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Bibliometric and literature synthesis on assisted natural regeneration: an evidence base for forest and landscape restoration in the tropics

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Assisted Natural Regeneration (ANR) is a set of restoration strategies and interventions primarily based on natural regeneration, aimed at accelerating succession and providing multiple benefits in degraded ecosystems and landscapes. These strategies have the potential to significantly contribute to global Forest and Landscape Restoration efforts. However, ANR faces challenges due to limited recognition, support, and formal integration into relevant sectors and restoration policies, particularly in tropical regions. The dearth of evidence-based syntheses further compounds these challenges. To address this gap, a bibliometric analysis of selected scientific publications on ANR ($n = 208$) from 1987 to 2023 was conducted, using Web of Science and Google Scholar databases. A systematic review was undertaken, using a subset of original research articles ($n = 44$), to synthesize published data on interventions, contexts, costs, and benefits of ANR and to identify major knowledge gaps. Analysis of bibliometric metadata revealed an increasing annual output of ANR publications in over 80 journals, encompassing various document types and authors from over 40 countries. Despite ANR's formal emergence in the Philippines, Brazil has taken the lead in both its research and implementation, and international collaboration in ANR research has grown. While ANR research focused mostly on ecosystem services and ecological outcomes, social aspects have been poorly studied. Diverse ANR interventions align not only with ecological restoration but also with integrated land management, biodiversity conservation, forest and landscape restoration, and forest management. The cost-effectiveness of ANR implementation, especially in restoration for carbon storage, exhibited considerable variability when compared to active tree planting, and varied with intervention types, time, land use history, and long-term costs. This synthesis provides critical insights and evidence to enhance the effective integration of ANR into restoration and reforestation programs and policies.

KEYWORDS

assisted regeneration, carbon, cost, farmer managed natural regeneration, forest regeneration, forest management, forest landscape restoration, research

1 Introduction

Global concerns and needs for restoring degraded lands have gained prominence, evident in the proliferation of ambitious international and local restoration targets and initiatives worldwide, including Bonn Challenge, New York Declaration on Forests, and Kunming-Montreal Global Biodiversity Framework (Chazdon et al., 2017; Navarro et al., 2017; Joly, 2023). While many restoration initiatives predominantly focus on active tree planting, implementing these approaches at large spatial scales can pose challenges. These challenges include limited availability of quality seeds, low seedling survival and establishment rates, and substantial costs associated with procuring seedlings, plantation establishment and management (Lamb et al., 2005; Gregorio et al., 2017; FAO, 2019). Consequently, restoration approaches with demonstrated potential to restore the ecological integrity of denuded or degraded lands on a large scale and at lower costs are urgently needed. Abandoning degraded ecosystems and allowing them to regenerate spontaneously and recover multiple ecosystem properties and functions through natural successional processes may require long timeframes, with success limited by local and landscape conditions such as soil degradation and lack of dispersal (Chazdon et al., 2016, 2020a).

In response to these challenges, Assisted Natural Regeneration (ANR) is increasingly advocated under suitable environmental and socio-economic conditions. ANR is described as a set of restoration strategies and interventions designed to enhance and accelerate the recovery of natural and managed ecosystems, particularly when the primary emphasis is on promoting natural regeneration (Chazdon et al., 2023). It is best implemented in areas with high natural regeneration potential and can complement active tree planting, which is more effective for restoring heavily degraded areas that lack natural regeneration potential (Holl and Aide, 2011; Brancalion et al., 2016; Vieira et al., 2021). ANR approaches aim to accelerate natural successional processes, fostering the growth and survival of native vegetation that can be otherwise impeded (Shono et al., 2007; FAO, 2019; Shono et al., 2020). ANR can also trigger succession in areas where natural regeneration is inhibited by specific factors (Holl, 2012; Rezende and Vieira, 2019). Since its emergence in the 1980s, ANR appears to be gaining traction globally and is being implemented across diverse local and regional contexts, restoration goals, and socio-economic environments. The potential ecological and socio-economic benefits of ANR contribute to its importance as a nature-based solution and component of ecosystem restoration, Forest and Landscape Restoration (FLR), and integrated land management. By triggering and accelerating natural succession in degraded landscapes, ANR can facilitate the recovery of native biodiversity, contribute to climate change mitigation and adaptation, and enhance ecosystem resilience. Native tree species regenerated through ANR can exhibit superior natural adaptation to local site conditions and climate change compared to actively planted ones, especially exotic tree species (Yang Y. et al., 2018; Huebner et al., 2022; Wilson et al., 2022). Native tree species can demonstrate higher diversity and are naturally adapted to the specific conditions of their native habitats, potentially giving them a better capacity to adapt than exotic species, depending on the invasiveness of the exotic species and habitat types (Evans et al., 2015; Oduor et al., 2016).

