

IMPACT OF CLIMATE CHANGE ON *Pinus hartwegii* Lindl. FOREST ECOSYSTEMS AS A SUBJECT OF INTERINSTITUTIONAL AND INTERNATIONAL STUDIES

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ABSTRACT

Pinus hartwegii Lindl. is a low-temperature-adapted species that forms the highest elevation tree lines in the world, reflecting its tolerance to extreme high mountain conditions. Studying the mechanisms that determine the variation of tree lines in different regions helps to more accurately assess the impact of climate change on forest ecosystems. Thus, assessing its impact on the ecological features that affect *P. hartwegii* is critical, as is identifying and defining information gaps that may lead to new, important, and significant research lines. In this work, an intensive literature search on the impact of climate change on *P. hartwegii* was carried out in Scopus and other specialized databases. The information was grouped and analyzed in VOSviewer by year of publication, institution, research topics, and study area. Scientific publications on *P. hartwegii* have increased exponentially since its first publication, reaching a total of 281 scientific papers until 2024. More than 66 % of all studies were conducted in protected areas such as Iztaccíhuatl-Popocatepetl, Nevado de Toluca, and Cofre de Perote in Mexico. The most studied topics were forest management, climate change, dendrochronology, and population dynamics. The high heterogeneity in the number of studies suggests that there is an uneven distribution of interinstitutional and international resources or research interests. This study highlights the need to intensify research on the ecology and biology of the species, as well as to foster inter-institutional collaboration and coordination to increase studies in specific areas to deepen the understanding of the adaptive capacity of *P. hartwegii* populations in the face of the current climate crisis.

Key words: Cofre de Perote, Trans-Mexican Volcanic Belt, Iztaccíhuatl-Popocatepetl, alpine tree line, Nevado de Toluca, high altitude pine.

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INTRODUCTION

Mountain ecosystems are inhabited by highly specialized and endemic plants that are particularly sensitive to climatic changes (Cavieres *et al.*, 2021). Recent studies show that rising mountain temperatures encourage species distributions to move upward along altitudinal gradients (Aitken *et al.*, 2008; Cavieres *et al.*, 2021; Petrov *et al.*, 2024). This would eventually put them at risk of extinction, given the difficulty of adapting their life and migration cycles at a slower rate than temperature changes (Aitken *et al.*, 2008). Because of the tangible and intangible benefits that mountain ecosystems have on human societies, it is imperative to understand the ecological processes that regulate abiotic and biotic pressures on these ecosystems.

Pinus hartwegii Lindl., also known as the pine of the heights or white ocote, is a species of great ecological value that has captured international attention in recent years (Pérez-Suárez *et al.*, 2022), being the subject of national and international studies. This species is reported to be the most widely distributed pine at the highest elevations in the world (Alfaro-Ramírez *et al.*, 2020; Pérez-Suárez *et al.*, 2022). It is characterized by the formation of tree lines due to its high tolerance to low temperature extremes and ability to withstand adverse environmental conditions such as high diurnal temperature variation, high precipitation, high winds, low soil quality, high UV intensity, and short growing season length (Richardson and Friedland, 2009).

According to Körner and Paulsen (2004) and Berdanier (2010), tree lines are associated with altitude or climatic conditions that limit the growth of arboreal life forms. Those individuals that exceed these lines grow stunted or structurally deformed, with a twisted trunk being the most common feature (krummholz). In the case of *P. hartwegii*, a diffuse line of trees is formed in krummholz (Alfaro-Ramírez *et al.*, 2017), with a gradual decrease in the diameter, height, and density of individuals. The physiology, biology, and ecology of this species are closely related to low temperatures, highlighting its potential sensitivity to temperature increases resulting from global warming (Manzanilla-Quiñonez *et al.*, 2019; Alfaro-Ramírez *et al.*, 2020; Pérez-Suárez *et al.*, 2022).

Several studies have focused on assessing the trend of changes in spatial distribution under different climate change scenarios (Malek and Verburg, 2021; Crespi *et al.*, 2023). Most studies agree that its range will decrease by up to 69 % in the next 50 years (Alfaro-Ramírez *et al.*, 2020). However, the underlying mechanisms that would lead to such a significant range reduction and whether these are shared locally or at the level of individual populations are unknown. The effects of high temperatures are not necessarily direct or immediate, as they are not simultaneous responses to stressors but the result of long processes of change in which several complex interacting factors come together, including the impact of human activities and topography, as well as their integration along elevation gradients (Gray and Brady, 2016; Balfagón *et al.*, 2020). Human activities play an important role in the degradation and anthropogenic pressure on these populations, so that a spatial distribution map does not provide the reason for the reduction or the dominant factor causing this process. In the case of

P. hartwegii, local and regional demand for the species as a raw material for furniture manufacture, among others, is a factor that significantly reduces its populations throughout its range. At the regional level, temperature regulates ecological processes in high mountain forests. However, other local site-specific factors must also be considered, as they can influence the potential impact of climate change or variability on forest ecosystems (Albrich *et al.*, 2020; Thakur *et al.*, 2021).

