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RESEARCH DYNAMICS AND FUTURE DIRECTION OF KOREAN PINE (*PINUS KORAIENSIS*): A GLOBAL BIBLIOMETRIC ANALYSIS

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Abstract

Korean pine is a five-needle big arbor pine species that dominated at natural coniferous broadleaved mixed forests in temperate regions, with the functions of high-quality timber, and pine nut production as well as potential ornamental and healthy wood entablement. However, a quantitative analysis of the global research landscape of Korean pine has been lacking and hindering a unified understanding of the field's trajectory. This study employs bibliometric analysis on 682 articles from the Web of Science database (2003-2025), to map the global research landscape of Korean pine and to identify future research directions. Result exhibits an average annual publication growth rate of 9.15% with overall trend best described by a logarithmic model (R^2 = 0.832), dominated by 76.83% publications from China, and Northeast Forestry University emerged as the leading institute. The collaboration network is highly polarized, with China at the center of it having strong Asia-Pacific affiliation and presenting a significant opportunity to deepen scientific ties with Western countries. Thematic evolution has no longer been grounded in studies on growth and ecology, but new frontiers are being set on climate change resilience, genetic diversity, and biotechnology. This strategic analysis references researchers to priority research on genetics & breeding, and ecological interactions of Korean pine, and supports two management innovations: genetically informed restoration using improved or locally adapted Korean pine material, and adaptive ecosystem-based management that integrates species interactions, mixed stand planning, and ecological monitoring.

Key words: *Pinus koraiensis*; Temperate regions; Growth; Genetics & breeding; Ecology interactions

Introduction

Forests, comprising 31% of the terrestrial landmass of the earth (4.06 billion ha), might potentially play an important role in global climate policy by storing carbon in land systems and wood products through sequestration and storage. Forests are also dynamic parts of the carbon cycle that are storing 45% (861 ± 66 Pg C) of the total terrestrial carbon as well as a source and a sink of emissions due to land use change and disturbance (Bonan, 2008; Kumar *et al.,* 2025; Pan *et al.,* 2011). Nevertheless, globally 3.75 billion ha of forests are naturally occurring forests, and 290 million ha are planted forests that are distributed unevenly. Naturally regenerating forests have been depleting since 1990, and plantation forests have grown by 123 million ha, which indicates a change in the composition and management of the world's forest (Anon., 2020). These global trends, namely the loss of naturally regenerating forests, the expansion of plantations, and the resulting shifts in forest composition and carbon storage, are often most clearly reflected in the status of individual keystone species, whose decline can affect entire ecosystems (Marjakangas *et al.,* 2023). Korean pine (*Pinus koraiensis*) exemplifies this, as a keystone species of both ecological and economic value in temperate forests. Its future is closely linked to the challenges of carbon sequestration, biodiversity conservation, and sustainable management (Liu *et al.,* 2020; Wu *et al.,* 2023). But its ability to remain in a position to provide these vital ecosystem services is at risk due to climate change, unsustainable exploitation, and ecological disruptions, which are reflective of the weakness that forests experience the world over (Boonman *et al.,* 2024). Thus, the study of the dynamics of Korean pine is not only a regional issue but also serves as a specific prism through which to consider other global issues of forest sustainability. Although research on Korean pine has expanded considerably in recent decades, these studies remain fragmented across disciplines, and a comprehensive synthesis is needed to consolidate current knowledge, identify research gaps, and guide future studies.

Pinus koraiensis Siebold & Zucc., Pinaceae is a foundation species that shapes the structure and function of temperate forests of Northeast Asia's. It forms complex and multiple-layered ecosystems that support high biodiversity, providing critical habitat and a staple food source, its protein rich seeds, for wildlife (i.e., squirrels, birds, and bears) (Petrenko *et al.,* 2022; Piao *et al.,* 2011). Additionally, it is also a significant long-term carbon sink with substantial biomass accumulation in natural and plantation forests (Xu *et al.,* 2024). Economically, it

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provides two major resources: high quality, lightweight timber used in construction and furniture, and edible pine nuts that support a million-dollar industry important to both local economics and the global market (Bao *et al.,* 2015). Despite its significance, its distribution has been very dynamic since the Last Glacial Maximum (LGM) and is likely to experience profound changes and fractures in response to climate change in the future (Petrenko *et al.,,* 2022). Climate change and human disturbance alter the habitat of Korean pine, for instance, by reducing habitat suitability, increasing diseases and pest's outbreaks, disrupting regeneration cycles, changing fire frequency and forest structures, and fragmenting its natural range. This pressure is compounded and threatens the essential ecosystem services provided by Korean pine (Li *et al.,* 2021; Petrenko *et al.,* 2022; Xu & Yan, 2001; Zhao *et al.,* 2014; Zhao *et al.,* 2013).

Although the Korean pine has many ecological and economic values, research on this species has increased rapidly in various research fields, including forest ecology, silviculture, conservation biology, biotechnology, and adaptation to climate change. As a consequence, the knowledge base has become increasingly dispersed and increasingly dispersed and fragmented across disciplines, journals, and research communities. For two distinct reasons, traditional narrative reviews are structurally unsuited to synthesizing this scattered body of knowledge. First, cross-national collaboration patterns cannot be reliably detected via narrative synthesis as characterizing which countries and institutions co-author with each other, and how those partnerships are organized at the global scale, requires systematic extraction and network analysis of author affiliation metadata across thousands of publications, which cannot be tracked though selective reading of a subset of the literature. Second, the evaluation of themes in a field, i.e., the development of research foci over time, their emergence, intensification, merging or decline, cannot be reconstructed objectively by a narrative review, whose topic groupings are inherently by which papers they happened to read, and how they chose to group them. Instead, detecting such changes needs quantitative time-scaled analysis of keywords co-occurrence and co-citation frequency across the entire corpus. Consequently, narrative approaches struggle to discern what are the key research directions, what are the emerging themes, what are the methodological changes, and what are the patterns of collaboration, especially on the global level. Up to present, most reviews are limited to a particular portion of the research, like the regeneration, physiology or silvicultural aspect. Furthermore, thorough quantitative synthesis of the intellectual structure and developmental process of Korean pine research is not available yet. Considering the significance of Korean pine in the forest restoration and biodiversity conservation and sustainable forest management in the era of global environmental change, timely bibliometric assessment is necessary to clarify the development of research priorities and to guide research efforts in the future (Lim *et al.,* 2024).

Building on these limitations of narrative synthesis, the present study carried out a thorough bibliometric study of Korean pine analyze the intellectual structure, thematic development, and collaborative structure directly addressing the gaps identified above. Specifically, the study aimed to: a) How has Korean pine research evolved in response to changing ecology, technological, and forest management priorities over time? b) Which thematic domains (i.e., regeneration, nutrient ecology, climate adaptation, biotechnology, restoration) have emerged as dominant or rapidly developing research frontiers in Korean pine studies? c) how are international collaborations structured among major Korean pine research regions, and what does this imply for future transboundary conservation and sustainable management efforts? These global systematic bibliometric reviews will answer the above said questions and provide data-driven overviews, identifying seminal works and pinpointing underexplored areas, thereby offering a strategic foundation for guiding future research investments and policy decisions. Specific objectives are, i. to quantify the growth trajectory and geographic distribution of Korean pine research, with particular attention to imbalances across its natural range, ii. identify the leading contributing countries, institutions, authors, and journals and to map the intellectual structure and pinpoint key research themes, iii. to trace evolution of keywords and identify emerging trends and suggest future research directions directly from bibliometric analysis findings.

Materials and Methods

Data collection and processing: The landscape of scholarly databases, including Web of Science (WoS), Scopus, Google Scholar, and Chinese Science Citation, provide the primary data for bibliometric studies. WoS is widely considered the predecessor of systematic bibliometrics, and its overall archive has been built since 1900 and offers the means of sound citation analysis (Mingers & Leydesdorff, 2015; Rodríguez-Soler *et al.,* 2020). The bibliometric analysis was performed to retrieve publications on Korean pine trees using the WoS collection. The Web of Science Core Collection was selected because it provides standardized, high-quality bibliographic and citation data, making it well suited for bibliometric analysis. Scopus was not included with WoS to prevent duplication of records metadata and citation counts differences, and Google Scholar was not included due to the less standardized coverage and reproducible metadata and citation counts. However, this could lead to publication and language bias because WoS mostly covers journals in English language and journals that are published internationally. As a result, some studies that are published in regional databases or local language from countries (Russia, Korea, and Japan) that have natural Korean pine occur partially omitted. The WoS was utilized to search the publications, from October 1st, 2025, based on the search criteria defining the topics (i.e., title, abstract, author keywords, and keywords plus) and document types (Appendix S1) and data from 2025 only reflect publications indexed in the WoS Core Collection up to 01 October 2025, and do not include the full year of publication. The search terms have been selected following some preliminary searches so as to merge all possible descriptions of *Pinus koraiensis* and the entire depth of

research topics related to it. The initial literature search was based on the combination of keywords related to Korean pine, as well as the critical research areas, i.e., ecology, silviculture, genetics, and management, among others.

The initial search had 1,007 publications and these results were then narrowed down using the subsequent filtering criteria to make them relevant. The initial filter was used to extract the documents due to future publication years (2026). The second filter excluded non-research document types, such as news items (short journalistic reports published in journals) and corrections (errata), because they do not report original research findings. The third and largest filter was used on the Web of Science Categories, which was narrowed down to a set of relevant fields, namely, biological, environmental, and forestry sciences, by excluding a large percentage of irrelevant fields such as telecommunications, physics, oceanography, and nanotechnology. The last narrowing was done with Citation Topics Meso, the most relevant sub-disciplines, including Forestry, Soil Science, and Plant Pathology. Publications in English were also restricted to the search. As a result of filtering, 682 publications were found to be relevant and formed the final dataset to be used in the following bibliometric analysis. The workflow of the study is presented in Fig. 1.

Statistical data analysis

The retrieved data from WoS was exported into BibTex and Excel file formats after screening to eliminate irrelevant articles. Bibliometrix R software (version R.4.4.1) (https://www.bibliometrix.org/home/) and VOSviewer (version 1.6.20) (https://www.vosviewer.com/) were applied to analyze the selected articles in terms of bibliometric analysis (Xi & Suhaiza, 2025). The statistical analysis has been conducted using Bibliometrix, a package of R, which was used to identify the number of publications, geographic distribution, and the number of times that research has been cited (Aria & Cuccurullo, 2017). Use logarithmic functions to model the growth of publications as it well represents the fast growth rate initially and the gradual rate at the end. Although several growth models were tested, the logarithmic model had a better fit (R^2 = 0.832) and theoretical consistency with known field maturation trends. The best fit and the most satisfactory residual behavior was obtained by the logarithmic model, which describes the publication trend. The residuals of its model were less systematically structured in time than the residuals of the other three models (linear, exponential and power-law), and were more randomly distributed around zero. This pattern is theoretically similar to "field maturation" in which the number of publications will grow at an increasing rate in early years, but at a smaller percentage in each successive year thereafter as the field matures. However, the alternative models had significantly reduced explanatory power ($\Delta R^2 > 0.15$) and more regular residual patterns, indicating that they were not suitable for modelling the observed deceleration in the growth of publications (Appendix S2). To adjust for differences in overall publication volume of countries, we analyzed collaboration patterns by comparing the observed number of collaborative publications with the number expected on the basis of total research output. The deviation of collaboration was calculated as the difference between the observed and expected collaboration frequency. Positive values indicate levels of collaboration are greater than expected and negative values indicate levels of collaboration are less than expected.