Despite its potential, ANR is under-utilized, and the formal integration of ANR practices into relevant sectors like restoration, forestry, and land management begs substantial consideration (Shono et al., 2007; Brancalion et al., 2019; Chazdon et al., 2020a). For example, ANR approaches were implemented in less than 15% of restoration projects across the three most widespread biomes in Brazil (Brancalion et al., 2019). The limited acknowledgment of ANR as an effective restoration approach is partly attributed to the lack of sufficient empirical evidence across various dimensions, including practices, impact, cross-contextual applicability, and cost-effectiveness (Hardwick et al., 2000; Wilson et al., 2022). While ANR projects hold promise for carbon sequestration and integration into carbon markets under categories like Afforestation, Reforestation, and Revegetation (ARR) or Improved Forest Management (IFM), they are currently overlooked or disqualified in relevant carbon accounting methodologies (Brancalion et al., 2024). A quantitative analysis of research on ANR is lacking, however.

ANR practices hold the potential to foster natural regeneration in diverse contexts, including logged and post-fire secondary forests, apart from their applications in the ecological restoration of converted ecosystems and the integrated management of agricultural lands (Shono et al., 2020). However, less attention focuses on cases or studies where ANR is implemented in forest regeneration and management for production or commercial purposes, especially in post-logging forests. These post-logging forests represent a considerable portion of degraded forest cover, particularly in tropical regions, and contribute significantly to global carbon emissions (Mills et al., 2023). This study analyzes the alignment and application of ANR interventions in all contexts.

Recent years have seen a surge in literature and guidance documents on ANR, primarily in grey literature documents such as thematic reviews, project reports, manuals, and policy documents published by organizations and agencies working in the environmental and resource management sector (e.g., FAO, 2019; Alves et al., 2022; Wilson et al., 2022; Chazdon et al., 2023). While grey literature faces critiques regarding reliability, transparency, accessibility, and quality control of findings (Farace, 2011), existing reviews provide valuable information on various aspects of ANR. Case studies of ANR implementation around the world have been compiled in several publications, some of which are reproduced across the rapid review studies (Shono et al., 2020; Alves et al., 2022; Wilson et al., 2022). Traditional thematic literature reviews often rely on qualitative, non-systematic summarization of existing research, involving a limited number of publications, which can lead to subjective literature selection, interpretation biases, and potential omissions (MacCoun, 1998; Guan et al., 2019; Xie et al., 2020). Moreover, existing ANR reviews lack temporal and spatial perspectives, resulting in an inaccurate understanding of global trends and changes over time.

This study aims to quantitatively and qualitatively analyze the global scientific production, evolution of research themes, interventions, and cost-effectiveness of ANR through a bibliometric analysis and a systematic review. Complementing literature reviews with bibliometric methods has proven valuable in quantitatively analyzing scientific research at a macro-scale, including its impact, knowledge domains, and research directions (Pritchard, 1969; Ramanan et al., 2020; Xie et al., 2020). A bibliometric analysis of ANR research is crucial to understand whether studies over time indicate a trend toward increased integration and adoption of ANR practices, as well as whether its evidence base is accumulating, and research is expanding to other countries. This analysis also sheds light on

opportunities for mainstreaming ANR within research and collaboration networks.

The overall objective of this study will be addressed by answering the following questions: (1) How is ANR described in the literature? (2) What are the trends of ANR research outputs in terms of the number of articles, citations, and topics investigated? (3) What are the patterns of collaboration in ANR research among authors, institutions, and countries? (4) What are the main research themes as well as gaps that can guide future research on ANR? (5) What types of interventions are reported in the literature as ANR approaches? (6) How does the implementation of ANR align with the contexts of ecological restoration, integrated land management, and forest regeneration and management? (7) What is the evidence in the literature regarding cost-effectiveness and socio-economic benefits of ANR interventions and what factors influence these benefits? The scope of this synthesis was not to exhaustively capture all literature on interventions that assist forest recovery, as many studies have used ANR practices without explicitly labeling them as such, which could complicate the synthesis. Instead, this study provides an unbiased evaluation of research that identify restoration practices as ANR. This approach serves as a credible reference for ANR in subsequent research and syntheses, from a systematic and scientific perspective.