In this context, the generation of knowledge on the impact of climate change on forest ecosystems is a challenge that must be addressed from multidisciplinary and interdisciplinary approaches, where the efforts of different institutions are combined to carry out complementary rather than duplicated work, allowing for the efficiency of material and human resources. This provides the necessary tools to identify the causes and take action to mitigate the loss of *P. hartwegii* in support of its conservation, in addition to maintaining the multiple services that its forest cover provides to society (Pérez-Suárez *et al.*, 2022; Wang *et al.*, 2024) and the recreational and cultural activities that are carried out throughout the species' range (Varo-Rodríguez *et al.*, 2019).

The biological, geological, and chemical processes that occur in the ecosystems inhabited by this species benefit both local communities in the mountains and those settling lower down, including the more populated valleys in central Mexico. This includes regulating water flows, local and regional temperature, carbon sequestration, and providing forest biomass for various economic activities such as furniture and fuelwood production. (Franco-Maass *et al.*, 2006; Endara-Agramont and Herrera-Tapia, 2016; Martínez-Luna *et al.*, 2020).

Predicting how temperature increases will affect *P. hartwegii* forest cover requires taking into account the majority of its range. This species has not received enough research, and little attention has been paid to how it relates to climatic factors. This limits the ability to draw conclusions at different levels of organization (species, population, etc.) (Pérez-Suárez *et al.*, 2022) and reduces the accuracy in predicting the effects of various global change factors on its biology, ecology, and adaptability. In this context, it is important to know the position of the climate change approach in studies on *P. hartwegii*, what the interest of institutions in studies on this species is, and which areas have been studied throughout its distribution in order to identify and delimit information gaps that can lead to new lines of research with greater relevance and impact. This is possible through collaborative work involving different institutions that will lead to the establishment of adequate and efficient strategies for the management and conservation of *P. hartwegii*.

MATERIALS AND METHODS

An intensive literature search on ecological aspects of *Pinus hartwegii* was conducted in Scopus (Elsevier; available at <https://www.scopus.com/>) and complemented with other specialized databases, such as Web of Science (Clarivate Analytics; <https://clarivate.com/>), SciELO (<https://www.scielo.org/es/>), Publons (<https://publons.com/>),

and Redalyc (<https://www.redalyc.org/>). To ensure the completeness and scientific reliability of the literature reviewed, a list of scientific publications was created that included synonyms and words related to the topic, or a combination of them, in the title, abstract, or keywords. Key words for the search were '*Pinus hartwegii*' OR '*Pinus rudis*' OR 'Hartwegs Pine' OR 'mountain pine' OR 'white ocote' OR '*Pinus*' OR 'highland pine' AND 'climate change.'

A database was constructed and purified, considering only scientific articles related to *P. hartwegii*, specifically those related to climate change and its impact on ecological aspects such as forest management, population dynamics, dendrochronology, climate change, hydrological cycle, conservation, phenology, histopathology, symbiosis, population genetics, fire ecology, systematics, physiology, community ecology, carbon capture and sequestration, forest health, biogeographical patterns, environmental pollution, nutrient flow, taxonomy, phytosociology, human impact, ethnobotany, and evolution. In addition, theses, books or book chapters, technical reports, and presentations or full-length papers from scientific meetings were excluded, as well as papers that did not address any ecological or biological aspect other than the occurrence of the species. References in the revision process or incomplete references were also excluded.

The final information contained in the database was grouped by year of publication to subsequently carry out an orderly review that would facilitate the identification of those areas with a lack of scientific studies related to *P. hartwegii*. The VOSviewer software (van Eck and Waltman, 2010, 2017) was used, which represents a high-performance solution with numerous bibliometric network visualization options. In this software, keyword co-occurrence networks, co-authorship relationships between institutions (or affiliations), and co-occurrence between main research topics and geographical areas (or study areas) are observed.

RESULTS AND DISCUSSION

Bibliometric aspects

A total of 281 scientific publications related to *P. hartwegii* were found, using 844 keywords (Figure 1). The most prominent words close to *P. hartwegii* were 'Mexico,' 'climate change,' and 'pine.' These words appeared most frequently within the papers as co-occurring keywords (Figure 1A and 1B). The more intense colors show areas with a higher density of co-occurrence between outstanding keywords that are more closely related to *P. hartwegii*, with 'climate change' again being the most prominent, while lighter colors indicate areas where terms are less frequent or have weaker connections to each other (Figure 1C and 1D).

