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Trajectory and global trends in two decades of scientific research on ecological restoration, natural regenerations, and forest recovery: a bibliometric synthesis

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Abstract

Considering global ecosystem degradation, ecological restoration is indispensable for sustainable development and climate mitigation. However, the fragmentation of research methods and perspectives underscores the need for a rigorous synthesis to guide scientific priorities in ecosystem restoration. This study conducted a longitudinal bibliometric analysis (2005–2025) of 18,582 documents from the Web of Science Core Collection to assess the intellectual structure and project the frontiers of ecosystem restoration globally. The results indicate that scientific output in this field has expanded rapidly (15.8% annually), with a critical surge in the volume of publications beginning in 2021. China leads quantitatively in terms of scientific output, while Brazil is established as the qualitative authority on tropical ecosystems. The four main emerging hotspots are functional biodiversity dynamics as a systemic driver, the integration of nature-based solutions to address climate change, natural regeneration as a low-cost scaling strategy, and soil biogeochemistry as a specialized technical niche. Network analysis revealed asymmetry in international cooperation characterized by strong cohesion in the Global North, contrasting with an urgent need to strengthen North-South collaborations to integrate technological capital with tropical biodiversity. Ecological restoration has matured as an implementation science, shifting from ecological theory toward social and economic governance. Future research should prioritize multi-objective and multi-scale assessments that integrate the functional monitoring of restoration efforts. This study clarifies the state of the art in the field and provides strategic guidelines to align academic research with global goals for climate resilience and the conservation of biodiversity.

Keywords: Ecosystem Restoration; Conservation; Biodiversity; Forest Recovery; Climate Resilience; UN Decade.

1. Introduction

Tropical and subtropical forests constitute one of the most crucial terrestrial biomes on the planet, harboring 80% of terrestrial biodiversity (Kalaba et al., 2013) and covering approximately 4.06 billion hectares (FAO, 2022). These forests play a vital role in the conservation of biodiversity and climate regulation (Zhang, Liang, and Sun, 2014). Over the last century, however, forest ecosystems throughout the world have undergone dramatic changes (Vijayan et al., 2021). According to Lambin et al. (2001) and Butchart et al. (2010), the intensification of changes in land use due to human activities, such as agriculture and logging, is the primary driver of such changes which result in a decline in biodiversity (Trisurat, Shirakawa, and Johnston, 2019) and ecosystem services, including carbon sequestration (Bullock and Woodcock, 2021; Ming et al., 2022), seriously threatening human habitats and sustainable development (He and Shi, 2022).

Restoring forest cover is one of the recommended solutions for mitigating deforestation and forest degradation (Berrahmouni, Regato, and Parfondry, 2015; Holl and Aide, 2011; Rinaudo, Muller, and Morris, 2020; Awono et al., 2023) and is increasingly recognized as a means of achieving global sustainability goals (Chazdon and Guariguata, 2016). Restoration refers to all practices aimed at restoring the ecological functioning of degraded habitats, thereby improving the living conditions of local populations (Rinaudo, Muller, and Morris, 2020; Awono et al., 2023). It involves adaptive processes that implement practices designed to restore ecological functioning and improve human survival in deforested or degraded habitats (Awono et al., 2023). Moreover, regeneration is a fundamental process that drives forest dynamics, as it ensures the continued existence of trees across generations (Feldmann et al., 2020), constituting a sustainable, ideal alternative to current forest loss (Holl and Aide, 2011).

Restoration based on natural regeneration is less costly and more effective than that based on planting trees (Chazdon and Uriarte, 2016; Crouzeilles et al., 2017). Naturally regenerated secondary forests are resilient, sequester large amounts of carbon (Chazdon et al., 2016; Cook-Patton et al., 2020), and harbor high species richness (Rozendaal et al., 2019). However, the benefits for restoration depend on how long the forests persist following new growth.

In response to climate challenges, a set of measures were taken to address issues of ecosystem degradation. In the 1950s and 1960s, Europe and North America pioneered the implementation of ecological projects to mitigate environmental crises (Romanelli et al., 2018). A pivotal turning point occurred during the United Nations Conference on Environment and Development (Rio-92), when biodiversity and ecosystem services were recognized as crucial for eradicating poverty, thereby addressing one of the foundations of the Strategic Plan for Biodiversity of the Convention on Biological Diversity (Carpenter et al., 2009).

In 2005, the Millennium Ecosystem Assessment highlighted the need for the conservation of biodiversity, given its fundamental role in sustaining human life (Millennium Ecosystem Assessment, 2005). In 2010, the Aichi Targets—specifically Target 15—set a goal to restore at least 15% of degraded ecosystems by 2020 (Butchart et al., 2010). Shortly after the launch of the Bonn Challenge in 2011, a target was introduced to restore 150 million hectares of degraded and deforested land.

With the Paris Agreement (UNFCCC, 2015), ecological restoration was recognized as an essential tool for climate mitigation and adaptation. The most significant contemporary milestone occurred in 2019 with the declaration of the United Nations Decade on Ecosystem Restoration (2021–2030), aimed at combating the loss of biodiversity, climate change, and the increase in pollution (Fischer et al., 2021).

Although ecological restoration has become a central issue in recent years, research in the field lacks data synthesis and systematization. Bibliometrics an indispensable tool for rapidly understanding scientific progress, aiding in the understanding of trends in the literature published within a given field, the journals and disciplines involved, as well as authors, countries, institutions, and collaborations (Rodríguez-Soler, Uribe-Toril, and De Pablo Valenciano, 2020). This tool is widely recognized for its ability to map underlying knowledge structures and integrate quantitative results with robust visual representations (Aria & Cuccurullo, 2017). Bibliometric analysis enables an objective assessment of the state of the art and the evolution of scientific frontiers through production and impact indicators across various geographic and institutional scales (Anand & Gupta, 2020; Bao et al., 2023), as well as the derivation of new research ideas and the contextualization of expected future contributions to the field (Romanelli et al., 2018; Donthu et al., 2021; Zhai et al., 2023).

The present study employed bibliometric analysis to synthesize global scientific output on ecological restoration and natural regeneration from 2005 to 2025 to map the evolution of the intellectual structure of the field and shifts in research priorities. Specifically, the objectives were to (i) quantify publication and citation dynamics, identifying centers of excellence, key authors, and high-impact journals; (ii) assess international collaboration networks and their role in advancing knowledge; (iii) analyze the evolution of thematic clusters and the transition toward emerging approaches; and (iv) identify spatial and thematic gaps while projecting trends to support global ecosystem restoration goals.