2 Materials and methods

2.1 Methods of data collection

2.1.1 Search databases

Data for this study were collected from two widely recognized international online academic citation databases: Web of Science Core Collection (Thomson Reuters) (hereafter referred to as WoS) and Google Scholar (henceforth abbreviated as GS), following a methodology consistent with previous bibliometric research (Bartol and Mackiewicz-Talarczyk, 2015; McNicholas et al., 2022). WoS was selected for its reputation as a reliable and comprehensive source of peer-reviewed journal publications with significant global biophysical and social research and citation impact. Google Scholar, established in 2004, was also included in the data collection process, as it offers broader access to a variety of literature records, including grey literature. This inclusion was essential for conducting an inclusive evidence review (Haddaway et al., 2015). The literature search covered the period from inception of ANR research (1987) to 2023.

2.1.2 Delineation of search terms and syntax

The concept of ANR has evolved extensively and has been employed in numerous publications, often without explicit reference to ANR itself. Interrelated terms such as Farmer-Managed Natural Regeneration (FMNR) (Reij and Garrity, 2016; Chomba et al., 2020), Applied Nucleation (Wilson et al., 2022), and Enrichment Planting (Shono et al., 2020; Wilson et al., 2022) are restoration techniques frequently described in the literature as interventions for promoting the establishment of woody vegetation in degraded areas. However, to maintain a focused approach in this study, the search utilized the term "assisted natural regeneration" within the context of literal descriptions and intentional focus on ANR practices and strategies. The decision to adopt this narrow approach stemmed from several considerations. First, it was designed to enhance clarity and precision, allowing for a focused exploration of the core concept and application of ANR. Second, the approach aimed at managing the scope of literature search outputs, ensuring that the analysis remains targeted. Third, it sought to prevent ambiguity with other restoration techniques, recognizing that the practices and evidence base for ANR may be diverse and originate from various sources.

Some variants of terminology were still considered to ensure inclusivity. These variants, which were verified through a preliminary review and expert input before initiating the search, encompassed phrases like "accelerated natural regeneration," "assisted succession," and "assisted natural succession." Employing the search algorithm and syntax outlined in Table 1, metadata were retrieved from publications that incorporated these ANR terms in their titles, abstracts, and keywords within the WoS. Comprehensive article records were extracted, encompassing data such as titles, authors, keywords, abstracts, country, affiliated organizations, journals, and publication years.

For GS, a software tool known as *Publish or Perish* version 8 (Harzing, 2007) was utilized to access, do bulk retrieval of publication records, and pre-analyze data from the database. *Publish or Perish* serves as both a reference management platform and a performance analysis tool, that facilitates systematic and efficient literature searches and enables data exports for research purposes (Harzing and van der Wal, 2008). It can compute certain bibliometric indices based on citation counts (McNicholas et al., 2022; Nandiyanto and Al Husaeni, 2022) and is among the most extensively used performance analysis tools in bibliometric studies (Moral-Muñoz et al., 2020). Considering that GS inherently provides extensive search results even with a single search term, only "Assisted natural regeneration" was retained while excluding the variants. To further refine the results and focus on records within the context of forestry and forest landscape restoration, the truncated term "forest" was appended to the search query. This focused approach tends to minimize potential selection bias resulting from purposely choosing a certain number of pages of GS search hits generated from multiple search terms. The search was not restricted to specific publication types, given the prior knowledge of the diverse forms of ANR publications, including conference proceedings and reviews.

Article metadata, retrieved between June 3–5, 2023, was gathered in both EndNote and BibTeX formats for subsequent analysis. All articles published up to the aforementioned data collection period was included.

2.1.3 Screening of retrieved articles

A total of 980 articles were initially retrieved from the GS database, whereas the search conducted on WoS yielded 128 publications. However, not all these publication outputs were deemed suitable for inclusion in the subsequent bibliometric analysis and systematic review due to their limited relevance and substantive content regarding ANR. All articles were screened based on the

TABLE 1 Search algorithm used in the Web of Science and Google Scholar.