Scientific work was published from 1962 to 2024 (Figure 2), showing an exponential growth over time. From 2000 to 2024, more than 80 % of the registered papers were published, with a total of 234 articles. In addition, 154 studies (54.8 %) were published

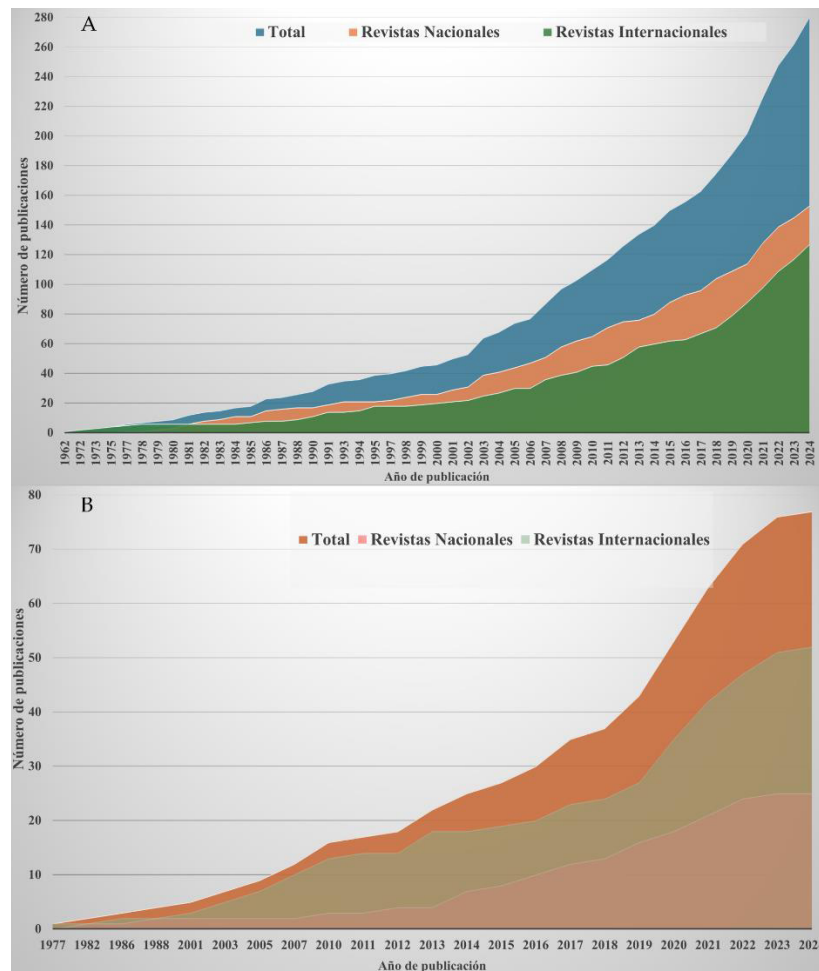


Figure 2. Trend of scientific publications analyzed in the time period from 1962 to 2024. A: total number of scientific publications on *Pinus hartwegii* Lindl.; B: number of publications on climate change.

The same pattern was found for climate change, with a total of 58 institutions having researched this topic (Figure 3B). Stronger colors show areas with a higher frequency of collaboration between institutions and which are more closely related to each other, while lighter colors indicate areas where collaboration between institutions is less frequent or has a low connection (Figure 3C and 3D).

In terms of the research topics studied, a total of 24 different topics were found (Figure 4). The more prominent and the closer they are, the greater the relationship between topics and the greater the number of documents with keywords that were linked together (Figure 4A and 4B), with forest management (103 papers), climate change (77 papers), population dynamics (58 papers), and dendrochronology (46 papers) standing out, while the rest of the topics had less than 30 publications.

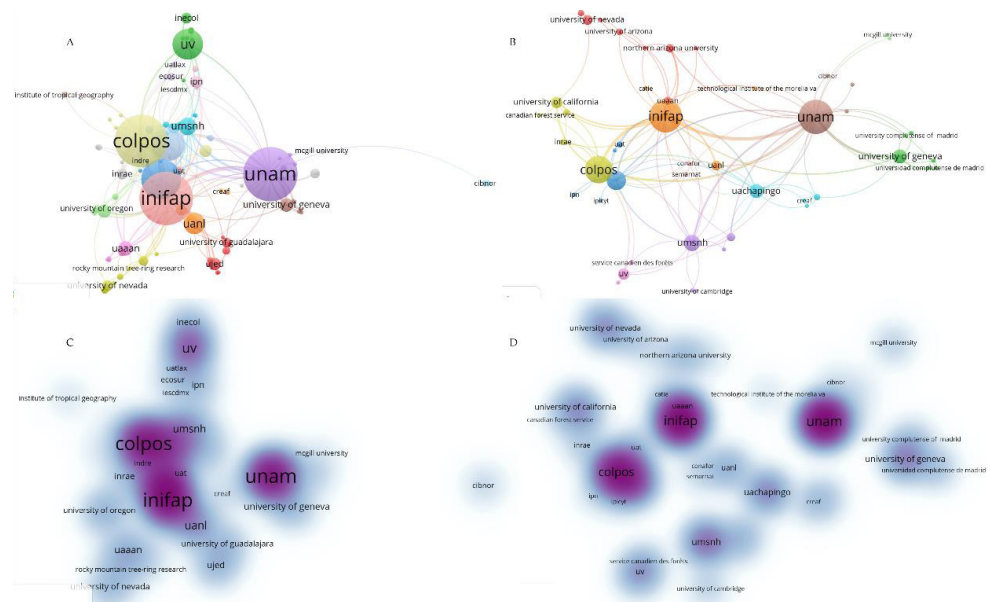


Figure 3. Bibliometric analysis of institutions (or affiliations) in scientific publications on *Pinus hartwegii* Lindl. from 1962 to 2024. A: network map of institutions; B: network map of institutions related to climate change; C: total density map of institutions; D: density map of institutions related to climate change.