In this study, geographical distribution and international collaboration networks were mapped using Bibliometrix build-in functions with node sizes and edge thickness reflecting articles and collaboration frequencies. In addition, institutional and author productivity ranked were derived from raw affiliations and authorship data with author names disambiguated manually. The Sankey plot was generated to visualize linkages among leading countries, keywords, and sources (core journals), and document co-citation networks and keywords co-occurrence clusters were constructed using VOS viewer's VOS clustering algorithm where co-citation strength measures how frequently two references are cited together. Besides, high-frequency keywords were visualized as a word cloud with font size proportional to occurrence frequency. To get the domestic verse international research collaboration, single-country publications (SCP) and multi-country publications (MCP) metrics were used. SCP refers to publications whose co-authors are all from the same country, while MCP denotes publications with co-authors from at least two different countries. Moreover, betweenness centrality is a network measure that quantifies how often a given node acts as an intermediary or bridge between other nodes in the collaboration network. Co-citation clusters are group of articles that are frequently cited together by later works which are then algorithmically grouped to reveal major research themes and intellectual fronts within the literature. By contrast, research frontiers are identified from the terms and topics whose use is rising and concentrated in the most recent literature, representing where the field is currently moving rather than where it has been. A systematic literature review of *Pinus koraiensis* research was used to get future research direction. The publications were classified and evaluated according to their present share of the literature and an increase rate over the course of time. Such metrics were presented as a map of the research territory and the areas of priority, shown in Appendix S8.

Appendix S1. Search criteria of publication in WoS database for bibliometric analysis.

	Seach criteria	Strings
Topic	Species descriptions	"*Pinus koraiensis*" OR "Korean pine"
	Research topics descriptions	"ecology" OR "forest" OR "silviculture" OR "growth" OR "genetic" OR "physiology" OR "pest" OR "disease" OR "climate" OR "conserve" OR "management" OR "nut" OR "seed" OR "timber"
Document types	Research article or review	

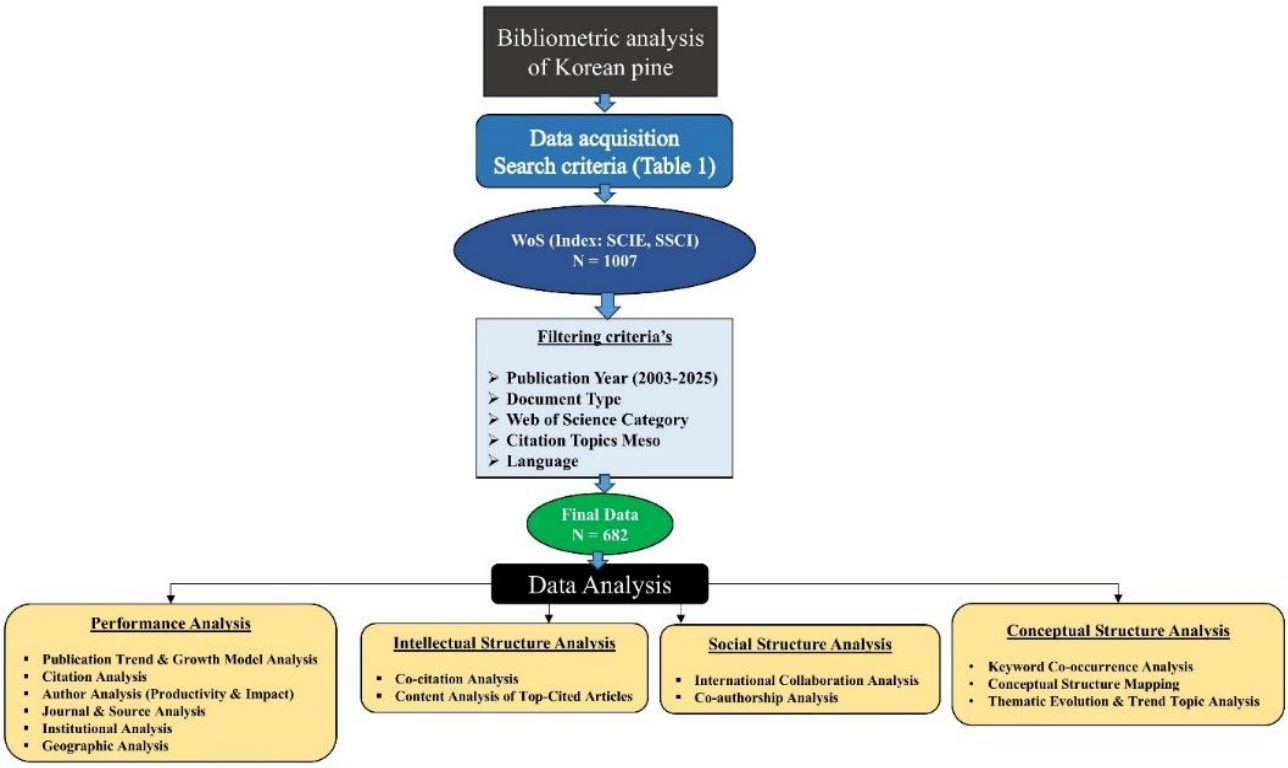
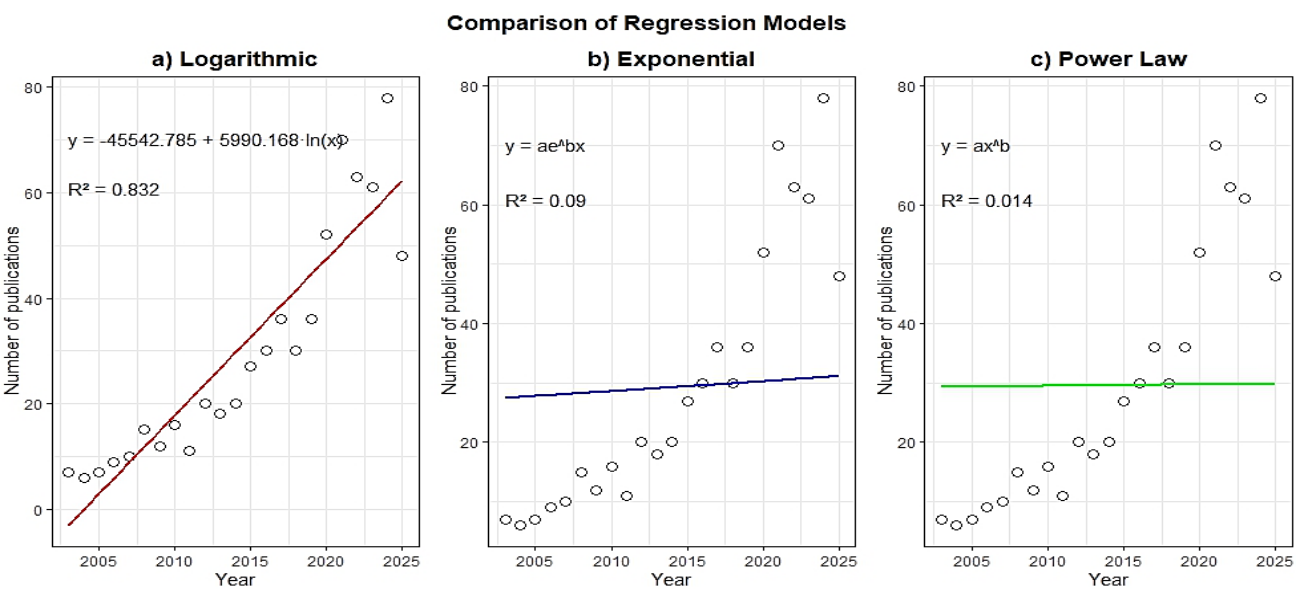


Fig. 1. Workflow of these studies. N refers to the number of articles.



Appendix S2. Comparison of regression models.

Results

Annual publication trend and growth trajectory of Korean pine research: The annual publication trend for the field, which is based on the 682 publications extracted from the Web of Science database (2003 - 2025) and provides a clear visualization of its development stage in Fig. 2. The logarithmic growth model (Y = - 45542.79 + 5990.168*ln(x), R^2= 0.832) indicated a robust fit, indicating a predictable and well-defined growth pattern over the observed time (Fig. 2A). It began with just seven articles in 2003, and gradually the number of publications increased to 75 in 2024 (Fig. 2B). From 2003 to 2006, fewer than 10 articles were published, but from 2014 onwards, the overall number of articles rose dramatically and peaked in 2024, though count the number of articles in 2025 until the end of September. Notably, scientific interest in Korean pine has grown since 2012. The research sector was booming with a annual growth rate of 9.15%. Three evolutionary periods have been observed in Korean pine research, the first stage (82 research articles, 2003-2010), the intermediate stage (274 research articles, 2011-2020), and the present maturation stage (311 research articles, 2021-2025). Investigators have devoted much focus to the growing recognition of Korean pine trees' critical ecological and economic value, particularly, their role in carbon sequestration, biodiversity, and as a source of high-

quality timber and pine in temperate forest, has fueled a sustained increase in global research output since 2003. The highest number of mean total citations per scientific article was recorded in 2006 (81.22), and a decreasing pattern was observed till 2025. Since it uses recently published documents, it takes long to build up a significant number of citations that have plummeted since 2022. However, the annual mean total citation exhibited a similar pattern with two peaks in 2006 (4.06) and 2021 (3.21).

Leading countries and international collaboration networks: Globally, China, South Korea, Japan, USA, Russia, Japan, Canada, and Germany are at the heart of this scientific elite of research (Appendix S3). Among them, China is known to have high-impact and innovative research, and South Korea has proven to have meteoric growth in volume, which currently is frequently leading in the number of publications over time. Analyzing the corresponding authors' countries of affiliation, it is possible to notice that this research topic is global since the 682 publications in the sample are distributed across 12 countries (Fig. 3). As shown in Fig. 3, the analysis indicates that China recorded 524 publications, contributing 76.83% to the total number of publications and representing the most significant country in terms of *Pinus koraiensis* studies. Moreover, multiple performance metrics such as single country publication (SCP) and numerous country publications (MCP) are used to rank the top 10 most prolific countries in Appendix S4. China ranked as the most prolific country for SCP (71.76%) and MCP (28.24%), and gradually other countries like Korea, Russia, USA, Japan, Canada, etc.