WoS	TOPIC: TITLE-ABS-KEY ("Assisted natural regeneration" OR "accelerated natural regeneration" OR "assisted succession" OR "assisted natural succession")
Google scholar	KEYWORDS: ("Assisted natural regeneration" AND "*forest*")

following inclusion criteria. Articles published in English or with English abstracts were included. While the justification for incorporating non-English publications in evidence syntheses has been acknowledged (Morrison et al., 2012), empirical studies argue that excluding them does not significantly impact overall conclusions (Nussbaumer-Streit et al., 2020). Nevertheless, diverse grey papers that are solely centred on ANR, especially from GS, were included to mitigate potential language restrictions, enhancing literature coverage and inclusivity. The screening process involved reading the full articles. Articles that did not focus on ANR as a primary subject or needed more substantial information about the restoration and regeneration concept were excluded. Following this rigorous screening process, 208 articles from GS and 91 from WoS met the criteria and were selected for bibliometric analysis. Due to redundancy, the 91 articles found in WoS records were excluded from GS. The WoS bibliographic format was used as a template for extracting data from the remaining GS articles.

2.2 Methods of data analysis

Various bibliometric tools were employed in the analyses for this study. Specific details such as author names, publication year, citation count, country of affiliation, article type, and journal were pre-processed and extracted from the records. Bibliometric analysis primarily focused on the number of records, the Global Citation Score – GCS, and annual growth in scientific production and citations related to ANR research. GCS represents the total number of times an article has been cited by all other articles. The number of records and citation scores are considered critical for analyzing author trends and impacts of publications (Xie et al., 2020). Information regarding the most relevant journals and countries with the highest scientific production and citations in the field of ANR were summarized. Additionally, publication records were summarized based on article types. All of these descriptive analyses were carried out using R Studio version 4.1.3 (R Core Team, 2022), after sorting the extracted and combined data in Microsoft Excel.

The major part of the bibliometric analysis was performed using a specialized package called "Bibliometrix" (Aria and Cuccurullo, 2017) within R Studio version 4.1.3 (R Core Team, 2022). This open-source analytical package has been widely employed in various bibliometric research studies worldwide (see Ekundayo and Okoh, 2018; Ramanan et al., 2020; Xie et al., 2020). It allows easy import and conversion of bibliographic data from different databases stored in various file formats (Aria and Cuccurullo, 2017). This tool was utilized to analyze and visualize several aspects, including the three-field plot indicating the connections between top authors, keywords, and journals in ANR research, as well as international collaboration networks, conceptual structure, and thematic evolution in ANR research. Another bibliometric and science mapping software, VOSviewer version 1.6.19 (Van Eck and Waltman, 2010), was utilized for the analysis and visualization of co-authorship networks among authors, research institutions, and countries. Author-level collaboration was considered when an article had multiple authors, while inter-organizational or international collaboration was noted when authors originated from different organizations or countries. Author keywords and generated keywords of an article reflect the publication focus and were broadly analyzed to evaluate emerging themes in ANR research (as in Song and Zhao, 2013; Xie et al., 2020).

The bibliometric analysis was complemented with a systematic review encompassing the interventions and applications of ANR within different contexts, names and approaches for implementation, and assessment of cost-effectiveness and benefits across various countries. From the initial pool of 208 publications, 44 research articles that provided practical findings from ANR case studies were selected for a comprehensive evidence review. The following inclusion criteria were applied: only research articles with ANR as the primary research topic, providing detailed information about interventions, contexts, costs, or benefits were included. Relevant data were carefully extracted, including information about authors, topical focus, methods used, interventions applied, costs of implementation, social and ecological effects, ecosystem types, the country where the research was conducted, and overall context of publication. Data were entered in Microsoft Excel, and descriptive analyses were performed using R Studio 4.1.3 along with thematic analysis (Braun and Clarke, 2006). A schematic representation of the methodology workflow is depicted in Figure 1.

3 Results and discussion

3.1 ANR research boom: contributions from FLR-focused organizations and conferences

Although there have been only a few articles on ANR since the 1980s (less than 6 per year on average), there has been an increased interest over the past six years and in some few peak periods, particularly driven by organizations aiming to scale up restoration efforts. The formal ANR intervention traces its roots back to 1987 in the Philippines (Dalmacio, 1987; Sajise, 1989), building upon longstanding traditional forest management practices (Butic and Ngidlo, 2003). Its concept and practices emerged as a reforestation approach in deforested areas dominated by cogon grass (*Imperata cylindrica*) (Dugan et al., 2003). Over the years, there has been a gradual increase in the number and diversity of studies, covering nearly all types of documents and attracting a growing number of global citations (Figure 2; Supplementary Figures S1A,B). Sixteen types of articles were identified amongst the 208 ANR publications analyzed in this study, including research and rapid review articles, conference papers, among others (see Supplementary Figure S1B).

