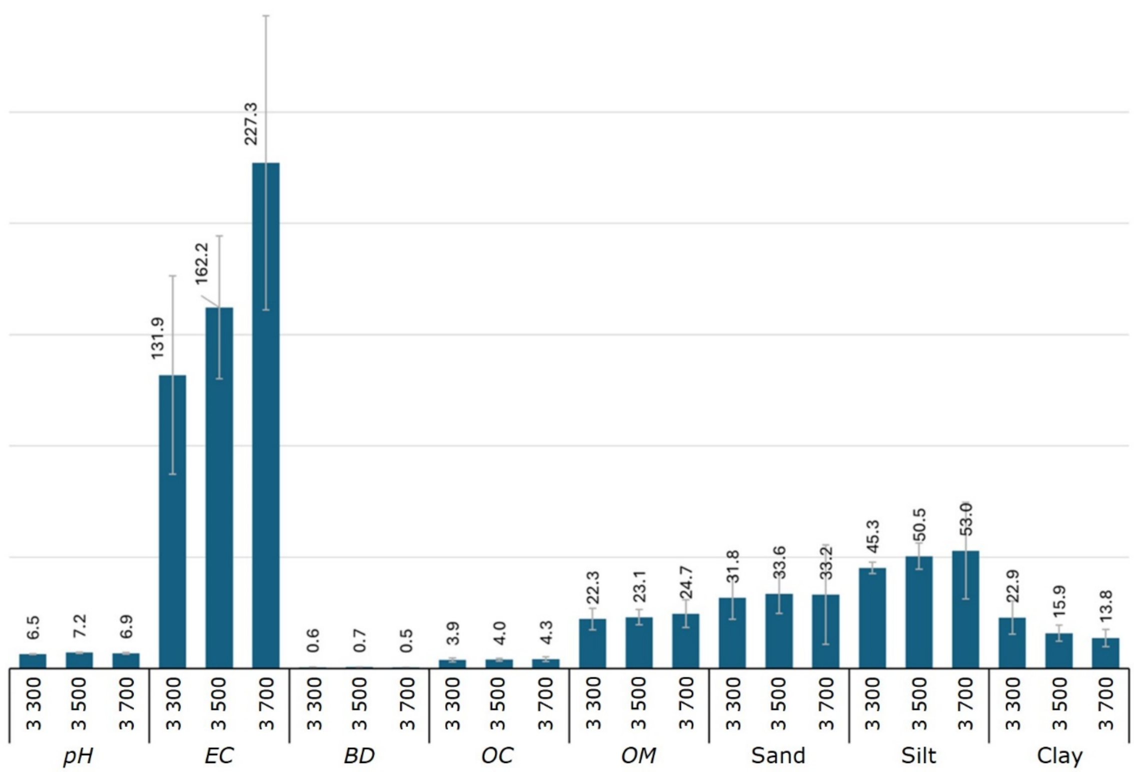


Figure 3. Mean values of soil parameters along the altitudinal gradient.

Correlation analysis

Significant correlation values were estimated between regeneration and the percentage of sand (*r*=0.61) at an altitude of 3 300 masl, as well as between *EC* with respect to sand (*r*=1), *OC*, and *OM* (*r*=0.76). Positive correlations (*r*=1) were observed between *OC* and *OM*, and between both and sand content. At 3 500 masl, regeneration (*r*=0.81) and *EC* (*r*=0.87) showed significant positive correlations with *OC* and *OM*. Similarly, positive associations were detected between *pH* and sand percentage (*r*=0.72). Finally, at 3 700 masl, a positive correlation was found between regeneration (*r*=0.82) and *EC* (*r*=0.8) with *OC* and *OM*, as well as a high correlation between *BD* and silt percentage (Table 2).

Table 2. Pearson correlation analysis of soil parameters.