The quantitative study of international research cooperation demonstrates a highly polarized network with China as its center (Fig. 4). China has remarkably high relationship scores, especially in the Asia-Pacific region, with link scores of more than 100 with New Zealand (171.48), Japan (138.03), Australia (134.49), and South Korea (127.84). Nonetheless, this strong regional network is balanced with deep collaboration voids with the main scientific giants of the West, as the values of frequency are strongly negative with the USA (-112.46) and Canada (-98.31). The latter trend of polarized cooperation is also replicated in the case of South Korea, which has a comparable profile, with a high level of connection to Japan (138.03) and a corresponding negative frequency with the USA (-112.46). However, the USA itself has surprisingly few linkages in this network, with its best relationship to date being with Japan (138.03) but with weak or negative relationships with others.

Analysis of influential institutions and authors: After analyzing the volume of publications, Chinese institutions were leading in the sphere of research, then the Northeast Forestry University is the most influential institution by far (574 articles), representing 84.16% (Fig. 5). The dominance of China is further confirmed by the Institute of Applied Ecology (218 articles, 31.96%), Beijing Forestry University (127 articles, 18.62%) and the Chinese Academy of Science system is a significant contributor through its combined output (108 articles, 15.84%). South Korea is heavily concerned with forestry and ecological studies in Northeast Asia, as evidence by Seoul National University (74 articles, 10.85%) and Korea University (52 articles, 7.62%) which are the major contributors within the region. The 682 publications represent the research studies of 1780 authors. Table 1 represented that among the top authors, Guangze Jin shown the highest number of publications (i.e., 42 articles), constituting 6.16% and representing the most productive among the authors. The most productive authors were identified regarding the number of articles while the influential (i.e., impact) authors were identified based on the number of citations (see Table 1). Thus, in terms of total citations, Xiaochun Wang recorded 916 citations from 40 articles, representing the most influential author.

Table 2 represent the lists of the top 10 cited articles in Korean pine, representing 16.25% (1939 citations) of the total citation of 11930. The analysis of these foundational papers indicated several key trends. This list of papers is dominated by forest carbon and climate change, ecosystem processes, tree morphology and remote sensing, tree physiology and stress response themes. Among the top ten articles, the article named "Biomass allometric equations for 10 co-occurring tree species in Chinese temperate forests" (Wang CK, 2006) received the highest number of citations (360 citations), representing 18.57% of the total citations. Furthermore, Yu, G. *et al.,* 2008 and Wang, C. *et al.,* 2006 had published in core high-impact journals named New Phytologist (IF: 8.1), and Global Change Biology (IF: 12).

The three-Fields plot explains the intellectual structure of the *Pinus koraiensis* research, and it shows a strong representation of the scholarly network where China is the most contributing country (Fig. 6). Chinese research is published mainly in leading forestry and ecology journals in the field like Forest Ecology and Management and the Journal of Forestry Research. The general themes in research, closely associated with this China-journal axis converge upon three main themes: basic ecological knowledge about the forest (e.g., its growth, biomass, soil properties), long-term effects of global environmental change, particularly climate change and nitrogen deposition, and the particular menace of pine wilt disease, with a research agenda that focuses on not only the ecological behavior of the species but also on its urgent conservation needs.

Core journals and intellectual foundations: The bibliometric analysis identified 682 publications distributed across 211 journals. The top 10 journals are presented in Appendix S5. Forests journal published the largest number of Korean pine studies, with 84 publications 12.32% of the total. Table 3 lists the top ten sources in the dataset, which together represent the main channels of scholarly communication in this field. Forest Ecology and Management leads the ranking, with substantially higher total citations and h-index than any other source, making it the central journal in the field. Its position is reinforced by other major forestry journals, including Forests and the Journal of Forestry Research, indicating that research on Korean pine is closely tied to applied forest science and management. The presence of ecological and soil science journals, such as Ecological Indicators, Plant and Soil, and Science of the Total Environment, further reflects the interdisciplinary basis of the field, which incorporates soil biology, ecosystem monitoring, and environmental science.

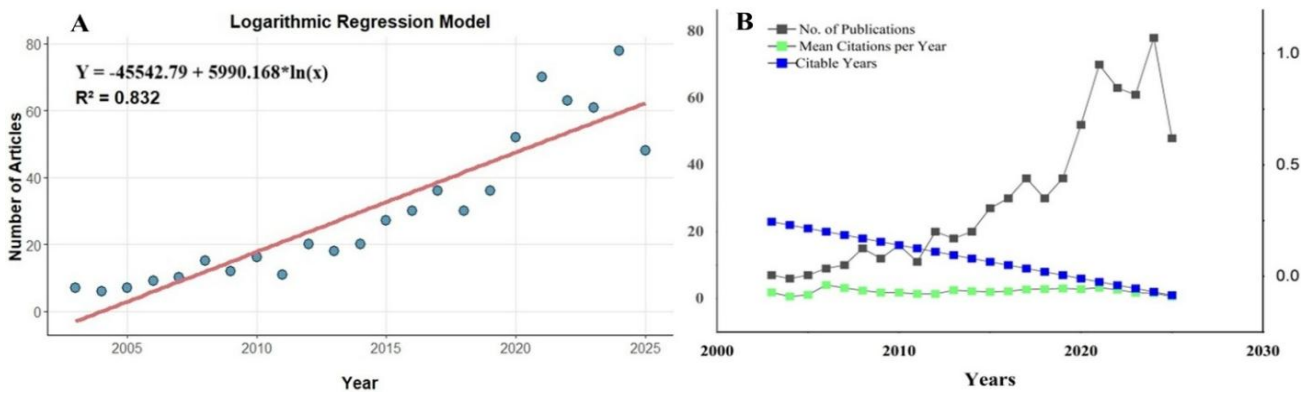


Fig. 2. Modeling publication growth with logarithmic function.



Fig. 3. Geographical distribution of the number of publications for Korean pine studies.

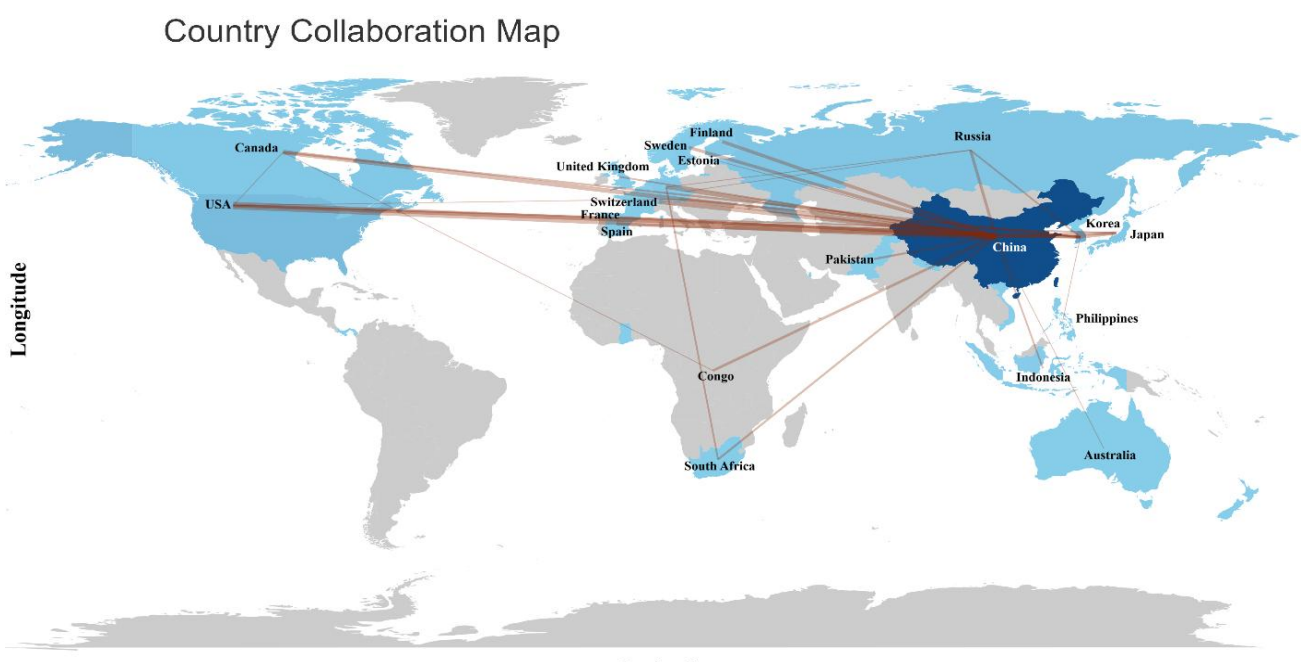
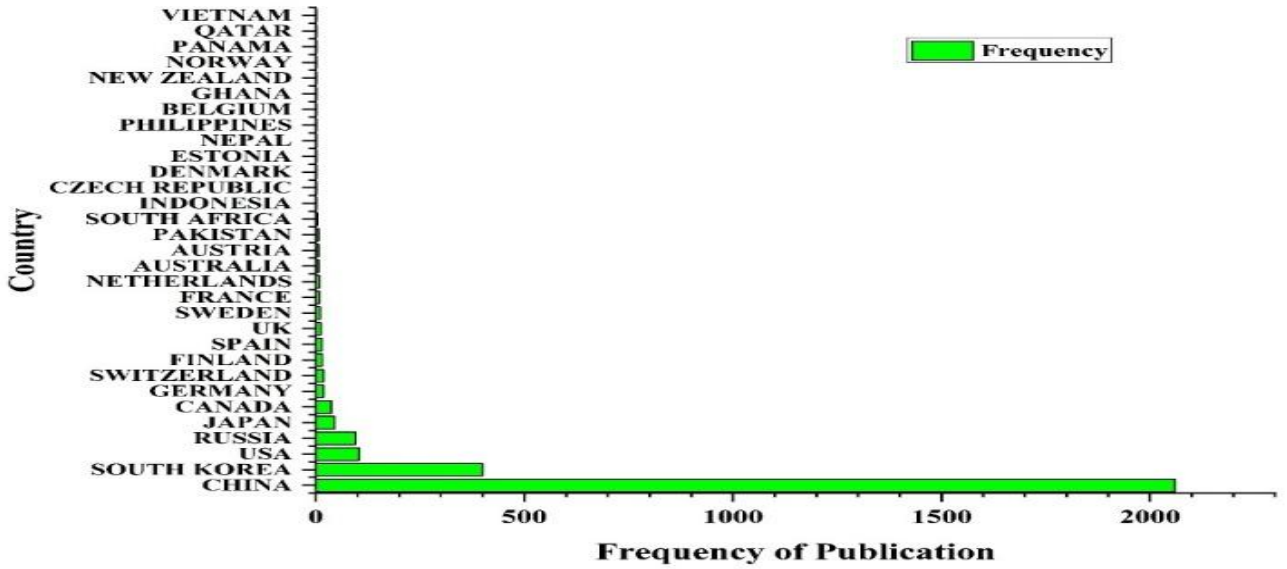
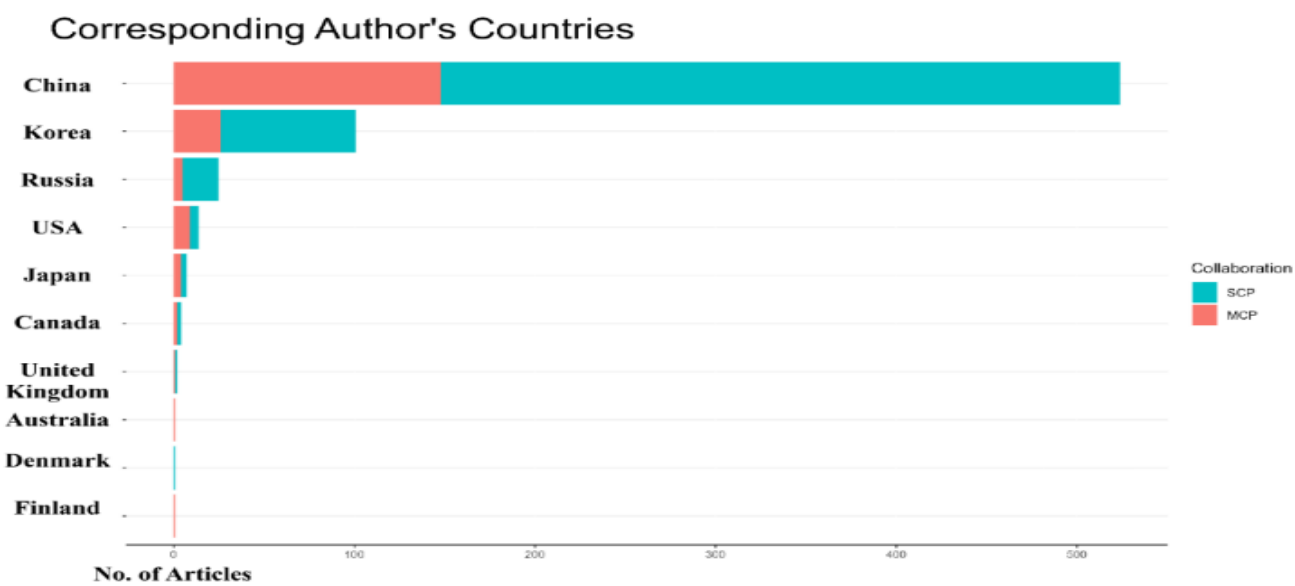