Most of these publications (60%) occurred within the last six to eight years, confirming the emerging status of ANR. This assertion aligns with the evidence of reviews, practical manuals and reports published recently by different organizations with forest restoration mandates. These organizations include World Resources Institute, WRI (Alves et al., 2022), Conservation International (Wilson et al., 2022), Food and Agriculture Organization (FAO, 2019), Forest Restoration Research Unit (FORRU) in Chiang Mai, Thailand (Elliott et al., 2023), and the newly formed Assisted Natural Regeneration Alliance (Chazdon et al., 2023). International conferences on natural regeneration and FLR, including those held in Rio de Janeiro (2014) and Manila (2019), have also stimulated talks and research on ANR, exemplified by special issue articles published by Chazdon and Uriarte (2016) and Chazdon et al. (2020b), respectively.

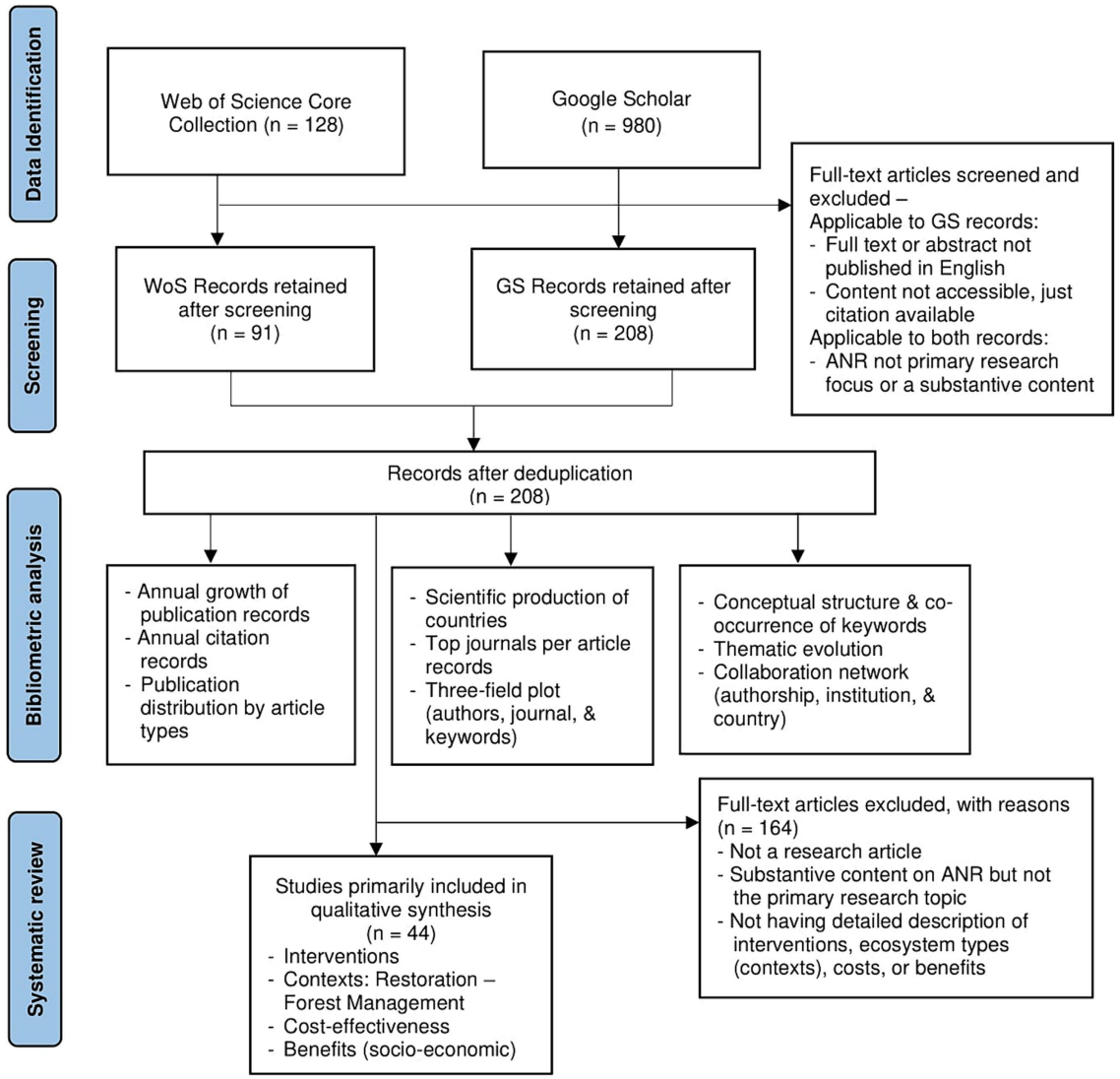

FIGURE 1
Workflow of research methodology.