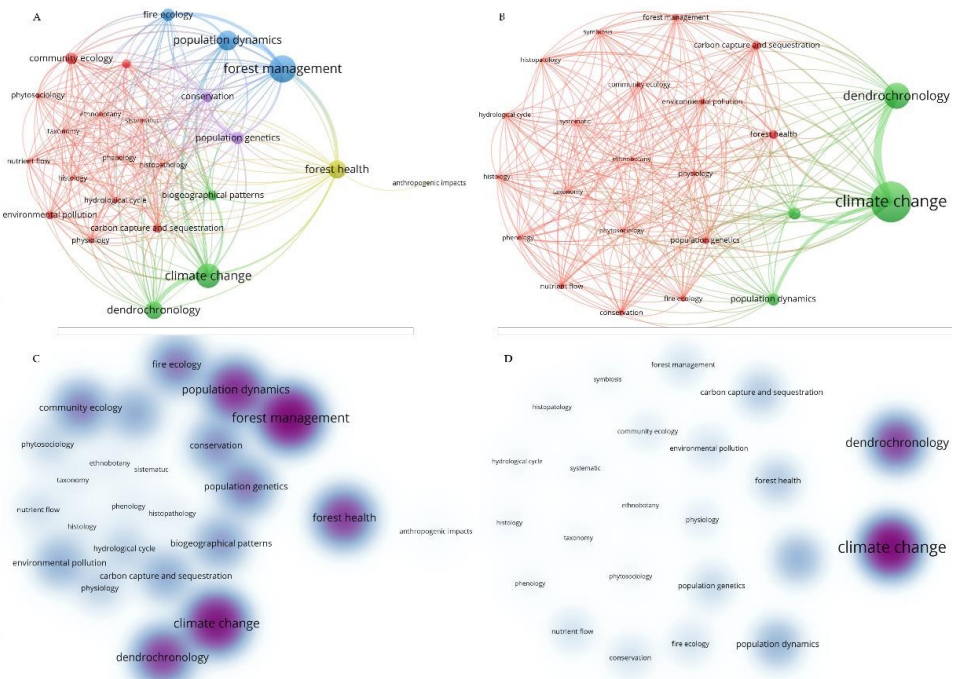


Figure 4. Bibliometric analysis of research topics in scientific publications on *Pinus hartwegii* Lindl. from 1962 to 2024. A: network map of research topics; B: network map of research topics related to climate change; C: total density map of research topics; D: density map of research topics related to climate change.

Recent publications have focused on climate change, nutrient flow, dendrochronology, hydrological cycle, ethnobotany, and systematics (Figure 4A). In terms of climate change, publications were focused on dendrochronology, population dynamics, and biogeography (Figure 4B). Stronger colors indicate areas with a higher density of co-occurrence between research topics, while lighter colors show areas with a lower density (Figure 4C and 4D). This can be explained by either emerging trends (which are yet to develop) or topics that are little frequented by researchers.

In relation to the most studied areas, the publications found show a concentration towards studies carried out in the Trans-Mexican Volcanic Belt, including the Iztaccíhuatl-Popocatepetl National Park (including Monte Tláloc and the Zoquiapan Experimental Forest Station), followed by the Nevado de Toluca Flora and Fauna Protection Area, Cofre de Perote National Park, Cumbres del Ajusco National Park, and Pico de Orizaba National Park (Figure 5A and 5B). Of these areas, an increasing trend was recorded on the survey of *P. hartwegii* populations found in both Iztaccíhuatl-Popocatepetl National Park and Nevado de Toluca Flora and Fauna Protection Area. Stronger colors show a higher frequency between study areas that are more closely related to each other, while softer colors indicate a lower frequency (Figure 5C).