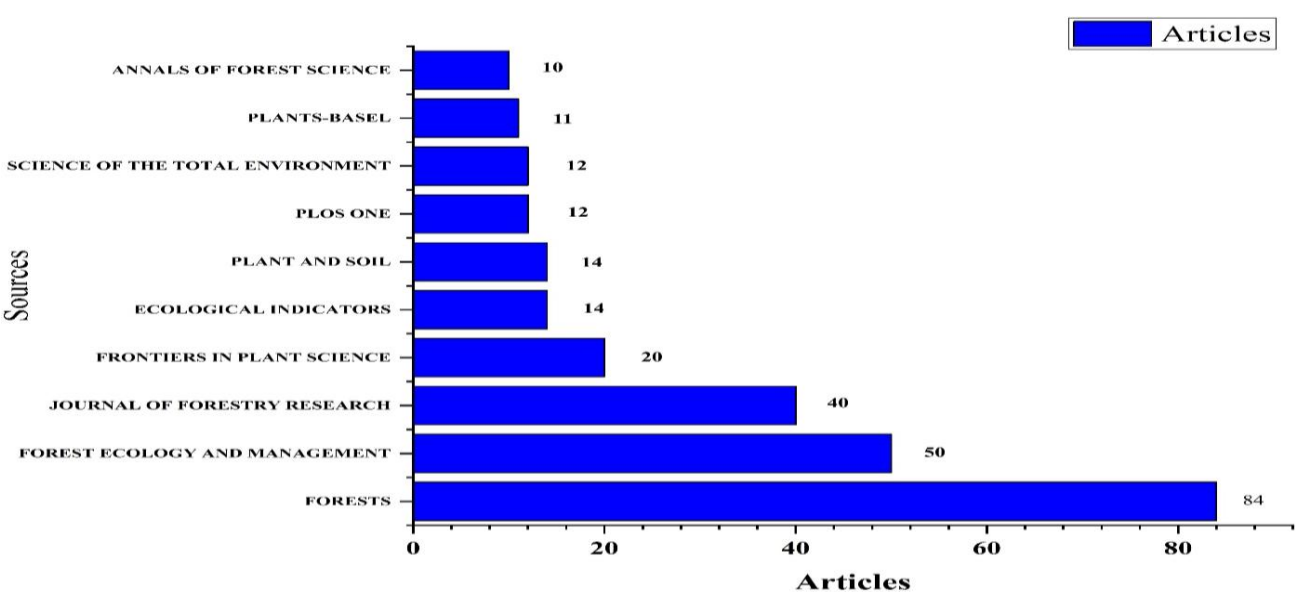
Fig. 4. Global research collaboration network map for Korean pine tree.



Appendix S3. Global trends in scientific publication volume among leading nations.



Appendix S4. Collaboration profile of the most prolific scientific countries.



Appendix S5. Shows the top 10 journals with the highest number of articles.

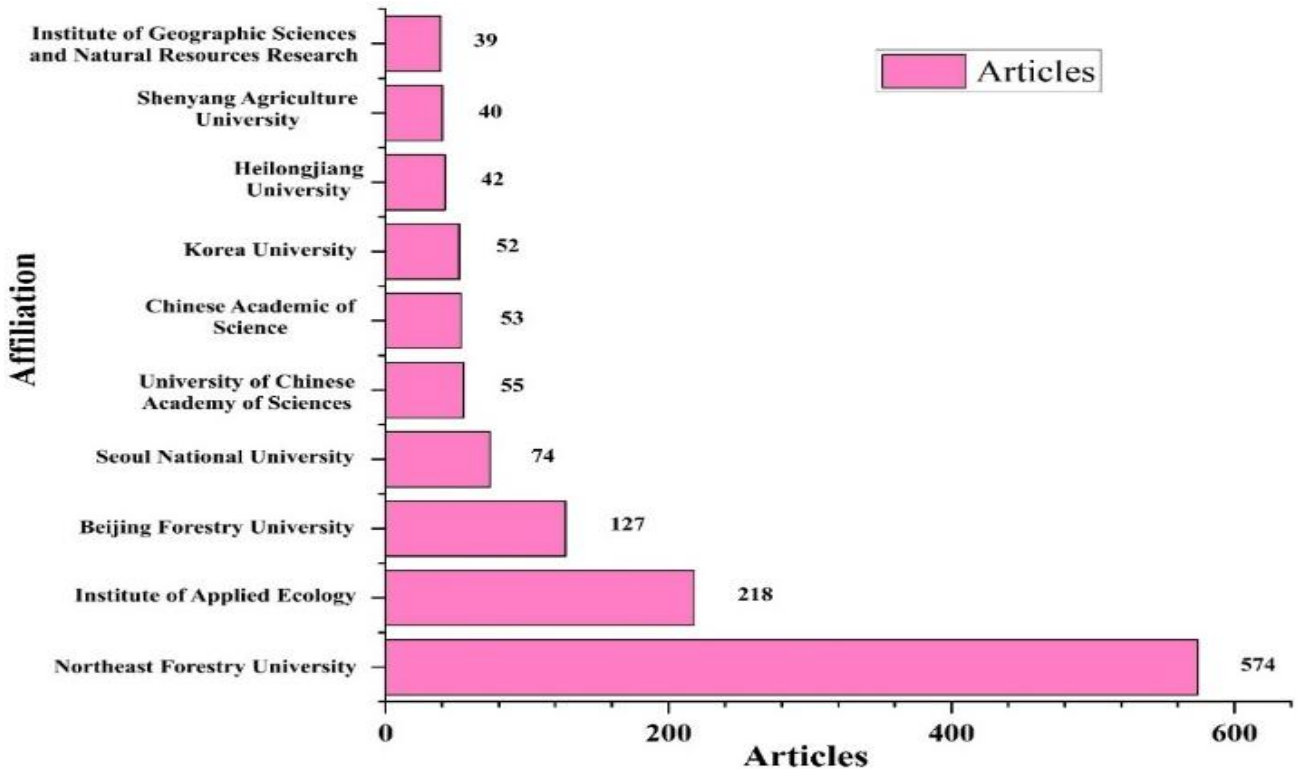


Fig. 5. Top 10 leading research institutions with the highest number of publications in Korean pine studies.

Table 1. Authors, publications, and total citations of the top 10 authors.

Authors	Number of publications	Total citation	Average citations	h-index
Guangze Jin	42	761	18.12	17
Xiaochun Wang	40	916	22.9	17
Yanxia Li	33	463	14.03	12
Jun Wang	33	303	9.18	12
Xuehan Zhao	32	326	10.19	12
Zhili Liu	28	345	12.32	12
Yanan Wang	25	311	12.44	9
Xingpeng Li	24	396	16.5	11
Lei Zhang	24	665	27.71	10
Mengmeng Zhang	24	349	14.54	10

To elucidate the intellectual structure underlying these core journals, a co-citation analysis of the most frequently cited references was conducted. The analysis identified four distinct clusters of frequently co-cited references (Fig. 7). The yellow cluster is centered on Wang CK (2006, Forest Ecology and Management) as the largest node, together with Pan YD (2011, Science) and Dixon RK (1994, Science), indicating a thematic focus on forest carbon dynamics and large-scale ecological science. The blue cluster contains classic methodological papers on soil microbial biomass, Vance ED (1987) and Brookes PC (1985), both published in Soil Biology and Biochemistry, together with Wright IJ (2004, Nature), suggesting a foundation in soil biochemistry and plant functional trait research. The red cluster, grouped around Yu DP (2011, Environmental Management), an anonymous 1992 citation from the Journal of Northeastern, and Li X (2020, Forests), appears to relate to the literature on forest management and environmental policy, with Shao GF (1994, Forest Ecology and Management) acting as a bridge to the blue cluster. The green cluster, comprising Yu DP (2011, Annals of Forestry Science), Yu DP (2013, Forest Ecology and Management), Holmes RL (1983, Tree-Ring Research) and (2013, Forest Ecology and Management), Holmes RL (1983, Tree-Ring Research) and He HS (2005, Journal of Biogeography), reflects a dendrochronology and spatial forest ecology theme.

Keyword analysis: Evolution of research themes.

High-frequency keywords, co-occurrence clusters and emerging research frontier: The most frequently used keywords were identified and analyzed to classify the 682 publications in the sample. Figure 8 shows the top ten keywords of the authors. The most common keyword was “growth”, occurring 122 times, followed by “pinus koraiensis”, and “forest”, used 100 and 87 times, respectively. These three dominant keywords define the main focus area of the field: the growth and ecology of Korean pine in a forest context.