While the trend aligns with the overall growth in ecological restoration research (Guan et al., 2019), the observed increase in ANR research could be attributed to its intersection with multiple sectors, including conservation, restoration, agriculture, and forestry (Chazdon et al., 2023). Peak periods of scientific publication on ANR in the last decades were in 2003, 2011, and 2022, coinciding with significant events in the development history of ANR, namely the conference on advancing ANR in Asia and the Pacific (Dugan et al., 2003), the "Forests Beneath the Grass" FAO regional workshop on ANR (Durst et al., 2011), and the establishment of the ANR Alliance by WRI in 2022 to promote global ANR implementation and advance multisectoral integration (Chazdon et al., 2023). These findings emphasize the pivotal role of these kinds of events and interdisciplinary gatherings of a diverse range of restoration stakeholders, including experts, academics, policymakers, and practitioners. These events, complemented by the efforts of FLR-oriented organizations, are crucial in advancing ANR, addressing knowledge gaps, and overcoming adoption challenges.

3.2 Country-based distributions of ANR articles

ANR research exhibits a broad geographical scope, and its research productivity is aligned with policy initiatives that support restoration through natural regeneration. The 208 articles originated from 42 countries, but the majority of the scientific publications were concentrated in a few countries (Figure 3). Brazil emerged as the most productive country in ANR research, contributing approximately 12%, which included national and international collaborative research efforts. Following Brazil, the Philippines and the United States contributed around 11 and 8% of the articles, respectively. Brazil's prominence is related to the country's recognition for pioneering the development of various environmental and restoration policies and actively promoting ecological restoration and conservation in degraded forestlands, agricultural areas, and pastures (Joly et al., 2010; Guan et al., 2019; Guerra et al., 2020).

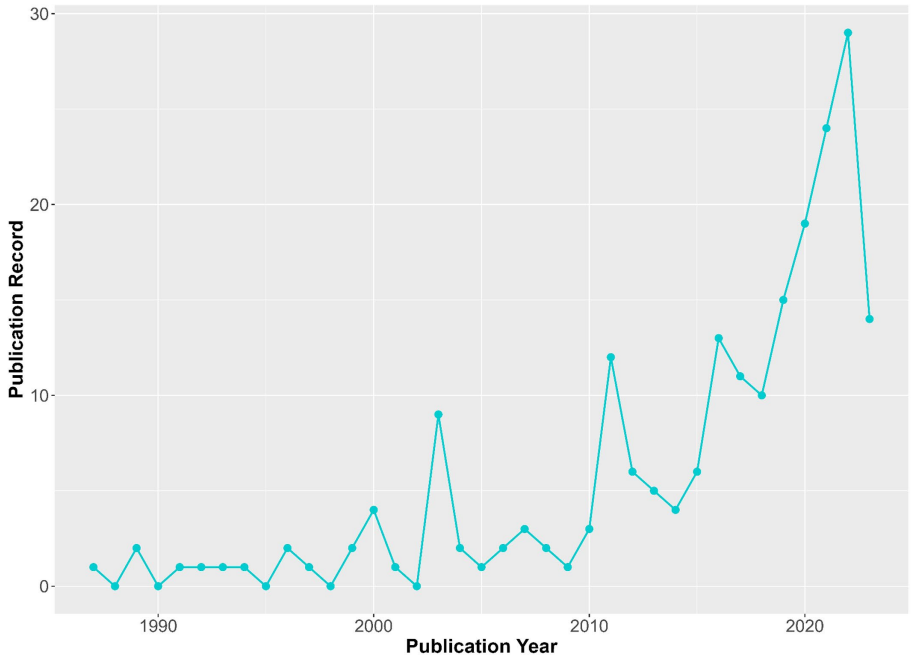

FIGURE 2
Annual publication records of scientific records (n = 208) on ANR between 1987 and 2023. 2023 was an incomplete year for the search, which likely accounts for the dip in the figure.