2. Materials and Methods

The database used for this analysis was the Web of Science Core Collection, which is recognized as one of the most comprehensive and reliable sources of academic metadata for high-precision scientometric studies (Liu et al., 2021). Data extraction was performed on May 4, 2026, using a search strategy based on Boolean operators applied to the topic sentence (TS): (“Ecological restoration” OR “Natural regeneration” OR “Forest recovery”).

The study period spanned from 2005 to 2025 for a two-decade longitudinal perspective on the evolution of the field, including the first half of the UN Decade on Ecosystem Restoration. To ensure quality and comparability, the search was restricted to “articles” and “reviews” published in English, thereby ensuring that the dataset consisted of original research and peer-reviewed syntheses with broad global reach.

The records were exported in BibTeX format, including the “Full Record and Cited References”. The raw data subsequently underwent a rigorous pre-processing stage, which included the normalization of metadata, the removal of irrelevant records, and the elimination of duplicates. This procedure resulted in a final set of 18,582 documents (Fig. 1).

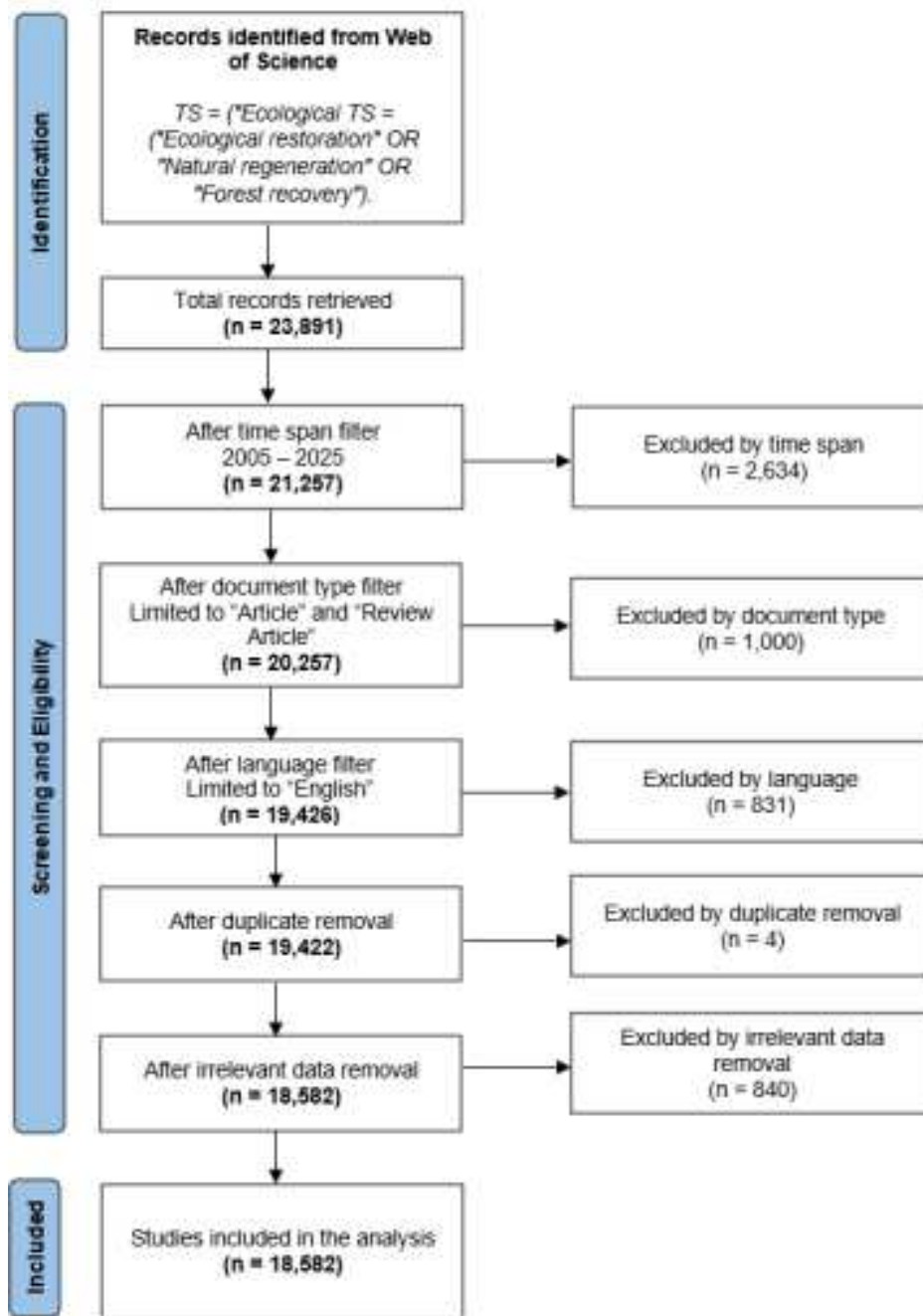


Fig. 1 Flowchart of methodological process in field of ecological restoration, natural regenerations, and forest recovery.

Computational processing was performed using Bibliometrix (version 5.3.0) and the Biblioshiny platform (Aria & Cuccurullo, 2017) running in the R statistical environment (version 4.5.3) (R Core Team, 2026), which is a specialized tool for scientific mapping. The results are structured around performance analysis (assessment of productivity and scientific authority via the h-index, total citations (TC), and citations per paper (CPP) for authors, journals, institutions, and nations), system cluster analysis via Multiple Correspondence Analysis applied to Keywords Plus, and an analysis of the evolution of the research agenda mapped through Trend Topics analysis (Callon diagram) to identify established issues and emerging frontiers of knowledge.

Prestige metrics such as the Journal Citation Reports (JCR) (Krampl, 2019) and Impact Factor (IF) (Garfield, 1994) were integrated into the bibliometric results to provide a holistic view of the influence of journals, distinguishing historical impact from contemporary relevance in the literature on the subject under analysis.

3. Results

3.1.1. Overview of scientific production and temporal dynamics in the field of ecological restoration, natural regeneration, and forest recovery

3.1.2. Volume of publications

The analysis of scientific output in ecological restoration, natural regeneration, and forest recovery over the last two decades reveals a rapidly expanding field—growing from 168 papers in 2005 to 3,159 in 2025 (Fig. 2), with an annual growth rate of 15.8% and an overall increase of 1,880.35% over the past 25 years. This demonstrates the importance of ecological restoration, natural regeneration, and forest recovery in the period studied.