The co-occurrence network analysis (Appendix S6) shows a well-defined research cluster (cluster 1) concerned with the ecology and dynamics of Korean pine forests, with central themes of growth, forest, diversity, and biomass. The keyword “growth” is the most influential node in the network, with the highest betweenness centrality (154.15) (Appendix S7), indicating that it is a strategic concept linking various research topics across the field. This central position suggests that “growth” acts as a conceptual “bridge” connecting diverse research themes, from physiological processes to ecosystem-level dynamics, and that growth performance is the unifying research lens of the field.

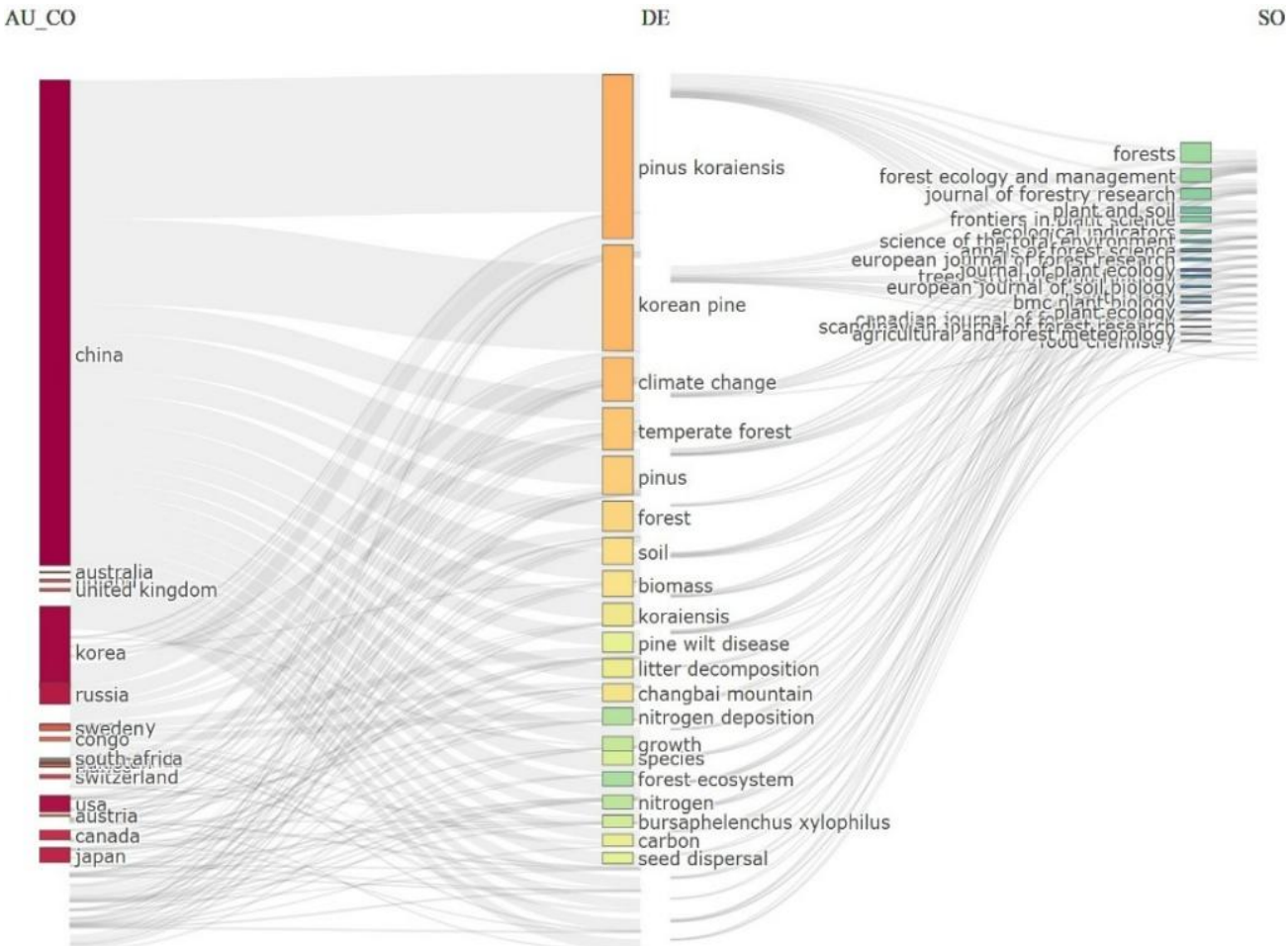


Fig. 6. Three-field plot of *Pinus koraiensis* publications: Country, Journal, and Theme linkages. The color have no substantive meaning.

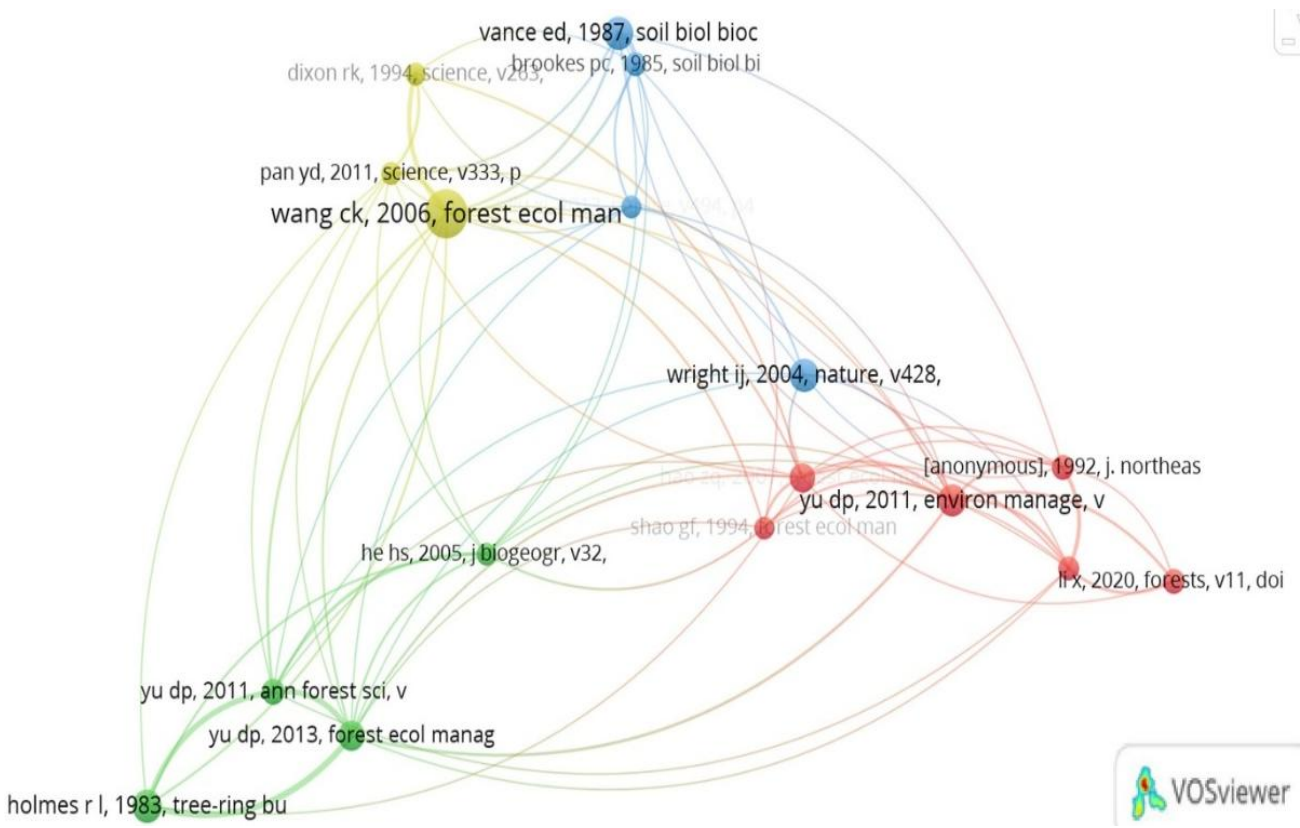


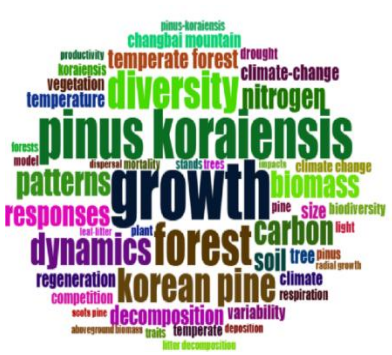
Fig. 7. Network visualization of document co-citation clusters.

Table 2. 10 top-cited articles in Korean pine studies.

Ranking	Title	Authors	Total citation (TC)	TC per year	Journal
1.	Biomass allometric equations for 10 co-occurring tree species in Chinese temperate forests	Wang CK, 2006	360	18	Forest Ecology and Management
2.	Water-use efficiency of forest ecosystems in eastern China and its relations to climatic variables	Yu, G. *et al.,* 2008	287	15.94	New Phytologist
3.	Soil respiration in six temperate forests in China	Wang, C. *et al.,* 2006	211	10.55	Global Change Biology
4.	Detection of individual trees and estimation of tree height using LiDAR data	Kwak, D.A. *et al.,* 2007	198	10.42	Journal of Forest Research
5.	A chronosequence of wood decomposition in the boreal forests of Russia	Yatskov, M. *et al.,* 2003	194	8.43	Canadian Journal of Forest Research
6.	Vertical structure and spatial associations of dominant tree species in an old-growth temperate forest	Hao, Z. *et al.,* 2007	157	8.26	Forest ecology and management
7.	Altitudinal changes in carbon storage of temperate forests on Mt Changbai, Northeast China	Zhu, B. *et al.,* 2010	139	8.69	Journal of Plant Research
8.	In vitro and in vivo antioxidant activity of *Pinus koraiensis* seed extract containing phenolic compounds	Su, X. Y. *et al.,* 2009	138	8.12	Food Chemistry
9.	Evaluation of morphological, physiological, and biochemical traits for assessing drought resistance in eleven tree species	Bhusal, N. *et al.,* 2021	138	28.6	Science of the Total Environment
10.	Density dependence across multiple life stages in a temperate old-growth forest of northeast China	Piao, T. *et al.,* 2013	117	9	Oecologia

Table 3. Top 10 most cited journals.