					3 300 masl				
	Reg.	***pH***	***EC***	***BD***	***OC***	***OM***	**Sand**	**Silt**	**Clay**
Reg.		0.2	0.55	0.22	0.01	0.01	0.61	-0.18	-0.72
pH	0.49		0.76	0.35	0.45	0.45	0.72	-0.61	-0.71
EC	0.42	0.31		-0.13	0.76	0.76	1.00	-0.89	-0.97
BD	-0.98	-0.65	-0.51		-0.68	-0.68	-0.14	0.51	0.01
OC	0.81	0.54	0.87	-0.87		1	0.74	-0.97	-0.61
OM	0.81	0.54	0.87	-0.87	1		0.74	-0.97	-0.61
Sand	0.48	1	0.3	-0.64	0.53	0.53		-0.87	-0.99
Silt	-0.3	-0.95	-0.01	0.45	-0.25	-0.25	-0.95		0.77
Clay	-0.66	-0.88	-0.7	0.81	-0.86	-0.86	-0.88	0.69	
					3 500 masl				
					3 700 masl				
Reg.		-0.96	0.32	0.24	0.82	0.82	-0.12	0.21	-0.47
pH	-		-0.25	0.05	-0.76	-0.76	-0.17	0.09	0.47
EC	-	-		0.16	0.8	0.8	0.01	0.16	-0.95
BD	-	-	-		0.22	0.22	-0.98	1	0.04
OC	-	-	-	-		1	-0.04	0.19	-0.88
OM	-	-	-	-	-		-0.04	0.19	-0.88
Sand	-	-	-	-	-	-		-0.98	-0.22
Silt	-	-	-	-	-	-	-		0.05
Clay	-	-	-	-	-	-	-	-	

Reg. = Regeneration; *pH* = Potential of hydrogen; *EC* = Electrical conductivity; *BD* = Bulk density; *OC* = Organic carbon; *OM* = Organic matter.

Discussion

Mensuration parameters

The crown area of adult trees was greater at 3 700 masl, while seedlings showed greater development at lower altitudes, which could reflect structural responses associated with the altitudinal gradient that might limit stem diameter (Yu *et al.,* 2011). Adult trees reached their greatest height at 3 500 masl, and seedlings were tallest at 3 300 and 3 500 masl. This pattern suggests that vertical growth could be related to environmental variations such as temperature, characteristic of altitude (Fortin et al., 2019).

The greater diameter recorded in adult trees at 3 700 masl and its decrease at lower altitudes suggests that diameter development could be influenced by environmental variation along the altitudinal gradient. In contrast, seedlings developed larger diameters at 3 300 masl, suggesting that, during the initial stages, diameter growth may respond more sensitively to the environmental heterogeneity of the site. Similar results have been recorded in other forest species, where environmental variations modulate radial growth (Keleş, 2020).

Natural regeneration density

Natural regeneration showed an inverse pattern between adults and seedlings along the altitudinal gradient: lower seedling density at low altitudes, higher *NRI* and adult density at 3 500 masl; and greater seedling abundance and low presence of adult trees at 3 700 masl. These results are consistent with other mountain ecosystems, where seedling density increases at mid- to high-altitude elevations; however, regeneration varies according to species, age class, local conditions, and anthropogenic disturbance (Negi et al., 2024). Early browsing is also a key factor limiting juvenile recruitment (Negi et al., 2018).

Kemp et al. (2019) indicate that the regeneration of *Pinus ponderosa* Douglas *ex* C. Lawson depends primarily on temperature, similar to that described by Stevens-Rumann et al. (2018), who highlight the determining role of climate in regenerative success, without referring to a particular species.

In the case of *P. culminicola*, this suggests that regeneration could be influenced by temperature variations associated with the altitudinal gradient, as well as by factors such as disturbance regime (fires, livestock grazing, and fragmentation), seed production and dispersal, the site's climatic history, and reproductive processes. In small and isolated populations, self-pollination may increase, reducing genetic variability and seedling vigor. According to Gutiérrez and Trejo (2022), disturbances usually decrease regeneration in conifers, therefore, the low regeneration observed in the analyzed species is probably the result of the interaction between environmental, anthropogenic and reproductive factors.

Physicochemical analysis of the soil

The highest *pH* was recorded at 3 500 masl, which contrasts with the results of Mangral et al. (2023), who documented a decrease in *pH* with altitude, attributed to changes in temperature, slope, and plant species composition. At varying altitudes, the latter influences soil acidity through the accumulation of organic acids (Egli et al., 2009). On the other hand, the values obtained (*pH* between 6.4 and 7.1) could be due to altitude, since soils located at high elevations have lower *pH* levels as a consequence of the loss of exchangeable bases associated with erosion and runoff from the surface horizon (Belay et al., 2023).

Although *EC* did not show significant differences, an increasing trend with altitude was observed, a pattern similar to that described by Mangral et al. (2023) in mountainous regions. This trend could be associated with processes related to the accumulation of organic matter at high altitudes, which influence soil ion exchange dynamics (Bardelli et al., 2017). Likewise, the variation in *EC* between altitudes could be associated with a reduction in soil moisture content (Serrano et al., 2013).