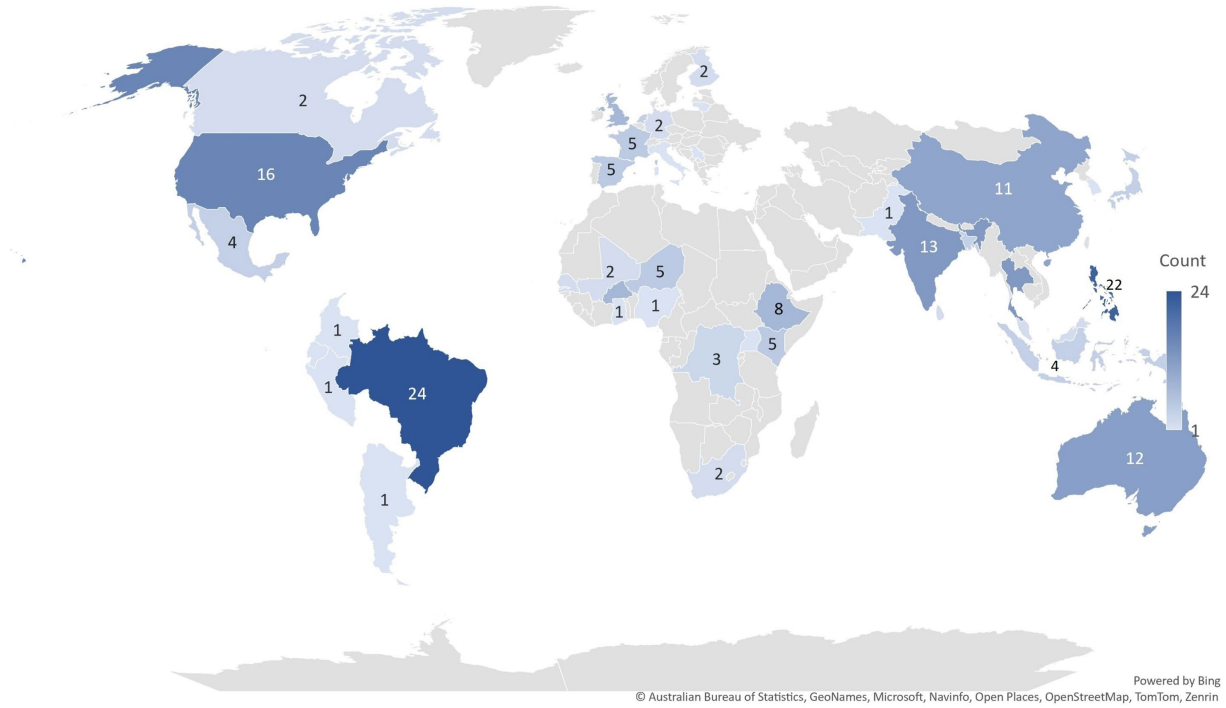

FIGURE 3
Complete scientific production of countries in ANR research as per number of articles from 1987 to 2023.

One notable policy supporting and promoting ANR implementation and research development in Brazil is the revised Brazilian Forest Code, which mandates private landowners to maintain between 20 and 80% of their land under native vegetation, considering that over 70% of the national territory is privately owned (Garcia et al., 2013). Consequently, many landowners and restoration programs are adopting ANR to enhance the recovery of native trees in their regenerating lands, especially in areas with up to a 40% regeneration probability or

favourability (Brancalion et al., 2016; Molin et al., 2018; Guerra et al., 2020). The interplay between policy and science is intricate, suggesting that the development of restoration-oriented policies may draw inspiration and evidence from the active engagement of restoration researchers in the country. Researchers in Brazil provided technical expertise and pioneered critical aspects of ANR research, including spatial predictive modelling of its potential and cost-effectiveness (see Nunes et al., 2017; Brancalion et al., 2019; Crouzeilles et al., 2020).

The second highest proportion of ANR publications recorded in the Philippines can be attributed to the formal adoption of the ANR concept in the country. Many of the earlier manuals, reports, and publications on this restoration strategy originated from the work of restoration scientists rehabilitating degraded landscapes dominated by *Imperata* grasses in the Philippines (Dalmacio, 1987; Sajise, 1989; Friday et al., 1999; Dugan et al., 2003). Also, the Philippine Department of Environment and Natural Resources (DENR) has developed supporting policies for ANR over the years, starting in 1989 when the method received official promotion and adoption into the national reforestation policy (DENR, 1989). For instance, the National Greening Program, launched in 2011, incorporated ANR into its strategy (DENR-FMB, 2019), albeit in a limited manner. Similar to Brazil, this policy recognition for restoration practices that are centred on natural regeneration may have contributed to or benefited from ANR research in the Philippines. However, the trend of scientific activity in ANR research in the country has declined in recent years, necessitating improvement.