Rank	Source	Total citation	h_index	g_index	m_index
1.	Forest Ecology and Management	1744	22	41	0.957
2.	Forests	704	14	22	1.167
3.	Journal of Forestry Research	483	13	20	1.083
4.	Annals of Forestry Science	200	8	10	0.444
5.	Ecological Indicators	225	8	14	0.727
6.	Plant and Soil	331	8	14	0.421
7.	PLOS One	215	8	12	0.571
8.	Science of the Total Environment	474	8	12	0.889
9.	European Journal of Soil Biology	244	7	8	0.538
10.	Frontiers in Plant Science	153	7	11	0.875



Rank	Words	Frequency
1	growth	122
2	pinus koraiensis	100
3	forest	87
4	diversity	79
5	korean pine	71
6	dynamics	66
7	carbon	60
8	patterns	59
9	biomass	55
10	responses	53

Fig. 8. Word-cloud showing most used high-frequency keywords or phrases.

Furthermore, the analysis of keyword co-occurrence and emergence revealed a mature thematic core and an emerging research front (Appendix S7). The core consists of high-frequency terms with earlier means publication years (growth, diversity, stand dynamics, climate change, and regeneration), reflecting the fields long-standing interest in forest dynamics and climate response. The emerging front, indicated by terms whose occurrences are concentrated in 2020-2025, comprises three groups: a molecular and tree-improvement cluster (somatic embryogenesis, embryogenic callus, transcriptome, gene expression, biosynthesis), a soil-microbial cluster (fungal community, bacteria, and enzymatic stoichiometry), and a nutrient-cycling and functional-trait cluster (nitrogen addition, functional traits, and seedling establishment). Notably, the same frontier pattern was found in two independently exported record sets, suggesting that the shift toward molecular and microbial themes is a stable feature of the literature rather than an artifact of a particular sample.

Thematic evolution over time: Multiple correspondence analysis explains the conceptual framework of the research field, where the initial two dimensions (Dim 1: 34.05%; Dim 2: 19.94%, Fig. 9) together explain 53.99% of the total variation. The map shows distinct thematic clusters: climate change, drought, and forest responses (upper left); biomass, productivity, and tree characteristics (lower left); and soil biogeochemistry and decomposition processes (right side). Together, these clusters depict a coherent field that integrates forest dynamics, ecological processes, and environmental change.

The trend topic analysis (Appendix S8) shows a clear temporal shift in *Pinus koraiensis* research, from traditional ecological studies toward advanced genetic and climate-change-related topics. Studies from the early part of the study period established the fundamental themes of forest ecology and management, including growth, seedlings, temperate forest, and diversity. Over time, the thematic range has expanded, with a clear move toward advanced subjects such as somatic embryogenesis' and gene expression, reflecting interest in genetic and biotechnological applications. At the same time, the prominence of topics such as carbon storage, soil respiration and climate change indicates that the field is increasingly concerned with the role of Korean pine forests in biogeochemical cycles and climate regulation.

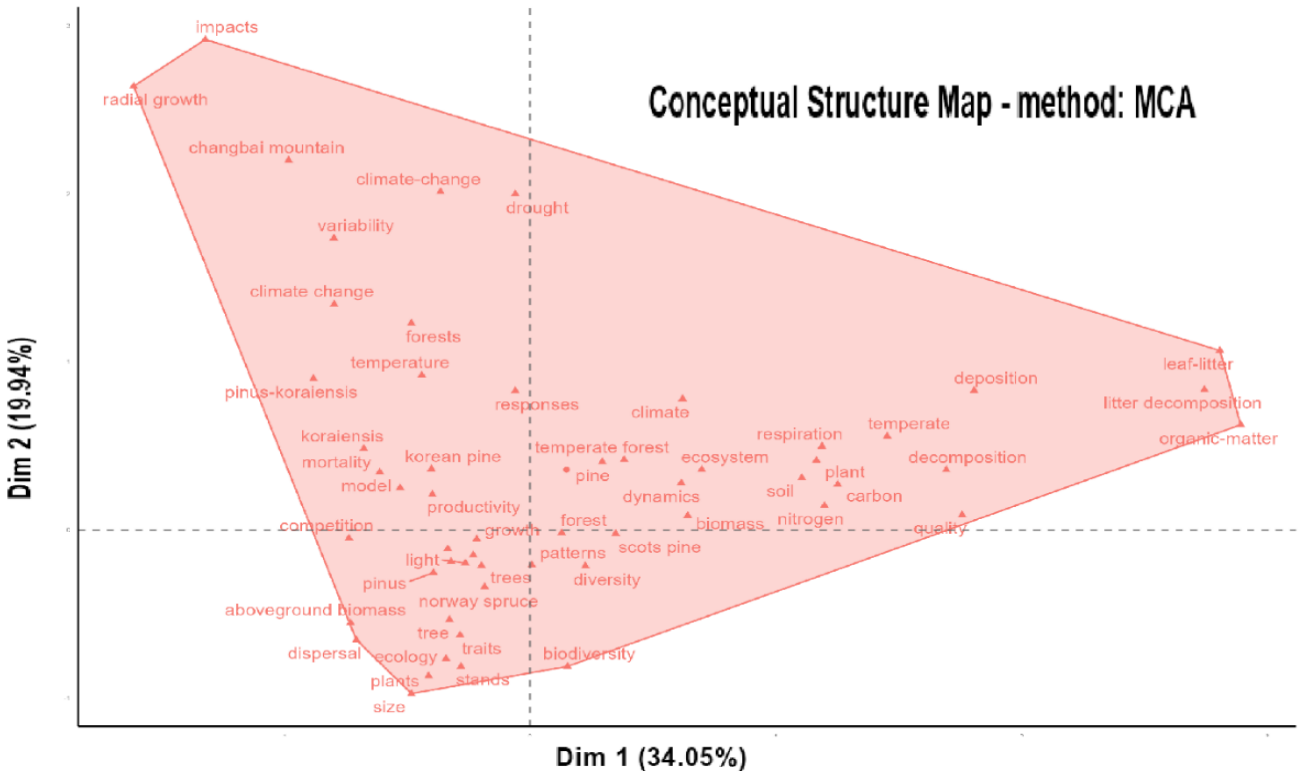
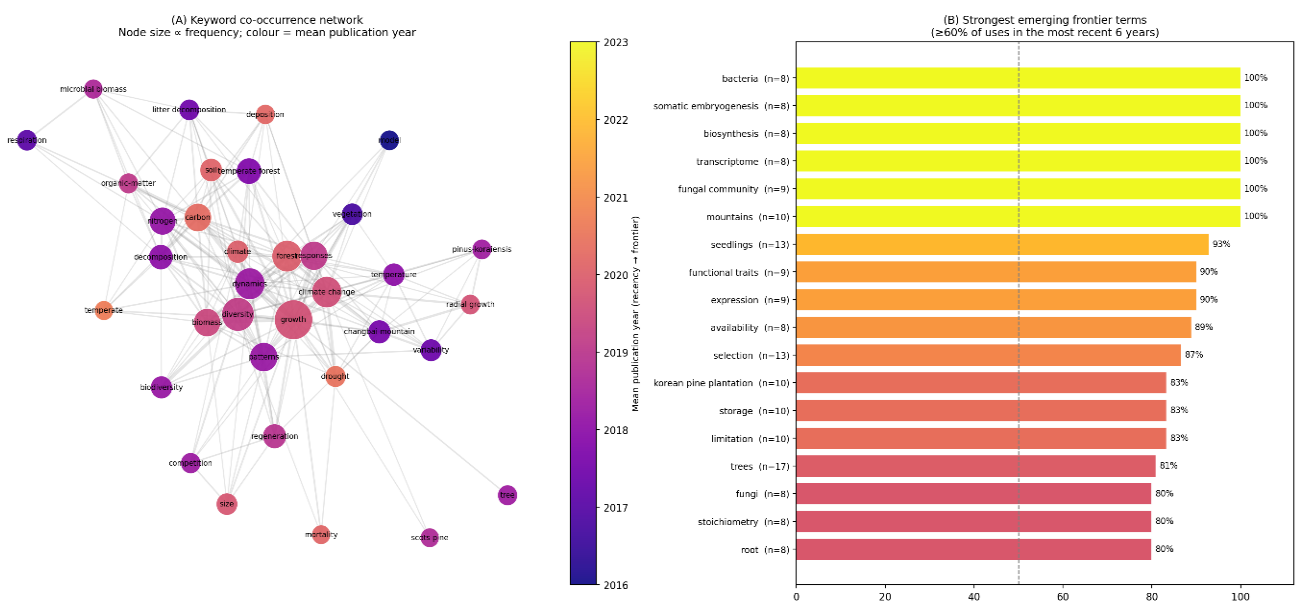


Fig. 9. Conceptual structure map of *Pinus Koraiensis* research based on Multiple Correspondence Analysis.



Appendix S6. Keyword co-occurrence network and emerging research frontiers in *Pinus koraiensis*.

Appendix S7. Co-occurrence network analysis of 10 highest occurring author keywords.

Keywords	Cluster	Betweenness	Closeness
Growth	1	154.15	0.020
Pinus koraiensis	1	31.76	0.017
Forest	1	81.745	0.020
Diversity	1	33.85	0.017
Korean pine	6	24.60	0.016
Dynamics	1	35.13	0.017
Carbon	2	23.51	0.016
Patterns	1	18.98	0.015
Biomass	1	20.05	0.016
Responses	1	32.51	0.018