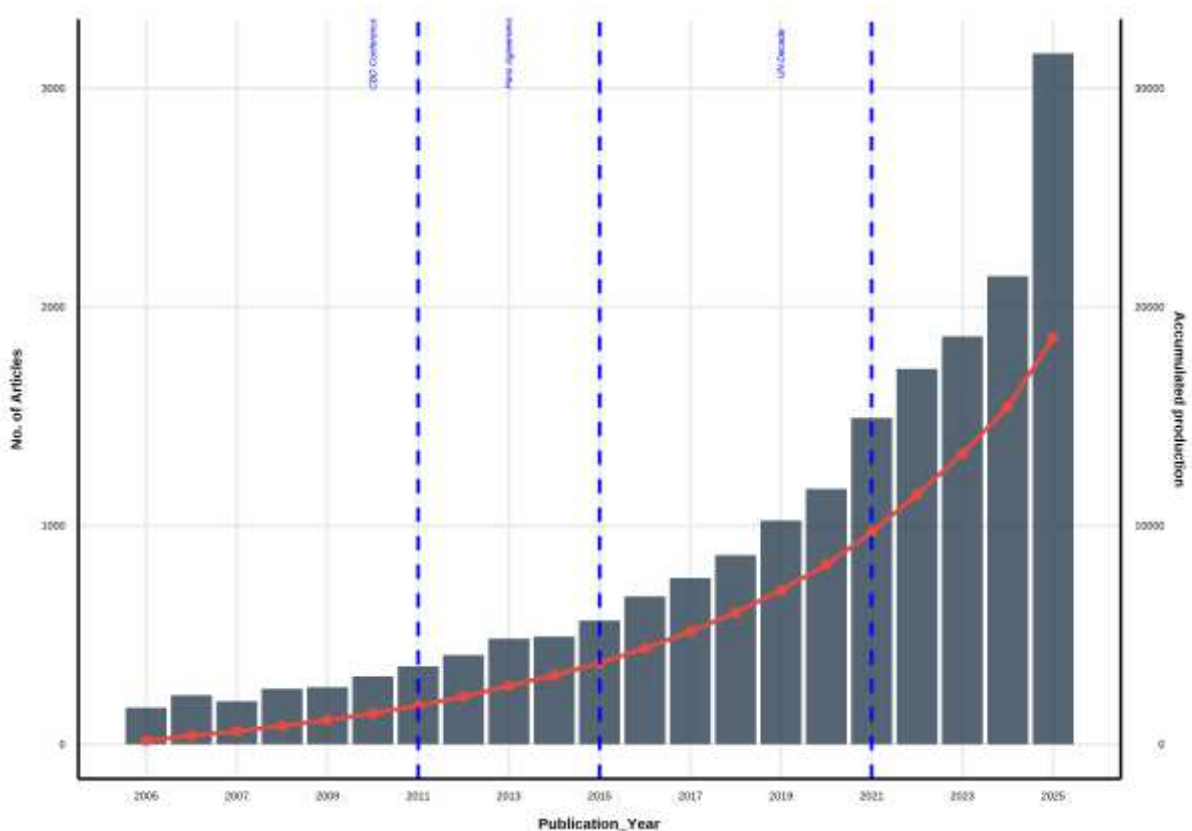


Fig. 2 Trajectory of global scientific production (2005–2025) on ecological restoration, natural regeneration, and forest recovery in Web of Science Core Collection (2026).

Between 2005 and 2020, the growth in publications was driven by the maturation of concepts in this field of knowledge and the inclusion of restoration as a goal in international conventions—specifically the 2010 Aichi Targets and Bonn Challenge (Chazdon; Brancalion and Chazdon, 2017).

The intensification in 2021 coincides with the official launch of the UN Decade on Ecosystem Restoration (2021–2030) (UNEP, 2021). This milestone redirected global funding flows and spurred the publication of scientific syntheses and technical guidelines. The scientific community responded to the call to prevent, halt, and reverse ecosystem degradation across all continents and oceans (UNEP, 2021), signaling a shift

in restoration science toward implementation-focused approaches—moving from purely ecological theory to considerations of social and economic viability and environmental governance.

The high number of publications recorded in 2025 highlights the consolidation of monitoring results from projects launched at the beginning of the UN decade, along with renewed commitments under the Paris Agreement. This growth indicates that the concept of ecological restoration has reached maturity, integrating remote sensing technologies, artificial intelligence, and precision ecology to monitor natural regeneration on a global scale (Brancalion et al., 2022).

These results indicate that research on ecological restoration is currently one of the most dynamic areas of environmental knowledge, reflecting the climate emergency and the need to generate robust evidence to support climate regulation projects. However, the challenge for the post-2025 period will be to ensure that this massive volume of scientific publications translates into real gains for biodiversity and climate resilience.

3.1.3. Scientific literature citations

The analysis of the temporal impact of citations (Fig. 3) reveals a multifaceted trajectory characterized by strategic peaks that coincide with key milestones in global environmental governance.