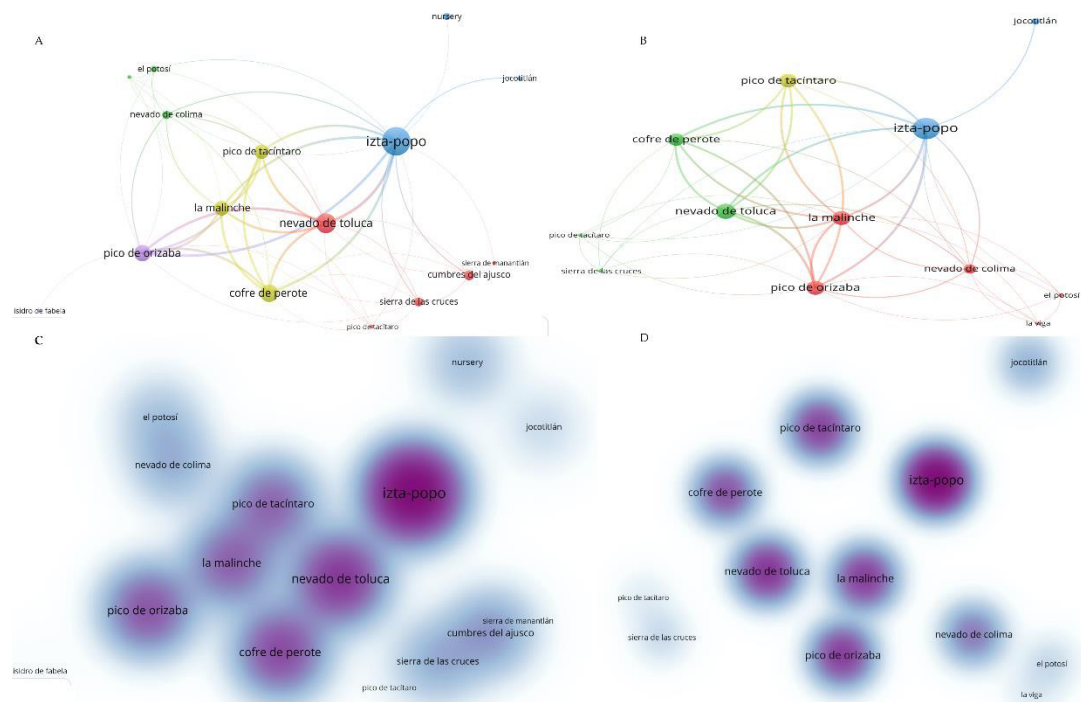


Figure 5. Bibliometric analysis of geographical areas (study areas) in scientific publications on *Pinus hartwegii* Lindl. from 1962 to 2024. A: network map of geographical areas; B: network map of geographical areas related to climate change; C: total density map of geographical areas; D: density map of geographical areas related to climate change publications.

This trend was also reflected for climate change and its proportion among these areas (Figure 5D). However, studies on population genetics and fire ecology were the exception, as these were more concentrated in Cofre de Perote National Park and fire ecology in Cumbres del Ajusco National Park, respectively. This emphasizes the need to consider populations of *P. hartwegii* located in other parts of its range, as well as study particularly important issues in terms of its adaptation to new environmental conditions, not only at the local level but throughout the species' range.

The results show a heterogeneity and frequency in the topics addressed in scientific publications throughout the distribution area of *P. hartwegii*, as well as the institutions that have contributed most to the generation of information. An exponential increase in scientific interest in *P. hartwegii* since 2000 was observed, with climate change being the main focus of most of these publications. This has also led to greater inter-institutional collaboration in the studies carried out.

Research topics

High mountain systems are characterized by the concentration of different transition zones in a relatively small area (Körner and Paulsen, 2004; Holtmeier and Broll, 2005), with the upper forest boundary ecotone being one of the best known (Franco-Ramos and Vázquez-Selem, 2017). Since the plant species present in the high mountains are highly adapted to low temperature conditions, extreme for many biological processes (Körner, 1995; Holtmeier and Broll, 2005), they have become ideal sites for analyzing the effects of climate change (Arriaga and Gómez, 2004; Körner and Paulsen, 2004).

Pinus hartwegii is the pine species that has been recorded at the highest altitude in the world, around 4200 m (Alfaro-Ramírez *et al.*, 2017, 2020), generating great interest in its structure, composition, and response to environmental changes. However, the problem with tree species that are part of the upper limit of high mountain forests is that there is not much surface area available to migrate upwards, and the natural migration speed would be too slow (Aitken *et al.*, 2008). Towards the lower boundary, climate change promotes increasingly unfavorable water stress conditions, increasing competition with other forest species that tend to benefit from higher temperatures.

The elevational movement of *P. hartwegii* has been evaluated (Alfaro-Ramírez *et al.*, 2017, 2020), concluding that populations of this species at different elevations will respond differently and at different rates to the impacts of climate change (Franco-Ramos and Vázquez-Selem, 2017). Under unfavorable climate scenarios (Arriaga and Gómez, 2004), it could migrate to higher altitudes or latitudes in search of sites with favorable conditions for its survival (Gómez-Mendoza and Arriaga, 2007; Alfaro-Ramírez *et al.*, 2020).

Some aspects have been little explored and go beyond the reduced surface area on mountain peaks, among which are the limitations of support and nutrition imposed by the shallow and poorly developed soils characteristic of volcanic areas (Körner and Paulsen, 2004). Biological interactions with other species that promote the establishment and survival of *P. hartwegii*, especially in early stages, also influence its population

structure (Almeida-Leñero *et al.*, 2004; Iglesias-Andeu and Tivo-Fernández, 2006), in addition to the potential migration of individuals of this species under the context of climate change (Franco-Ramos and Vázquez-Selem, 2017).