Discussion

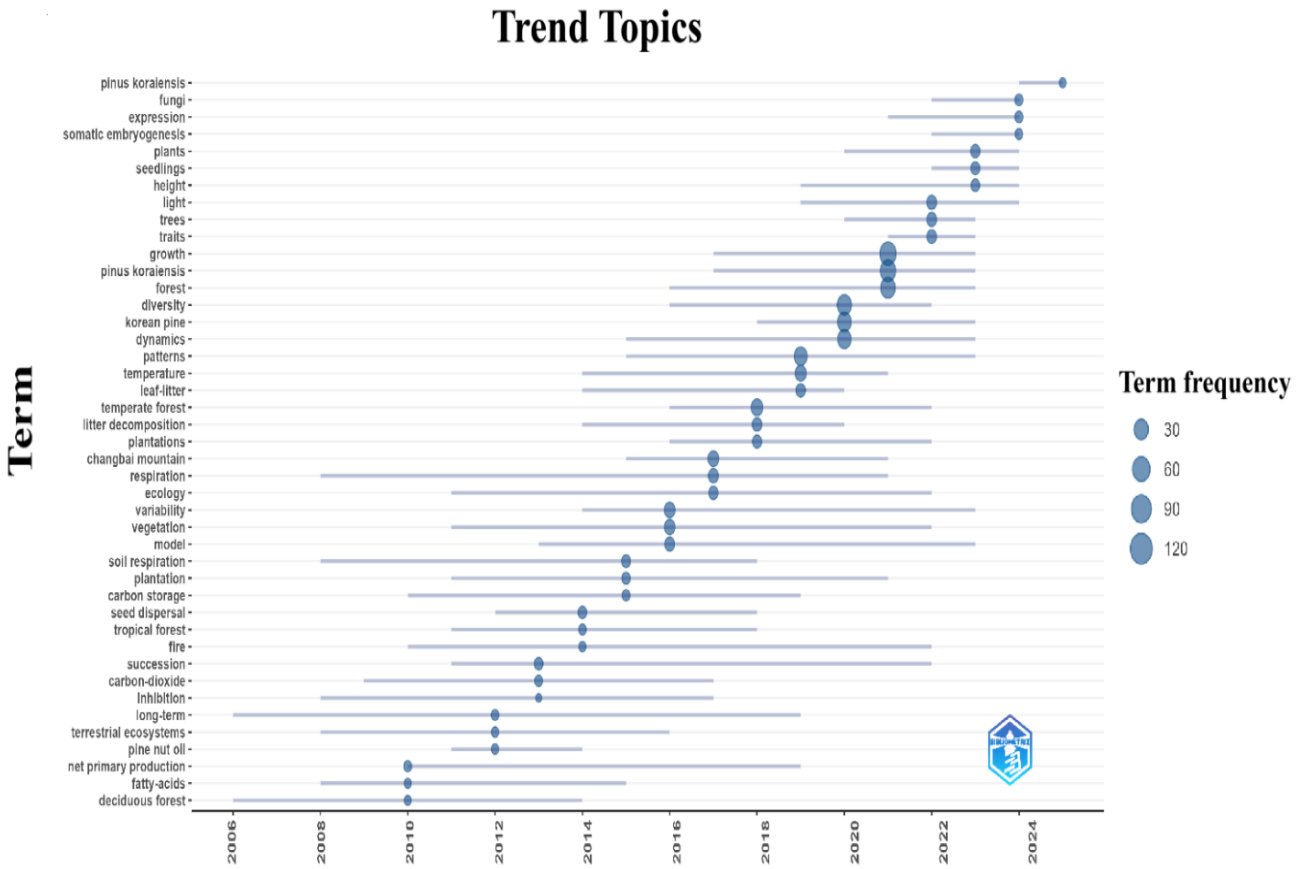
Maturation of a research field: from foundation to application: Trends of the publication create a clear picture of how the fields have grown. The logarithmic growth model shows a strong fit (R^2 = 0.832), suggesting that the field has moved beyond early stage, toward a more stable and predictable phase of growth, which is characteristic of an established scientific discipline. This development can be divided into three periods: the stage of developing a baseline (2003-2010) with limited output, an intermediate stage (2011-2020) in research with rapid

expansion, and the current maturation stage (2021-2025) of high research output. This pattern reflects a direct response to global and regional needs, as the increase in publications since 2012 coincides with growing recognition of the importance of temperate forests worldwide, particularly for carbon sequestration as a means of mitigating climate change (Lal & Lorenz, 2012; Wang *et al.,* 2019; Zhao *et al.,* 2025). As a key species in these ecosystems, Korean pine has naturally become a focus of study, and this driver is supported by the prevalence of keywords and trend topics such as carbon storage, biomass, and climate change (Kweon & Comeau, 2023; Zhao *et al.,* 2025).

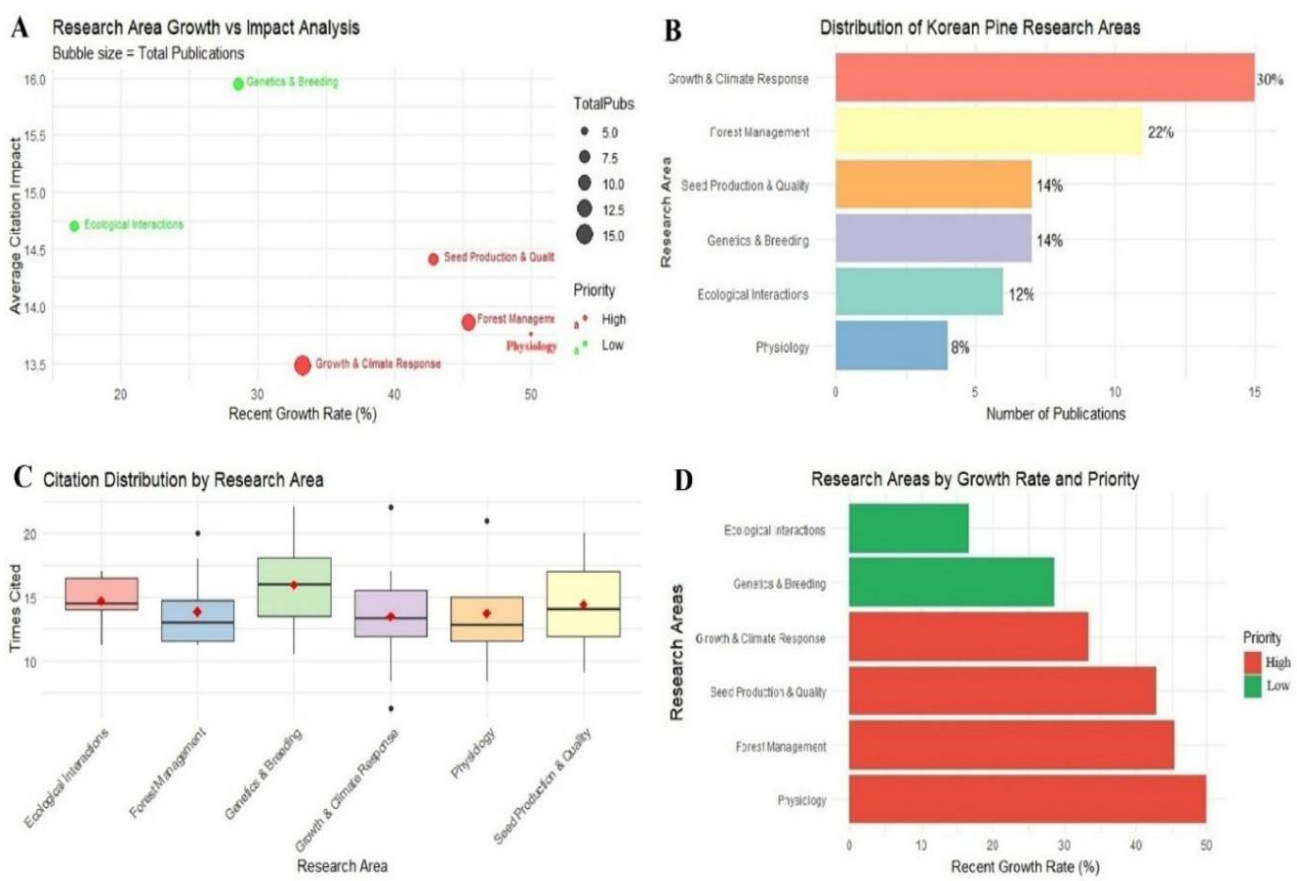
In addition, the field has shifted from basic ecology (e.g., growth, and diversity) toward more complex and applied research fronts, driven by urgent global need to mitigate climate change, the availability of advanced technologies for genetic analysis and growth modeling, and the increasing socio-economic importance of sustainable forest management for ecosystem services (Dong & Liu, 2017; Kang *et al.,* 2024). New high-technology terms such as "somatic embryogenesis" and "expression" point to growing interest in genetic conservation and biotechnology, aimed at improving the resilience and economic value of the species. Somatic embryogenesis has become an important research objective, probably owing to both technological advances in plant biotechnology and practical forestry needs. Korean pine regenerates slowly in nature and produces seeds irregularly, which complicates afforestation and germplasm conservation. These challenges are further exacerbated by the increasing frequency of climate-induced stressors, which outpace the adaptive capacity of natural regeneration and heighten the need for alternative propagation strategies. Tissue culture and cryopreservation techniques have enabled large-scale clonal propagation and ex-situ conservation, thereby increasing research interest in somatic embryogenesis. Similar trends have been reported for other commercially and ecologically important tree species, in which biotechnology has become increasingly integrated into breeding and restoration programs (Gao *et al.,* 2020; Pérez-Molina *et al.,* 2025; Ley-López *et al.,* 2026). This integration has been driven largely by the falling costs and increasing efficiency of molecular and tissue culture platforms which have transformed these tools from experimental curiosities into operational forestry assets. For major conifer species, such as *Pinus sylvestris*, *Picea abies,* and *Pinus taeda*, a similar gradual transition in research themes has been observed, from traditional silviculture and growth assessment toward molecular biology, stress physiology, genetic improvement, and tissue culture technologies (Guner *et al.,* 2026; Przybylski *et al.,* 2025). In addition, Korean pine research exhibits distinct thematic priorities linked to the species ecological and economic importance in Northeast Asia, particularly seed production, nut yield, management of mixed broadleaf conifer forests, and restoration under human disturbance and climate change. Consequently, somatic embryogenesis has emerged not merely as a research theme but as a practical bridge between fundamental ecological understanding and applied biotechnological intervention, offering a direct pathway to securing genetic resources and accelerating reforestation in a rapidly changing environment. Although the average number of citations per article has recently declined, because older papers have had more time to accumulate citations, the growing number of publications demonstrates that the field remains active, and the impact of recent research is not yet fully apparent.

Global research hotspots and collaboration patterns: Research on *Pinus koraiensis* is strongly concentrated geographically within the species native range, with China accounting for 76.83% of publications. This dominance is unsurprising, given that the species is mostly found in Northeast China, which contains extensive temperate forests dominated by Korean pine (Chen *et al.,* 2024; Pak *et al.,* 2023). The high productivity of Chinese institutions, especially Northeast Forestry University and the Chinese Academy of Sciences, has further secured China's leading position, as the species has become a regional research priority (Pak *et al.,* 2023; Yan *et al.,* 2023). China's substantial investment in forestry and ecological restoration programs (e.g., the National Forest Protection Program) has directly supported Korean pine research. In addition, the contribution of this species to carbon cycling in temperate forest ecosystems has been studied extensively in China. Similarly, the strong performance of South Korea, Japan, and Russia corresponds to the natural distribution of the species and its considerable economic and ecological value in these countries (Petrenko *et al.,* 2022). The high concentration of research also reflects the established leadership and deep expertise of Northeast Forestry University established in Korean pine research. Meanwhile, it highlights a valuable opportunity for the field, such as broadening contributions across institutions would enrich the citation landscape, introduce complementary methods and perspectives, and enrich the citation landscape, introduce complementary methods and perspectives, and strengthen the independent, cross-institutional replication that underpins robust science. Ecologically, *Pinus Koraiensis* spans a range across Northeast China, where populations experience different climates, soils, and disturbance regimes and often exhibits local adaptation and provenance based trat variation. Consequently, the findings on carbon cycling, regeneration, or management drawn largely from Northeast Chinese stands regionally specific rather than generalizable across the species full range.