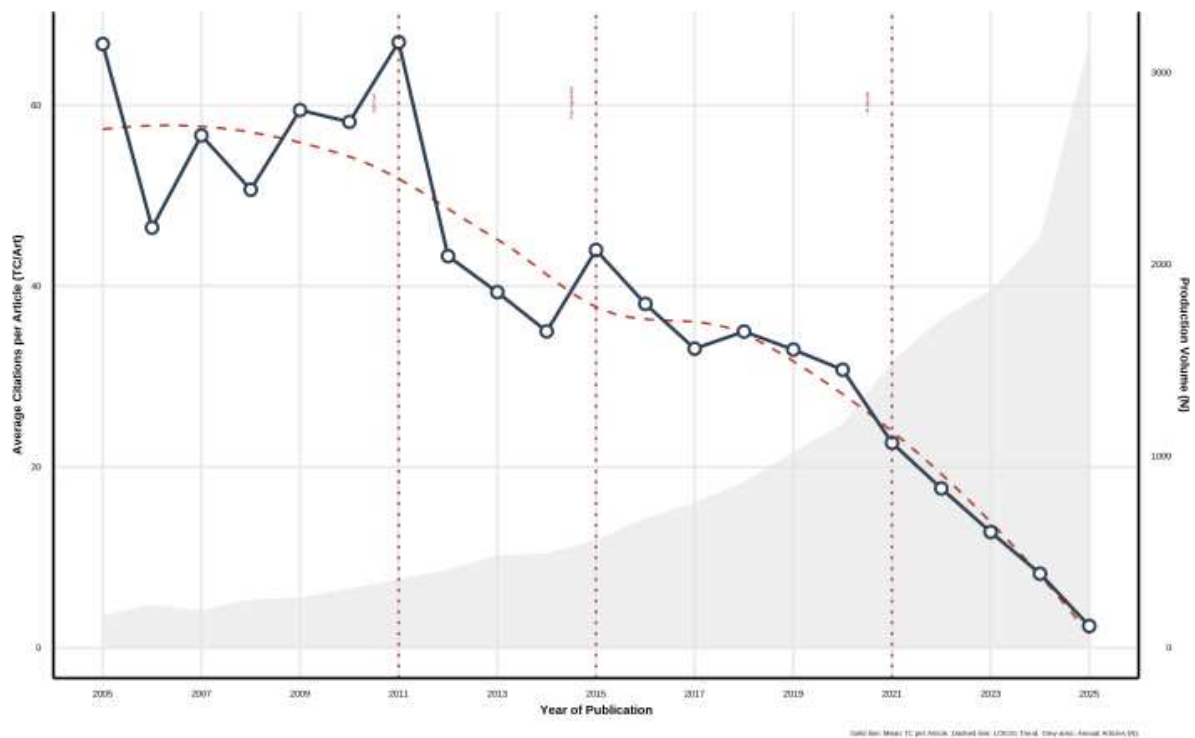


Fig. 3 Dynamics of citation impact and longevity of research (2005–2025) on ecological restoration, natural regeneration, and forest recovery obtained from Web of Science Core Collection (2026).

The high average citation impact of papers observed in 2005 highlights the phase of theoretical consolidation in the field of ecological restoration. During this period, although the absolute volume of publications was low, scientific output focused on establishing conceptual frameworks and groundbreaking definitions that serve as the foundation for contemporary research in ecological restoration and natural regeneration (Ruiz-Jaen & Aide, 2005).

A second significant spike in citations occurred in 2011, the year marking the launch of the Bonn Challenge (Verdone and Seidl, 2017) and the establishment of the Aichi Targets (Ortiz et al., 2011)—specifically

Target 15, which calls for the restoration of 15% of degraded ecosystems. This increase in impact reflects the scientific community's immediate engagement in providing technical support for the new landscape restoration targets and the integration of this topic with ecosystem services (Barbier et al., 2011).

The subsequent decline in citation rates between 2012 and 2014 can be interpreted as a period of research project implementation. This phenomenon is characteristic of experimental fields (e.g., restoration), as the interval between the establishment of policy guidelines and the publication of robust field results requires time for biological and analytical maturation (Holl, 2020).

The resurgence in the average citation impact of papers in 2015 may be linked to the adoption of the Paris Agreement and the Sustainable Development Goals (SDGs). During this period, restoration science shifted from a conservationist perspective to a central pillar of nature-based climate mitigation strategies (Nature-Based Solutions) (Brançalion and Chazdon, 2017).

From 2016 onwards, the average citation impact curve has a persistent downward trend extending to 2025. This can be attributed to two critical bibliometric factors. First is the dilution effect, by which the 15.8% annual growth rate in scientific output expands the publication denominator more rapidly than the accumulation of citations, fragmenting the attention of scientists in a massive volume of literature. Second is the phenomenon of citation lag. Therefore, works published over the last decade—particularly during the UN Decade on Ecosystem Restoration (2021–2030)—are still in their rising phase of influence, with a latent impact potential that is expected to fully materialize in subsequent bibliometric cycles (UNEP, 2021; Brançalion et al., 2022).

3.2. Centers of excellence and reference periodicals in the field of ecological restoration, natural regeneration, and forest recovery

3.2.1. Main authors of scientific papers

The analysis of the h-index identifies a scientific elite whose trajectories shape the frontiers of knowledge on ecological restoration, natural regeneration, and forest recovery between 2005 and 2025 (Table 1).

Table 1. Ten main researchers based on h-index in terms of scientific papers on ecological restoration, natural regeneration, and forest recovery obtained from Web of Science Core Collection (2026).

Rank	Author	Country	h_index	Total_Citations	Articles
1	Liu, Y.	China	51	10803	392
2	Wang, Y.	China	46	9224	467
3	Li, Y.	China	44	7862	419
4	Zhang, Y.	China	44	9007	496
5	Wang, J.	China	43	8003	351
6	Wang, L.	China	43	5827	244
7	Brançalion, Brazil		42	5933	84
8	Fu, B.	China	42	6988	89
9	Zhang, X.	China	42	6124	339
10	Wang, X.	China	41	7178	343

Table 1 reveals a dominance of authors affiliated with institutions in China, with Liu, Y., Wang, Y., and Li, Y. at the top of the list. This phenomenon directly reflects massive Chinese state investments in large-scale restoration programs, such as the Three-North Shelter Forest Program and Grain for Green, which have

transformed the country into a living laboratory for applied ecology (Liu et al., 2020), mirroring China’s rapid rise to a leading position in global scientific output (Xie and Freeman, 2019).

A critical point of differentiation among the leading authors resides in the relationship between the volume of scientific article production and the qualitative impact of the publications. Although Zhang, Y. (2005–2025) ranks fourth in terms of the h-index, the author produced the highest absolute volume of publications (496) in the period. This pattern suggests a large-scale science strategy—common among major Chinese research clusters—that prioritizes extensive data coverage. In contrast, Brazilian researcher Brancalion, P.H.S. had the lowest volume among the top ten (84) but holds a highly prestigious 7th place position. This contrast indicates that Brancalion’s output has a significantly higher citation density per article than that of the other authors on the list, which is a characteristic of work with high theoretical and practical impact in tropical restoration (Brancalion & Holl, 2020).

The presence of Brancalion’s as the only non-Chinese author in Table 1 demonstrates Brazil’s leading role in global restoration science. While Chinese leadership often focuses on the recovery of degraded areas and soil erosion control in temperate and arid zones, Brazilian research leads the debate on biodiversity hotspots and the integration of ecosystem services with production chains (Brancalion and Chazdon, 2017). This asymmetry suggests that, although China dominates in terms of volume and infrastructure, Brazil serves as a vital qualitative benchmark for the governance and conservation of more diverse ecosystems.

The prevalence of the surnames Wang and Zhang also reflects the central role of the Chinese Academy of Sciences within the global bibliometric network. In the context of the UN Decade on Ecosystem Restoration (2021–2030), however, ecological restoration requires aligning the quantitative efficiency demonstrated by China with the ecological depth demonstrated by Brazil as a basis for recovery policies that are resilient in the face of global climate change (UNEP, 2021).

3.2.2. *Main periodicals*

The ten most influential periodical based on the h-index (Table 2) reveal the intellectual structure and editorial priorities that currently sustain the science of ecological restoration and forest recovery.

Table 2. Ten main periodicals based on h-index in terms of scientific literature on ecological restoration, natural regeneration, and forest recovery obtained from Web of Science Core Collection (2026).