Finally, extreme scenarios such as extinction and adaptation are displayed. In the first case, it is predicted that this species could reach local extinction (Gutiérrez and Trejo, 2014), so that the remaining populations would have the same effect in the long term; the second case would involve the adaptation of the physiological processes of *P. hartwegii* to the new environmental conditions through phenotypic plasticity mechanisms (Arzate-Fernández *et al.*, 2016). However, the scientific information to predict with certainty which pathway to follow is not yet available. Therefore, it is necessary to study several aspects, such as genetic diversity and gene flow among its populations (Viveros-Viveros *et al.*, 2009; Arzate-Fernández *et al.*, 2016; Pérez-Suárez *et al.*, 2022). In addition, there is insufficient information on the mechanisms that regulate the presence of each population and how resilient they may be to climate change (Arriaga and Gómez, 2004; Pérez-Suárez *et al.*, 2022), nor on their ability to modify or conserve an ecological niche in the long term (Gómez-Mendoza and Arriaga, 2007; Gutiérrez and Trejo, 2014). Another aspect in which scientific interest has increased the most is the health status of forest cover, given that it depends on various abiotic factors such as temperature, humidity, and nutrient availability. Increases in global temperature have a strong impact on the susceptibility of forest species to pest incidence (Hawksworth and Wiens, 1996; Queijeiro-Bolaños *et al.*, 2011). *Pinus hartwegii* is no exception, as its biology and ecology are closely dependent on the temperature extremes that dominate along its elevational distribution gradient. Thus, this pine species is considered particularly susceptible to the direct and indirect impact of ambient temperature increases.

Currently, an increased incidence of pests has been recorded, mainly mistletoes such as *Arceuthobium globosum* and *A. vaginatum* (Mathiasen *et al.*, 2008; Queijeiro-Bolaños *et al.*, 2011; Queijeiro-Bolaños and Cano-Santana, 2016). Among the main recorded effects of these pests on *P. hartwegii* are the reduction in growth and survival of infested individuals (Mathiasen *et al.*, 2008; Queijeiro-Bolaños and Cano-Santana, 2016). However, some authors point out that this interaction has an important ecological role, particularly in forest regeneration (Queijeiro-Bolaños and Cano-Santana, 2016), arguing that mistletoe reduces the number of susceptible individuals, giving way to more resistant individuals (Queijeiro-Bolaños *et al.*, 2011). However, there is no precise information on the infestation ranges that *P. hartwegii* can tolerate or the physiological mechanisms that cause mistletoe damage and death in trees.

Another pest affecting *P. hartwegii* is *Dendroctonus adjunctus* (Billings *et al.*, 2004). This bark beetle causes high mortality of pine individuals in susceptible stands (Biondi *et al.*, 2005), causing severe damage to pine populations. However, as in the case of mistletoe, there is very little information on the infestation mechanisms, the factors that promote it, the population dynamics of this insect in *P. hartwegii*, and the impact that the increase or modification of climatic conditions could have on the intensity

and speed of infestation. All these questions have generated growing scientific interest in this species, both nationally and internationally. This is evidenced not only by the increase in publications but also by the increase in the number of study topics and the number of institutions involved.

Several questions remain to be addressed: (i) whether there is variability in tree exposure to temperature; (ii) the effect of climate variability on biogeochemical cycles and on the dynamics of plant communities at both the upper and lower distributional limits, as well as along the entire distribution gradient; (iii) the impact of densification on the regenerative dynamics of trees and the redistribution of resources; (iv) seed viability throughout the species' distribution range; and (v) the characteristics of microsites that influence germination, establishment, and growth. Addressing these questions will be essential in the future to understand, at the population level, the impact of climate change on this species more clearly. Such understanding would support the implementation of management and conservation strategies with a higher likelihood of success.

CONCLUSIONS

Interest in the study of *Pinus hartwegii* has led to an exponential increase in scientific publications, particularly in recent years, with forest management, climate change, population dynamics, and dendrochronology being the main topics addressed in these publications. The locations where most of these studies have been carried out include the Trans-Mexican Volcanic Belt, mainly in the Iztaccíhuatl-Popocatepetl National Park and the Nevado de Toluca Flora and Fauna Protection Area. It is necessary to conduct more studies that cover its entire distribution area in order to better represent populations and gain knowledge of the species and its interactions with various biotic and abiotic factors, so that conclusions can be reached at the species level that allow for prediction of its behavior in the face of new environmental conditions.

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REFERENCES

- Aitken SN, Yeaman S, Holliday JA, Wang T, Curtis-McLane S. 2008. Adaptation, migration or extirpation: Climate change outcomes for tree populations. *Evolutionary Applications* 1 (1): 95–111. <https://doi.org/10.1111/j.1752-4571.2007.00013.x>
- Albrich K, Rammer W, Seidl R. 2020. Climate change causes critical transitions and irreversible alterations of mountain forest. *Global Change Biology* 26 (7): 4013–4027. <https://doi.org/10.1111/gcb.15118>