The limited research linkage with the USA may in part be due to the geographical distribution and regional management relevance of Korean pine. Korean pine is a native species of Northeast Asia, and it plays an important ecological and economic role in China, Korea, Russia and Japan (Pak U *et al.,* 2023). Therefore, these countries attach great importance to research on its conservation, restoration, genetics, productivity and forest management. However, Korean pine is not a native species in North America, where forestry research is more often focused on native conifer species and local issues such as forest restoration, wildfire, pests, diseases, and climate adaptation. Thus, limited USA involvement may be more a function of differences in species distribution, management priorities, available field sites and research funding rather than a lack of scientific capacity. But greater collaboration with U.S. researchers could bring valuable expertise in forest genetics, ecological modelling, climate-change adaptation and advanced monitoring technologies (Burns & Honkala, 1990).



Appendix S8. Temporal evolution of research themes in *Pinus koraiensis* literature.



Appendix S9. Analytical framework for *Pinus koraiensis* research prioritization: (A) research area impact vs growth, (B) priority classification of research area, (C) publication distribution by research area, and (D) research focus timeline.

Nevertheless, international collaboration analysis shows a very polarized and region-specific network. Although the research theme is global in terms of having 12 countries, the collaborative texture is closely knit around China as the main center, with outstanding connections with other countries of the Asia-Pacific region such as Japan, Australia, and New Zealand. In addition, the elevated relationship scores with New Zealand (171.48) and Australia (134.49) reflect methodological rather than biogeographic ties, both countries maintain strong exotic conifer and plantation forestry research programs that routinely evaluate non-native pine species for silvicultural and invasion risk purposes, and their research groups are predominant contributions to shared quantitative methods such as climate envelope modelling, dendrochronology, and forest genetics that Korean pine studies frequently draw (Howell CJ, 2019; Edwards P *et al.,* 2020). The negative collaboration deviations for the USA (−112.46) and Canada (−98.31) point to a less frequent collaboration with these countries than expected based on the total publication volumes. These results are not evidence that there was no collaboration or negative relationship. Instead, they show a relative gap between observed and expected collaboration levels. The relatively high negative deviations may suggest that there is room for more research collaboration, institutional exchange and projects with researchers from the USA and Canada. The development of these unique, strong networks provides an ideal platform for future collaborations, in which the synthesis of various scientific practices and methodologies might initiate new levels of innovation in the area (Shi *et al.,* 2024). Most probably, the drivers are multifaceted involving geographics proximity, common research interests unique to the Asia-Pacific region (Fung & Wong, 2017).

Strong intra-regional collaboration can facilitate knowledge exchange within Asia, but limited engagement with research centers in other regions may constrain the diversity of perspectives, methods, and comparative insights brought to Korean pine research. Future efforts should create international research consortia that link Northeast Asian institutions with research centers in Europe and North America to break down intellectual siloing and promote cross-regional knowledge sharing. Such cross-fertilization could be facilitated by jointly funded comparative projects, shared ecological and genomic data sets, researcher and student exchange programs, joint graduate training, and regular international workshops. Collaborative studies that integrate regional field expertise with novel approaches in forest genetics, remote sensing, ecological modelling and climate-change adaptation have potential to broaden the methodological base of the field and increase the global relevance of Korean pine research (Looney *et al.,* 2020).

Intellectual structure and major research fronts: Co-citation and keyword analysis of the Korean pine research intellectual structure can be said to reveal a cohesive and structured intellectual framework with several interconnected thematic clusters. Cluster 1 (Soil Ecology and Biogeochemistry) of the field was based on seminal contributions in soil biology and nutrient cycles and comprises the fundamental knowledge of below-ground processes. It answers the crucial question of how the functioning of Korean pine forests as an integrated system is carried out with regard to soil organic matter, decomposition, and nutrient availability. This study is essential to productivity and health of forests (Fu *et al.,* 2021; Teng *et al.,* 2021; Tian *et al.,* 2015). Cluster 2 (Forest Dynamics and Climate) reflects the macro-level view, in which the ecology of the Korean pines is related to global change biology. It combines the studies of large-scale forest dynamics, carbon budgets, and the effects of climate change (Xu & Yan, 2001; Xu *et al.,* 2024). The strong overlap shown in the co-citation analysis between Cluster 1 and Cluster 2 reflects a well-developed research paradigm that directly connects below-ground biogeochemistry (Cluster 1) and above-ground forest structure and global climate feedback (Cluster 2). Cluster 3 (Regional Forest Management and Monitoring) is the applied side of the field. Specialized in management and monitoring, it will apply the knowledge base of Clusters 1 and 2 to practical uses of sustainable forestry, conservation and reaction to such threats as pine wilt disease (Back *et al.,* 2024; Pak *et al.,* 2023; Xu *et al.,* 2024).

This structure is further authenticated and narrowed down by the keyword co-occurrence network and multiple correspondence analysis. The keyword centrality of the word “growth” is used to indicate that it is one of the bridge words, which unites the investigations on tree physiology, forest management, and ecosystem productivity. The conceptual map identifies the sub-themes, which are the climate change and drought response group, the biomass and productivity group, and the soil biogeochemistry group. Combined, these analyses create the account of a discipline that has been able to combine basic ecological studies with the pressing ecological and management issues. This trend topic analysis proves the given evolution, as the trend under discussion presents a strong sequence of traditional forestry topics through the recent research agenda, which addresses the genetics, biotechnology, and the role of Korean pine ecosystems in world carbon and climate processes (Belyanin & Belyanina, 2021; Gong *et al.,* 2020).

Emerging trends and future research agendas: The future research priorities identified here are based on the bibliometric structure, thematic evolution, and growth rate analysis of Korean pine research and are not intended as general recommendations for all tree species. Thematic analysis identified Growth & Climate Response (30%) and Forest Management (22%) as the dominant research subcategories, whereas the fastest-growing mechanistic subcategories were Physiology (50%) and Seed Production and Quality (42.9%) (Appendix S9). These trends reflect growing scientific awareness of the ecological significance of Korean pine and its vulnerability to accelerating climate change. Although considerable research has recently targeted physiological factors, several key knowledge gaps remain. The bibliometric evidence shows a strategic shift from descriptive ecological studies to mechanistic studies, which are increasingly published in high impact journals such as Tree Physiology and Global Change Biology. For example, hydraulic research has begun to clarify thresholds formation and changes in non-structural carbohydrate allocation under drought-induced carbon limitation, but the effects of compound drought and heat stress on hydraulic failure thresholds remain poorly understood (Natale *et al.,*

2023). Future studies should therefore prioritize identifying species-specific thresholds of hydraulic dysfunction, understanding carbon allocation among growth, defense, and reproduction under chronic stress, and determining genetic and molecular indicators of climate resilience. Such mechanistic understanding is essential for improving mortality prediction models and selecting suitable genotypes for assisted migration under future climate scenarios. Moreover, despite their potential importance in restoration ecology, the role of soil microbiomes, especially mycorrhizal fungi, in enhancing drought resistance and nutrient uptake remains poorly understood.

Studies on seed production and quality (42.9% growth rate) indicate an emerging research frontier that links reproductive ecology with climate adaptation. Viable seed production has been found to decline under warmer winter conditions, which may threaten the long-term regeneration stability of Korean pine forests (Zait *et al.,* 2020). Future research should focus on identifying genetic markers associated with seed quality, yield stability, masting behavior, and climatic resilience. Genetic conservation technologies and practices, such as cryopreservation and climate-informed seed transfer protocols, are also urgently needed to match genetic material to future environments. These efforts would directly support breeding programs and adaptive forest management strategies for the long-term viability of the species.

The dominance of the Growth & Climate Response and Forest Management themes indicates increasing attention to the ecological stability of Korean pine forests under changing environmental conditions. Drought related reductions in radial growth and modeled shifts in the distribution of suitable habitat have been reported for this keystone species, indicating its susceptibility to climate change (Cavin & Jump, 2017; Jing *et al.,* 2022). As a keystone species in temperate forest ecosystems, Korean pine supports many ecosystem functions, such as carbon sequestration and seed dispersal mutualisms, which could be disrupted by future population losses, and with cascading consequences for the ecosystem. Future management-oriented studies should therefore be designed and tested to optimize carbon storage while maintaining structurally complex and ecologically functional stands. Further studies are also needed to assess genetic diversity in chemical defense traits that could improve resistance to pests and pathogens in a warming environment. Integrating physiological, ecological, and management-based strategies will be pivotal for sustaining productivity, conserving biodiversity, and ensuring long-term ecosystem resilience.

The bibliometric analysis also showed that Korean pine research is highly concentrated geographically in China and South Korea, with limited international integration despite the global relevance of climate adaptation and forest restoration research. Broder international cooperation that brings together expertise in climate modeling, forest genomics, remote sensing and ecosystem restoration, is needed for future progress. Increased multinational cooperation and long-term data sharing networks would enhance predictive modeling capacity and help establish conservation and management strategies for Korean pine forests under future climate scenarios at a global level.

Conclusion

This study used a bibliometric analysis of 682 articles to provide a comprehensive overview of the research landscape of *Pinus koraiensis* from 2003 to 2025. The results reveal a field experiencing robust logarithmic growth, with a notable increase in annual publications since 2012 and a peak in 2024. Research area is highly concentrated geographically and institutionally, with China leading production (76.83% of total publications) and Northeast Forestry University as the leading institute. The intellectual structure comprises three major themes: (1) basic forest ecology and growth processes; (2) responses to global environmental change, such as climate change and nitrogen deposition; and (3) genetic and biotechnological applications. The field has evolved from early research on growth and biomass toward more advanced research on carbon sequestration, climate change effects, and somatic embryogenesis. For researchers, particularly those new to the field, this analysis provides an overview of the intellectual structure, including foundational papers, current trends (e.g., genetics and climate change), and potential collaborators. The research gaps identified, including the relative lack of close cooperation between Asian and Western research institutes, point to clear opportunities for future international projects. These findings can guide conservation priorities and direct investment toward research areas of high practical relevance, such as mitigating pine wilt disease and enhancing forest resilience to climatic change. The strong interest in climate change and carbon storage also positions Korean pine forests as key components of national and global climate mitigation strategies. Theoretically, this study demonstrates the maturation of the field through its predictable pattern of development and well-defined thematic clusters. The close connection between below-ground biogeochemistry (Cluster 1) and forest-level climate processes (Cluster 2) illustrates an integrated understanding of ecosystem processes and could serve as a model for studying other keystone tree species. The main limitations of this study are its reliance solely on the WoS database and the underrepresents of non-English literature, which may provide an incomplete view of research conducted in some non-English speaking countries. Future studies could incorporate records from Scopus, regional databases, and carefully screened Google Scholar results, with systematic deduplication and metadata-harmonization.

Author's Contribution: SS & HW contributed equally to this work. SS & HW: Conceptualization; Methodology; Data Curation; Software; Visualization; Formal analysis; Writing - Original Draft; Validation; and Writing - Review & Editing. XM, LH, MKH, and BL: Validation and Writing - Review & Editing. XW: Methodology, Validation, and Writing - Review & Editing. HS and PZ: Conceptualization; Investigation; Methodology; Supervision; Resources; Validation; Writing - Review & Editing; Project administration; and Funding acquisition. All authors reviewed the final manuscript.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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