Rank	Journal	Country	h_index	Total Citations	Articles
1	Forest Ecology and Management	USA	80	30930	935
2	Restoration Ecology	USA	75	25585	847
3	Science of the Total Environment	China	72	17695	345
4	Ecological Indicators	China	62	14715	471
5	Ecological Engineering	China	61	13406	405
6	Journal of Applied Ecology	USA	59	10074	206
7	Biological Conservation	Australia	50	7309	164
8	Catena	China	42	4949	175
9	Journal of Environmental Management	China	42	7460	350
10	Ecological Applications	USA	41	4973	141

At the top of Table 2, Forest Ecology and Management and Restoration Ecology stand out as the leading journals in the field. Both had solid, stable Impact Factors (IF) in 2025 (3.7 and 2.7, respectively), which,

combined with high h-indices, establishes them as benchmark journals for international protocols. While Restoration Ecology serves as the primary forum for the theoretical foundations of the subject (Holl, 2020), Forest Ecology and Management leads in practical and forest applications, prioritizing long-term monitoring studies that are crucial to the goals of the UN Decade on Ecosystem Restoration (2021–2030) (UNEP, 2021).

A notable phenomenon in this ranking is the rise of multidisciplinary journals with high impact factors, such as *Science of The Total Environment* and *Ecological Indicators*. These journals serve as platforms with a global reach, attracting a massive volume of citations due to their open-access model and a thematic scope that links ecological restoration to environmental health issues and geochemistry (Brancalion and Chazdon, 2017).

The periodicals *Journal of Applied Ecology* and *Ecological Applications*, founded in 1964 and 1991, respectively, remain at the top of the list due to their rigorous editorial selection and longevity, which enable the sustained accumulation of citations, while their impact factors reflect continued leadership in the definition of global scientific agendas (Walker et al., 2002).

The dominance of journals based in the United States and China reflects the economic power of these nations and the consolidation of distinct publishing niches. The absence of journals from the Global South in this ranking underscores the need to strengthen regional publishers so that academic prestige keeps pace with the ecological importance of tropical biomes on the global climate agenda.

3.2.3. *Main institutions with scientific publications*

The analysis of the geographic distribution of the ten main scientific research institutions in ecological restoration, natural regeneration, and forest recovery reveals a massive center of excellence in Asia (Table 3).

Table 3. Ten main research institutions in terms of scientific literature on ecological restoration, natural regeneration, and forest recovery obtained from Web of Science Core Collection (2026).

Rank	Institution	Country	Articles
1	Chinese Academy of Sciences	China	260
2	Beijing Normal University	China	245
3	Beijing Forestry University	China	228
4	Northwest A&F University	China	203
5	Institute of Geographic Sciences and Natural Resources Research	China	192
6	Northern Arizona University	USA	112
7	China University of Geosciences	China	108
8	Guizhou Normal University	China	105
9	Lanzhou University	China	103
10	China University of Mining and Technology	China	102

The leadership of the Chinese Academy of Sciences and Institute of Geographic Sciences and Natural Resources Research demonstrates that restoration science in China is coordinated by large national centers that operate as regional references. Added to the diverse national funding, these institutions operate in an integrated manner under the command of national academies, facilitating the flow of data among national universities (Liu et al., 2020). A determinant factor for this performance is the geographic location of the institutions in relation to the biomes that they study.

Northwest A&F University and Lanzhou University are located near the Loess Plateau in northern China—one of the world's major areas for restoration efforts under the "Grain for Green" program, which has

enabled the management of long-term experiments and the maintenance of public-private partnerships to monitor the effectiveness of carbon sequestration and soil erosion control in real time (Wang et al., 2021). The success of these Chinese institutions is also due to their interdisciplinary structure. This synergy is fundamental to contemporary restoration, requiring economic models that validate the recovery of degraded areas, especially in mining zones (Brancalion and Chazdon, 2017). The resilience of Northern Arizona University in the ranking highlights the historical strength of ecosystem ecology research in the United States, supported by agencies that prioritize long-term monitoring studies.

3.2.4. Main countries with scientific publications

The data in Table 4 reveal a clear division in the volume of scientific articles published on ecological restoration, natural regeneration, and forest recovery between the Global North, which is firmly established as possessing technological and financial capital, and the Global South, represented primarily by Brazil and India.

Table 4. Ten main countries in terms of production volume of scientific articles on ecological restoration, natural regeneration, and forest recovery obtained from Web of Science Core Collection (2026).

Rank	Country	Articles	Total Citations	Citations_per_Paper
1	China	7344	144521	19,68
2	USA	1974	68894	34,9
3	Brazil	1209	24959	20,64
4	Australia	1134	46629	41,12
5	Canada	830	24123	29,06
6	United Kingdom	448	17248	38,5
7	Germany	416	11931	28,68
8	France	365	10570	28,96
9	Spain	308	8057	26,16
10	India	279	3691	13,23

The leading positions held by China (7,344 articles) and the USA (1,974 articles) reflect massive investments in research infrastructure and national reforestation policies (Liu et al., 2020). However, Brazil's prominent role (1,209 articles) is particularly significant. By ranking third globally in scientific output, the country reaffirms its leadership within the Global South, transitioning from a technology recipient to a hub for generating primary knowledge on tropical ecosystems—knowledge that is essential for achieving the goals of the UN Decade on Ecosystem Restoration (Brancalion and Holl, 2020).

The performance of the United States and European nations (United Kingdom, Germany, France, and Spain) may be correlated with aligning the Bonn Challenge and Paris Agreement with European Union guidelines. Research in these countries focuses on optimizing ecosystem services and climate resilience, translating international commitments into academic robustness (UNEP, 2021).

Although China leads in absolute volume, Australia has the highest scientific efficiency, with 41.12 citations per paper (CPP), followed by the United Kingdom with 38.5 CPP. Australia's scientific efficiency may be linked to its primary research specialization in dryland degradation and the restoration of coniferous forests in the cold temperate zone (Rapport and Whitford, 1999). This pattern suggests that these nations serve as hubs for synthesis in ecological restoration, leading meta-analyses and high-impact global studies that shape the guidelines of the field.

With a CPP of 20.64, Brazil demonstrates competitive efficiency for a developing nation. However, the disparity compared to leading nations in terms of citations indicates that much of the science produced in the Global South is still directed at local solutions with immediate application, whereas the Global North dominates global analyses (Brancalion and Chazdon, 2017).

Ranking 10th, India signals an emerging trend driven by the integration of ecosystem restoration goals with rural development policies, with the aim of ensuring the sustainability of agricultural production and the livelihoods of vulnerable populations (Li et al., 2020).

3.2.5. Main publications of scientific articles

Ecological restoration has attracted considerable interest from important institutions and researchers, with the majority of important scientific findings published in high-impact journals (Table 5).