- Alfaro-Ramírez FU, Arredondo-Moreno JT, Pérez-Suárez M, Endara-Agramont AR. 2017. Ecotono del límite superior del bosque de *Pinus hartwegii* Lindl.: estructura y límites altitudinales en el Nevado de Toluca, México. *Revista Chapingo Serie Ciencias Forestales y del Ambiente* 23 (2): 261–273. <https://doi.org/10.5154/r.rchscfa.2016.10.055>
- Alfaro-Ramírez FU, Ramírez-Albores JE, Vargas-Hernández JJ, Franco-Maass S, Pérez-Suárez M. 2020. Potential reduction of Hartweg's pine (*Pinus hartwegii* Lindl.) geographic distribution. *PLoS One* 15 (2): e0229178. <https://doi.org/10.1371/journal.pone.0229178>
- Almeida-Leñero L, Giménez-de Azcárate J, Cleef AM, González-Trápaga MA. 2004. Las comunidades vegetales del zacatonal alpino de los volcanes Popocatepetl y Nevado de Toluca, Región Central de México. *Phytocoenologia* 34 (1): 91–132. <https://doi.org/10.1127/0340-269x/2004/0034-0091>
- Arriaga L, Gómez L. 2004. Posibles efectos del cambio climático en algunos componentes de la biodiversidad de México. In Martínez J, Fernández A. (eds.), *Cambio Climático: una Visión desde México*. Instituto Nacional de Ecología y Cambio Climático: Ciudad de México, México, pp: 255–265.
- Arzate-Fernández AM, Gutiérrez-González G, Heredia-Bobadilla RL. 2016. Diversidad genética de dos especies de coníferas en el Nevado de Toluca: una alternativa de conservación. Universidad Autónoma del Estado de México. Toluca, México. 136 p.
- Balfagón D, Zandalinas SI, Mittler R, Gómez-Cárdenas A. 2020. High temperatures modify plant responses to abiotic stress conditions. *Physiologia Plantarum* 170 (3): 335–344. <https://doi.org/10.1111/ppl.13151>
- Berdanier AB. 2010. Global treeline position. *Nature Education Knowledge* 3 (10): 11.
- Billings RF, Clarke SR, Espino-Mendoza V, Cordón-Cabrera P, Meléndez-Figueroa B, Ramón-Campos J, Baeza G. 2004. Bark beetle outbreaks and fire: A devastating combination for Central America's pine forests. *Unasylva* 217 (55): 15–21.
- Biondi F, Hartsough PC, Galindo-Estrada I. 2005. Daily weather and tree growth at the tropical treeline of North America. *Arctic, Antarctic and Alpine Research* 37 (1): 16–24. [https://doi.org/10.1657/1523-0430\(2005\)037\[0016:dwatga\]2.0.co;2](https://doi.org/10.1657/1523-0430(2005)037[0016:dwatga]2.0.co;2)
- Cavieres L, Valencia G, Hernández C. 2021. Calentamiento global y sus efectos en plantas de alta-montaña en Chile central: una revisión. *Ecosistemas* 30 (1): 2179. <https://doi.org/10.7818/ecos.2179>
- Crespi A, Renner K, Zebish M, Schauser I, Leps N, Walter A. 2023. Analysing spatial patterns of climate change: Climate clusters, hotspots and analogues to support climate risk assessment and communication in Germany. *Climate Services* 30: 100373. <https://doi.org/10.1016/j.cliser.2023.100373>
- Endara-Agramont AR, Herrera-Tapia F. 2016. Deterioro y conservación de los bosques del Nevado de Toluca y el rol de los actores locales. *Ciencia Ergo-Sum* 23 (3): 247–257.
- Franco-Maass S, Regil-García HH, Ordoñez-Díaz JAB. 2006. Dinámica de perturbación-recuperación de las zonas forestales en el Parque Nacional Nevado de Toluca. *Madera y Bosques* 12 (1): 17–28. <https://doi.org/10.21829/myb.2006.1211247>
- Franco-Ramos O, Vázquez-Selem L. 2017. Trabajo de campo dendrocronológico para estudios de geografía física. Experiencias en los volcanes Popocatepetl e Iztaccíhuatl, 2006–2017. *Investigaciones Geográficas* 94: 1–13. <https://doi.org/10.14350/rig.59574>
- Gómez-Mendoza L, Arriaga L. 2007. Modeling the effect of climate change on the distribution of oak and pine species of Mexico. *Conservation Biology* 21 (6): 1545–1555. <https://doi.org/10.1111/j.1523-1739.2007.00814.x>