Along the altitudinal gradient, *BD* remained low (0.52-0.67 g cm^{-3}) and without significant differences, indicating areas without soil compaction on *Cerro El Potosí*. Low and homogeneous *BD* values are characteristic of mountain soils with high porosity and minimal disturbance (Cantú-Silva et al., 2018); therefore, this parameter does not appear to have acted as a limiting factor or contributed to the variations observed in the other assessed soil properties.

Although *OC* (3.8-4.3 %) and *OM* (22.3-24.7 %) content increased with altitude, the lack of statistical significance indicates little variability among sites. In mountainous gradients, low temperatures and changes in *OM* productivity favor the accumulation and stabilization of soil carbon (Jasso-Flores et al., 2020). This trend generally increases with altitude and is influenced by the type of forest and the dynamics of soil microbial activity (Massaccesi et al., 2020). These results could be explained by the greater carbon supply in soils of conifer-dominated stands compared to those composed of angiosperms (Devi, 2021).

The textural change from loam (3 300 masl) to silty loam (3 500-3 700 masl) is consistent with weathering processes in high mountain areas, where physical fragmentation and the redistribution of fine particles predominate (Schoeneberger et al., 2017). This pattern can vary depending on geology, slope, and land use. In *Pinus hartwegii* Lindl. forests, an increase in sand with altitude has been documented, while silt and clay have not shown consistent trends (Carrillo-Arizmendi et al., 2025). Since texture regulates soil moisture and permeability, it influences the development of woody vegetation (Roșca et al., 2019).

Correlation analysis

At 3 300 masl, the positive association between sand and regeneration could be linked to greater soil aeration and drainage, conditions that promote seedling emergence (Schoeneberger et al., 2017). However, the low density recorded at this altitude suggests that regeneration does not depend solely on soil texture, but is likely determined by multiple environmental and anthropogenic factors that influence seedling establishment, survival and recruitment.

The high correlation between *EC* and sand (r=1) at the lowest altitude, as well as between *OC* and *OM* (r=1) across the entire gradient, coincides with what has been reported in *Pinus hartwegii* forests in Mexico, where carbon content is associated with soil texture and is influenced by mean annual temperature (Carrillo-Arizmendi et al., 2025). At the intermediate altitude level (3 500 masl), the correlation between regeneration and *OC* (r=0.81) suggests that the accumulation of *OM* could be associated with more favorable nutritional conditions for seedling establishment.

Likewise, the correlation between *pH* and sand content (3 300 and 3 500 masl) supports what has been reported in European ecosystems, where soil texture regulates moisture, permeability, and consistency—factors that directly influence soil volume and the growth of woody vegetation (Roșca et al., 2019). At 3 700 masl, the positive relationship between regeneration and *EC* with *OC* and *OM* reinforces the role of these parameters in the dynamics of tree species in temperate forests. The correlation between *BD* and silt (r=1) suggests high compaction that modifies redox conditions and the microbial microhabitat (Abdullah et al., 2025) and, in excess, reduces soil macroporosity, limiting the water and nutrients available to roots and plant growth (Cantú-Silva et al., 2018).

Conclusions

This study demonstrated that the physicochemical parameters of the soil (*EC*, *BD*, *OC*, *OM*, sand, silt and clay) did not vary significantly along the altitudinal gradient of *Cerro El Potosí*, except for *pH*.

The dasometric parameters of the seedlings decreased with increasing altitude, while they increased in adult trees. Regeneration showed a positive trend with altitude, with lower adult density and a greater presence of seedlings; however, its overall condition remained between poor and fair.

The positive correlation between regeneration and organic carbon suggests that the accumulation of organic matter favors soil conditions associated with seedling establishment.

Acknowledgments

The authors thank the Secretariat of Science, Humanities, Technology and Innovation (*Secihti*) for providing Aldo Tovar-Cárdenas's doctoral scholarship.

Conflict of interest

The authors declare no conflict of interest.

Contribution by author

Aldo Tovar-Cárdenas: manuscript development and statistical analysis; Homero Alejandro Gárate-Escamilla: interpretation of results; Luis Gerardo Cuellar-Rodríguez: data analysis; José Israel Yerena-Yamallel and María Inés Yáñez Díaz: manuscript review.

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