Table 5. Ten publications of most cited scientific articles on ecological restoration, natural regeneration, and forest recovery obtained from Web of Science Core Collection (2026).

Rank	Reference (Short)	Year	Journal	Total Citations	DOI	Citations per Year
1	Barbier, 2011	2011	Ecological Monographs	4308	10.1890/10-1510.1	269,25
2	Allen, 2015	2015	Ecosphere	2107	10.1890/ES15-00203.1	175,58
3	Hobbs, 2009	2009	Trends in Ecology & Evolution	1395	10.1016/j.tree.2009.05.012	77,5
4	Rey Benayas, 2009	2009	Science	1344	10.1126/science.1172460	74,67
5	Gann, 2019	2019	Restoration Ecology	1317	10.1111/rec.13035	164,62
6	Bryan, 2018	2018	Nature	1208	10.1038/s41586-018-0280-2	134,22
7	Bai, 2010	2010	Global Change Biology	833	10.1111/j.1365-2486.2009.01950.x	49
8	Ruiz-Jaen, 2005	2005	Restoration Ecology	813	10.1111/j.1526-100X.2005.00072.x	36,95
9	Wortley, 2013	2013	Restoration Ecology	786	10.1111/rec.12028	56,14
10	Fu, 2011	2011	Ecological Complexity	778	10.1016/j.ecocom.2011.07.003	48,62

The list of the ten most cited articles is dominated by meta-analyses and comprehensive reviews. The work by Barbier (2011), with 269.25 citations per year, exemplifies the integration of social and economic aspects into modern restoration. Barbier (2011) integrated ecology with sustainable development, becoming a key reference in conservation economics by focusing on the value of ecosystem services and the economic benefits of environmental recovery.

Another key article is the meta-analysis by Rey Benayas et al. (2009), which provided the empirical basis for the claim that restoration increases biodiversity and ecosystem services compared to degraded systems, establishing restoration as a viable global recovery strategy (Rey Benayas et al., 2009).

Table 5 shows a coexistence of classic and emerging high-impact articles. The work by Ruiz-Jaen and Aide (2005) remains at the top after two decades, highlighting its historical importance in defining metrics for restoration success. Gann et al. (2019) and Bryan et al. (2018) represent the new frontier of the field. Gann et al. (2019) established international standards for ecological restoration practice, becoming a practical protocol widely cited in guidelines of the UN Decade on Ecosystem Restoration, FAO, and IUCN (Gann et al., 2019), while Bryan et al. (2018) analyzed 16 major large-scale ecological restoration and conservation programs implemented in China since 1998.

The thematic focus of the top articles reveals a shift from biological aspects to climate resilience and water security. Allen et al. (2015) and Fu et al. (2011) addressed ecosystem vulnerability in the face of global

changes, while Hobbs et al. (2006) introduced the concept of “Novel Ecosystems”, challenging the traditional view of always returning to the pre-degradation historical state (Hobbs et al., 2006).

Bryan et al. (2018) discussed environmental policy reform in China, highlighting how large-scale restoration is intrinsically linked to governance and public funding. These findings, alongside those reported by Barbier (2011) and Gann et al. (2019), demonstrate that the most highly cited authors are those who successfully integrate social participation and human well-being into their analyses, shifting restoration from a biological niche to a tool for socio-ecological survival (Bryan et al., 2018).

The high annual citation rates of recent works by Gann et al. (2019) and Bryan et al. (2018) (with 164.62 and 134.22 citations per year, respectively) demonstrate that their field of study is in a phase of rapid expansion and technical implementation driven by a global environmental mitigation agenda.

3.3. Collaboration networks and leadership in the field of ecological restoration, natural regeneration, and forest recovery

3.3.1. Author collaboration network

Figure 4 displays the collaboration network among authors who published scientific articles on ecological restoration, natural regeneration, and forest recovery in the period of analysis, completely dominated by the Chinese.

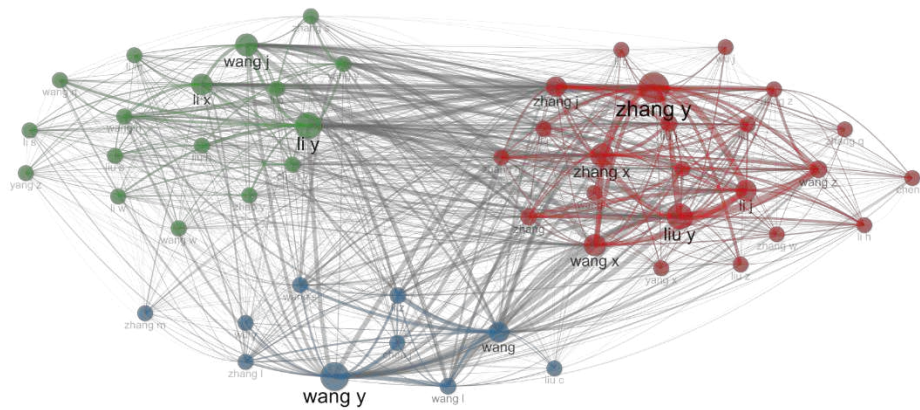


Fig. 4 Collaboration network of authors who publish scientific papers on ecological restoration, natural regeneration, and forest recovery obtained from Web of Science Core Collection (2026). Each node represents an author; size of node represents number of publications; lines represent co-citation relationship among documents; thicker lines denote stronger ties.

An analysis of the collaboration network among key authors reveals the microstructure of intellectual capital in the field of ecological restoration, natural regeneration, and forest recovery. The formation of three main clusters (red, green, and blue) demonstrates a landscape of high specialization regarding the topics investigated.

The red cluster corresponds to the core of greatest influence and density within the author network, exhibiting robust centrality metrics. The strong presence of Zhang, Y., followed by Liu, Y., Zhang, X., and Wang, X., suggests that this group is the primary driver of innovation in the field. The intense internal interaction among these authors indicates long-term collaboration, likely rooted in major national laboratories or large-scale government projects. Authors with high closeness and betweenness centrality, such as Zhang, Y., serve as

knowledge mediators controlling the flow of information and shaping the research agendas to be pursued by the academic community (Liu et al., 2020).

The interaction between the red and green clusters, led by Li, Y., Wang, J., and Li, X., demonstrates that, despite operating in distinct niches, these research groups share resources, data, or co-authorships that strengthen the Chinese scientific foundation. This inter-cluster collaboration is crucial to the scalability of restoration efforts, enabling ecosystem-level findings to be translated into management protocols (Chang et al., 2022). Conversely, the blue cluster led by Wang, Y. and Li, Z. occupies a more peripheral position relative to the main red-green axis. The relatively weak interaction between the green and blue groups suggests thematic fragmentation across distinct biomes or different stages of the recovery chain. This can lead to the formation of isolated knowledge hubs, hindering the standardization of success metrics on the national level (Brancalion and Chazdon, 2017).