- Gray SB, Brady SM. 2016. Plant developmental responses to climate change. *Developmental Biology* 419 (1): 64–77. <https://doi.org/10.1016/j.ydbio.2016.07.023>
- Gutiérrez E, Trejo I. 2014. Effect of climatic change on the potential distribution of five species of temperate forest trees in Mexico. *Revista Mexicana de Biodiversidad* 85 (1): 179–188. <https://doi.org/10.7550/rmb.37737>
- Hawksworth THFG, Wiens D. 1996. Dwarf mistletoes: Biology, pathology and systematics. U.S. Department of Agriculture, Forest Service: Washington, DC, USA. 410 p.
- Holtmeier FK, Broll G. 2005. Sensitivity and response of northern hemisphere altitudinal and polar treelines to environmental change at landscape and local scales. *Global Ecology and Biogeography* 14 (5): 395–410. <https://doi.org/10.1111/j.1466-822X.2005.00168.x>
- Iglesias-Andeu LG, Tivo-Fernández Y. 2006. Caracterización morfométrica de la población de *Pinus hartwegii* Lindl. del Cofre de Perote, Veracruz, México. *Ra Ximhai* 2: 449–468. <https://doi.org/10.35197/rx.02.02.2006.08.li>
- Körner C, Paulsen J. 2004. A world-wide study of high altitude treeline temperatures. *Journal of Biogeography* 31 (5): 713–732. <https://doi.org/10.1111/j.1365-2699.2003.01043.x>
- Körner C. 1995. Alpine plant diversity: A global survey and functional interpretations. In Chapin FS, Körner C. (eds.), *Arctic and Alpine Biodiversity: Patterns, Causes and Ecosystem Consequences*. Springer: Berlin, Germany, pp: 45–62. <https://doi.org/10.1007/978-3-642-78966-3>
- Malek Ž, Verburg PH. 2021. Representing responses to climate change in spatial land system models. *Land Degradation and Development* 32 (17): 4954–4973. <https://doi.org/10.1002/ldr.4083>
- Manzanilla-Quiñones U, Aguirre-Calderón OA, Jiménez-Pérez J, Treviño-Garza EJ, Yerena-Yamallel JI. 2019. Distribución actual y futura del bosque subalpino de *Pinus hartwegii* Lindl. en el Eje Neovolcánico Transversal. *Madera y Bosques* 25 (2): e2521804. <https://doi.org/10.21829/myb.2019.2521804>
- Martínez-Luna JE, Carrillo-Anzures F, Acosta-Mireles M, Romero-Sánchez ME, Pérez-Miranda R. 2020. Ecuaciones alométricas para estimar carbono en brinzales de *Pinus hartwegii* Lindl. *Revista Mexicana de Ciencias Forestales* 11 (60): 1–16. <https://doi.org/10.29298/rmcf.v11i60.726>
- Mathiasen RL, Nickrent DL, Shaw DC, Watson DM. 2008. Mistletoes. Pathology, systematics, ecology and management. *Plant Disease* 92 (7): 988–1006. <https://doi.org/10.1094/pdis-92-7-0988>
- Pérez-Suárez M, Ramírez-Albores JE, Vargas-Hernández JJ, Alfaro-Ramírez FU. 2022. A review of the knowledge of Hartweg's pine (*Pinus hartwegii* Lindl.): Current situation and the need for improved future projections. *Trees* 36 (1): 25–37. <https://doi.org/10.1007/s00468-021-02221-9>
- Petrov D, Ocołjčić M, Galečić N, Skočajić D, Simović I. 2024. Adaptability of *Prunus cerasifera* Ehrh. to climate changes in multifunctional landscape. *Atmosphere* 15 (3): 335. <https://doi.org/10.3390/atmos15030335>
- Queijeiro-Bolaños ME, Cano-Santana Z, Castellanos-Vargas I. 2011. Distribución diferencial de dos especies de muérdago enano sobre *Pinus hartwegii* en el área natural protegida “Zoquiapan y Anexas”, Estado de México. *Acta Botánica Mexicana* 96: 49–57. <https://doi.org/10.21829/abm96.2011.258>

- Queijeiro-Bolaños ME, Cano-Santana Z. 2016. Growth of Hartweg's pine (*Pinus hartwegii*) parasitized by two dwarf mistletoe species (*Arceuthobium* spp.). *Botanical Sciences* 94 (1): 51–62. <https://doi.org/10.17129/botsci.218>
- Richardson AD, Friedland AJ. 2009. A review of the theories to explain arctic and alpine treelines around the world. *Journal of Sustainable Forestry* 28 (1–2): 218–242. <https://doi.org/10.1080/10549810802626456>
- Thakur S, Negi VS, Dhyani R, Satish KV, Bhatt ID. 2021. Vulnerability assessment of mountain forest ecosystems: A global synthesis. *Trees, Forest and People* 6: 100156. <https://doi.org/10.1016/j.tfp.2021.100156>
- van Eck NJ, Waltman L. 2010. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* 84 (2): 523–538. <https://doi.org/10.1007/s11192-009-0146-3>
- van Eck NJ, Waltman L. 2017. Citation based clustering of publications using CitNetExplorer and VOSviewer. *Scientometrics* 111 (2): 1053–1070. <https://doi.org/10.1007/s11192-017-2300-7>
- Varo-Rodríguez R, Ávila-Akerberg V, Gheno-Heredia J. 2019. Uso tradicional de la fitodiversidad de los bosques de *Pinus hartwegii* en dos comunidades mexicanas de alta montaña. *Caldasia* 41 (2): 327–342. <https://doi.org/10.15446/caldasia.v41n2.69477>
- Viveros-Viveros H, Sáenz-Romero C, Vargas-Hernández JJ, López-Upton J, Ramírez-Valverde G, Santacruz-Varela A. 2009. Altitudinal genetic variation in *Pinus hartwegii* Lindl.: Height growth, shoot phenology and cold damage in seedlings. *Forest Ecology and Management* 257 (3): 836–842. <https://doi.org/10.1016/j.foreco.2008.10.021>
- Wang Z, Wang T, Zhang X, Wang J, Yang Y, Sun Y, Guo X, Wu Q, Nepovimova E, Watson AE, Kuca K. 2024. Biodiversity conservation in the context of climate change: Facing challenges and management strategies. *Science of the Total Environment* 937: 173377. <https://doi.org/10.1016/j.scitotenv.2024.173377>

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