The dominance of Chinese surnames across all groupings reaffirms the country's position as the leading producer of knowledge in these fields. However, the network structure highlights the need for greater international diversification—particularly involving the Global South, where the challenges of tropical biodiversity require solutions that integrate statistical rigor with the ecological complexity of tropical ecosystems (Brancalion and Holl, 2020).

3.3.2. Institutional collaboration network

An analysis of the institutional collaboration network for the publication of scientific articles on ecological restoration, natural regeneration, and forest recovery (Fig. 5) reveals a highly compartmentalized, geographically polarized structure.

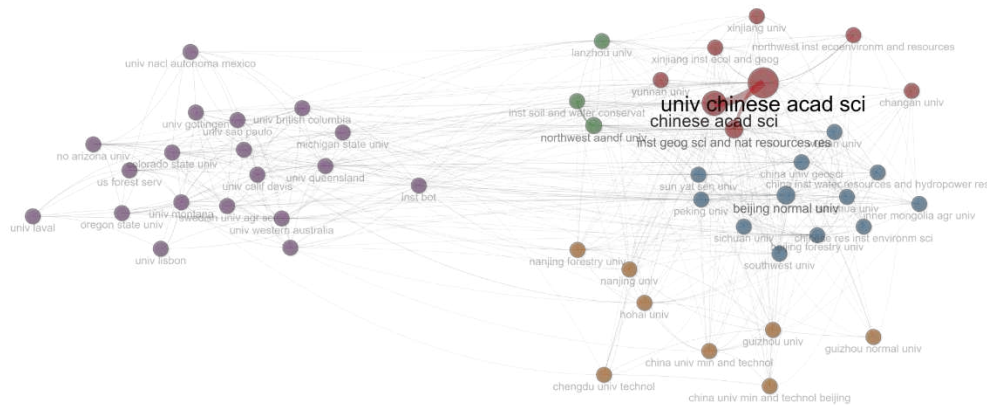


Fig. 5 Collaboration network of institutions that published scientific papers on ecological restoration, natural regeneration, and forest recovery obtained from Web of Science Core Collection (2026). Each node represents an institution; size of node represents number of publications; lines represent co-citation relationship among documents; thicker lines denote stronger ties.

The configuration of the five main clusters reveals the emergence of major research hubs, notably highlighting the dominance of Asian institutions. The proximity and intense interaction among the red, green, and blue clusters constitute the current global epicenter of ecological restoration research. The red cluster, led by the University of Chinese Academy of Sciences, stands as a benchmark of excellence. The strong connection between

this group and the green cluster (Northwest A&F University and Institute of Soil and Water Conservation) demonstrates a scientific focus on soil restoration and the control of desertification, particularly on the Loess Plateau (Liu et al., 2020).

The blue cluster, led by Beijing Normal University and Peking University, reveals a strategic integration between forest ecology and water resource management, represented by the presence of the China Institute of Water Resources and Hydropower Research. This triad of clusters confirms that restoration science in China is treated as an integrated national priority, where biodiversity is restored with the aim of ensuring the provision of essential ecosystem services, including the regulation of water flow (Wang et al., 2021).

The purple cluster located on the far left represents the most heterogeneous and globalized collaboration network, integrating prominent institutions such as the University of Queensland, the University of California Davis, Oregon State University, and the University of São Paulo (USP). The position of the group, maintaining interactions with Chinese superclusters, suggests that it serves as a bridge for technological and methodological transfer between the West and the East.

The presence of the University of São Paulo (USP) and the National Autonomous University of Mexico (UNAM) in the purple cluster is scientifically significant, as it indicates that the leadership of restoration in Latin America is integrated into global networks that define international standards in the field (Brancalion and Holl, 2020). This group is responsible for the key theoretical syntheses and meta-analyses published in the field, focusing on the diversity of biomes represented by the member institutions (Brancalion and Chazdon, 2017).

The yellow cluster located in the bottom-right corner is the most isolated and has weak internal interactions, despite including renowned institutions such as the China University of Mining and Technology. This isolation can be interpreted as a specialization in technical niches, specifically, the recovery of areas degraded by mining and heavy environmental engineering.

The fact that institutions such as Nanjing Forestry University and Guizhou University are less connected to the mainstream flow suggests that their research may be more focused on specific industrial applications and local remediation protocols, temporarily distancing itself from discussions on global theoretical ecology (UNEP, 2021). These results show that the effectiveness of the UN Decade on Ecosystem Restoration will depend on the ability of these clusters to break out of isolation and unify restoration protocols under a shared ecological perspective.

3.3.3. *Country collaboration network*

The analysis of international collaboration networks in ecological restoration, natural regeneration, and forest recovery (Fig. 6) reveals a tripartite global structure characterized by productivity asymmetries and the existence of preferential scientific cooperation alliances.

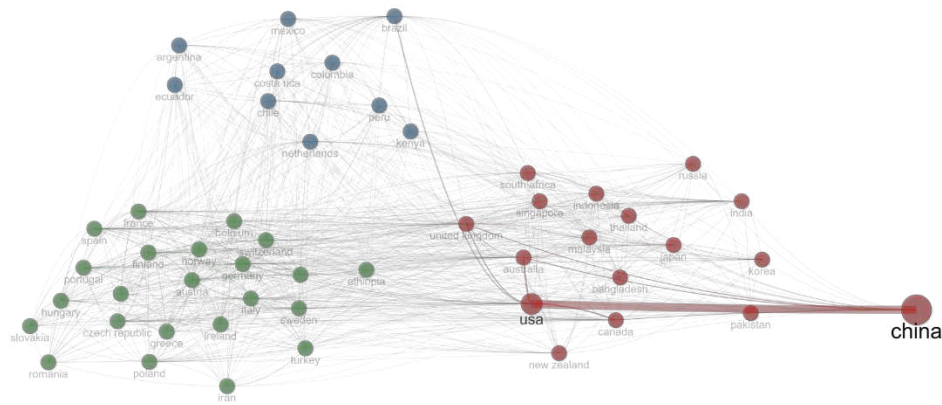


Fig. 6 Collaboration network of countries that published scientific papers on ecological restoration, natural regeneration, and forest recovery obtained from Web of Science Core Collection (2026). Each node represents a country; size of node represents number of publications; lines represent co-citation relationship among documents; thicker lines denote stronger ties.

The dominance of China and the USA in the red cluster—connected by the densest line of cooperation—forms the backbone of contemporary restoration science. This bilateral connection reflects a convergence of interests between the world's two largest economic powers, both seeking to lead innovation in nature-based solutions for climate mitigation (Liu et al., 2020). The red cluster serves as a technological and financial reference, integrating Commonwealth nations (Australia, the UK, and Canada) with Asian countries.

The strong interaction between the China-US bloc and the green cluster—dominated by European nations such as Germany, Switzerland, and France—reinforces the position of the Global North as the primary producer of synthesis science, centered in high-investment hubs that dictate global research agendas (Wagner, Whetsell, and Leydesdorff, 2017). Euro-Asian collaboration is crucial to meeting the goals of the Paris Agreement, combining European technological sophistication in ecosystem ecology with China's capacity for large-scale implementation (UNEP, 2021).

The blue cluster—led by Brazil and composed primarily of Latin American nations and Kenya—holds the majority of the world's remaining tropical biodiversity, which is essential to the effectiveness of any global ecological restoration strategy. However, the limited interaction between this and other clusters suggests geopolitical isolation and/or a reliance on specific alliances. Nonetheless, Brazil interacts more with the USA than with its Latin American peers, highlighting a “North-South” collaboration (Brancaion and Holl, 2020).

Although Brazil is established as a qualitative leader in tropical restoration (Brancaion and Chazdon, 2017), the low connectivity of its cluster indicates that the Global South still faces barriers to establishing a robust “South-South” cooperation network, which could strengthen scientific sovereignty in more diverse biomes.

Fragmentation in collaboration networks could compromise the success of the UN Decade on Ecosystem Restoration (2021–2030). For ecological restoration to be resilient and socially fair, collaboration networks must evolve beyond dominant bilateral axes, fostering global integration that values knowledge generated in the Global South (Brancaion et al., 2022).

The analysis of the thematic map using the Callon diagram (Londe, Pessoa, and Andrade, 2024) (Fig. 8) enables identifying the maturity and centrality of the topics that sustain the scientific literature on ecological restoration and natural regeneration.



Fig. 8 Evolution of topics of scientific literature on ecological restoration, natural regeneration, and forest recovery obtained from Web of Science Core Collection (2026).

The distribution of clusters across the quadrants of the map reveals a dichotomy between the theoretical foundations of conservation and the urgency of functional metrics. The upper-right quadrant (motor themes) shows the coexistence of two fundamental clusters. The cluster with “diversity,” “vegetation,” and “restoration” stands out as the primary driver of the field, with the greatest volume and strong relevance (centrality). This result lend strength to the notion that the restoration of vegetation and the enhancement of biodiversity remain the structural pillars of ecological restoration (Brancalion and Chazdon, 2017).

The high centrality of this cluster indicates that it serves as the theoretical nexus connecting the other subfields of knowledge, reinforcing the understanding that taxonomic richness and diversity are prerequisites for ecosystem functioning (Tilman, Isbell, and Cowles, 2014).

Adjacent to the previous node, the node comprising the themes “climate-change,” “impacts,” and “land use” has greater density but less relative relevance. This configuration suggests that research on the impacts of

land use and climate change has reached a high degree of technical specialization and internal cohesion, integrating landscape dynamics with carbon sequestration (Brancalion and Chazdon, 2017).

The lower-left quadrant reveals themes that, while essential, have not yet reached the “driving” stage or are undergoing a process of conceptual redefinition. The cluster comprising “soil,” “carbon,” and “nitrogen” appears as a dense, specialized field but has low centrality. This indicates that, although soil biogeochemistry (carbon and nitrogen cycles) is robust, it often operates as a niche within restoration—focused on below-ground processes that are not always fully integrated with vegetation monitoring indicators (Lal, 2015).

The large volume of the node comprising “ecological restoration,” “biodiversity,” and “conservation” in this quadrant suggests a transitional phenomenon. Although these are fundamental terms, their significant magnitude compared to the “driving” stages shows that the conservation of biodiversity remains the dominant ethical and scientific motivation, even as the literature shifts toward more specific applications of adaptive management (Holl, 2020).

4. Conclusions and Perspectives

This article examined the development of research on ecological restoration, natural regeneration, and forest recovery from a macro standpoint, identifying trends in publications, key journals, institutions, countries, and scientific articles. The evolution of core themes (hotspots) and thematic clusters was analyzed and future research directions were discussed.

Between 2005 and 2025, the number of articles published in the field of ecological restoration grew exponentially—rising from 168 to 3,159 articles per year, corresponding to a robust annual growth rate of 15.8% and an overall increase of 1,880.35% over the study period. In terms of volume, the scientific elite of this period is led by Zhang, Y., Liu, Y., and Wang, Y. Their work has established China as a leading power in knowledge production in the field. Despite a lower absolute volume of publications, the work by Brancalion’s maintains superior qualitative prestige, positioning Brazil as a global reference in tropical ecosystems and functional restoration.

China led in publication volume, followed by the USA and Brazil. The top three institutions are located in China, with the University of Chinese Academy of Sciences (UCAS) being the most prolific. The field shows an interdisciplinary trend, integrating ecology with areas such as climate economics and precision ecology. The most productive journals were *Forest Ecology and Management*, *Restoration Ecology*, and *Science of the Total Environment*.

The thematic analysis identified four focal points: diversity and vegetation dynamics, climate change and nature-based solutions, soil biogeochemistry, and natural regeneration as a large-scale strategy.

Currently, the main research directions are forest restoration, landscape resilience, and the valuation of ecosystem services. However, a critical challenge revealed by the collaborative networks is the urgent need to strengthen integrated research between the Global North and Global South. Breaking the isolation between these regions is essential to ensuring scientifically robust restoration protocols that are sensitive to the ecological and socioeconomic complexity of tropical biomes.

This study contributes to ensuring environmental sustainability—specifically the Millennium Development Goals (MDG 7)—by demonstrating that large-scale natural regeneration and nature-based solutions are pillars for maintaining ecosystem services.

Lastly, scientific research on ecological restoration, natural regeneration, and forest recovery guides the strengthening of the integration of social and economic issues as a response to global sustainability challenges.

5. Author contributions

All authors contributed to the study conception and design. Literature search, data analysis and the first draft of the manuscript were performed by Nelson Virgílio Rafael. Evandson José dos Anjos-Silva had the idea for the article and critically revised the work. All authors read, commented on previous versions of the manuscript and approved the final manuscript.

6. Statements and Declarations

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6.2. Competing interests

The authors declare no conflicts of interest (financial or non-financial).

6.3. Ethics, Consent to Participate, and Consent to Publish declarations

Not applicable.

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