The active involvement of countries like the United States, China, and Australia in ANR research aligns with Guan et al. (2019), who reported that these countries dominated and substantially contributed to the broader field of ecological restoration. However, low- and middle-income countries are increasingly taking the lead in ANR research, constituting 67% of the top 15 countries in this study. These countries typically have a higher potential for natural regeneration. According to Williams et al. (2023), Brazil, Indonesia, Mexico, and Colombia account for nearly 50% of the total estimated global potential for natural regeneration. FMNR is predominantly researched across Sub-Saharan Africa, including Niger, Ethiopia, and Burkina Faso (Kelly et al., 2021; Boukary et al., 2023). At the same time, other ANR practices are assessed and applied as reforestation efforts in Asia-Pacific like China and Thailand, and in Latin-America, including Brazil and Mexico (Yang Y. et al., 2018; Rivas-Alonso et al., 2021; Elliott et al., 2023). While active tree planting and seeding of broadleaved species appear more prevalent in forest restoration and regeneration in Europe (Stanturf and Madsen, 2002; Martiník et al., 2014), the application of assisted natural regeneration in restoring and rehabilitating forest landscapes or managing forest stands is not uncommon (Leinonen et al., 2008; Martinez-Baroja et al., 2022). The limited report of ANR in Europe in this synthesis may be attributed to the usage of generic terms such as *ecological rewilding* and the *close-to-nature restoration* approach to describe the concept of facilitating natural processes (Stanturf and Madsen, 2002; Navarro and Pereira, 2015), which were not considered in this study's search.

3.3 Attributes of main journals, keywords, conceptual structure, and thematic evolution of ANR research

Themes in forest restoration studies that focus on ANR are evolving, spanning different multidisciplinary journals, with a growing emphasis on the ecological outcomes of the restoration strategy more than the social aspects. Peer-reviewed studies on ANR have been published in 86 journals (a complete list of these journals is provided in Supplementary Table S1). The distribution of articles in journals is relatively clustered, with approximately 35% of the publications concentrated in the top 15 listed journals, based on their number of articles. The remaining papers are distributed widely, with most journals featuring only one or two papers. The largest number of studies were published in *Forest Ecology and Management* ($n = 13$), *Forests* ($n = 7$), *Biotropica* ($n = 6$), *Restoration Ecology* ($n = 6$), and *Frontiers in Forests & Global Change* ($n = 5$). Other journals covering ANR studies include *New Forests*, *Land Degradation and Development*, *Biological Conservation*, and *Science Advances*. These journals focus on diverse aspects related to the fundamental principles and objectives of ANR, spanning forest and land restoration, reforestation, conservation, land management, forest ecology, forest regeneration and management, sustainable development, tropical and biological conservation, among other themes.

The array of keywords used in the ANR studies highlights its application in facilitating diverse forest restoration outcomes while aligning with various modes of rehabilitation, restoration, and regeneration. Keywords serve as valuable indicators of the research focus, themes, or hotspots, providing a high-level summary of the essential content in the articles (Zhang et al., 2010; Xie et al., 2020). Frequently used, unique keywords such as *forest restoration*, *biodiversity*, *conservation*, *landscape restoration*, *tropical forest*, *regeneration*, and *succession* convey essential themes of ANR studies (Figure 4A). Other common keywords, including *ecological restoration*, *rehabilitation*, *silviculture*, *agroforestry*, *reforestation*, *management*, and *tree planting*, confirm the practical relevance and alignment of the spatial context of ANR with various approaches to restoration, emphasizing its cross-contextual application (Chazdon et al., 2023). The recurring mention of *climate change*, *land-use change*, *resilience*, *biodiversity conservation*, *biomass*, *recovery*, *rainforest*, and *Sahel* indicates that ANR has the potential to help address global environmental change and recovering multiple ecosystem services, including biomass carbon sequestration.

Three main thematic clusters emerged from the literature (i.e., ecological, social, and large-scale application aspects) with the cluster related to ecological themes being by far the predominant one. The conceptual structure of ANR is illustrated through thematic clustering based on the co-occurrence of keywords using a two-dimensional multivariate analysis (Figure 4B). The first cluster in "red" broadly centres on ecological themes related to tropical forest regeneration, restoration, and succession (e.g., *land-use changes, tropical forests, regeneration, growth, establishment, dynamics, conservation,* and *recovery*). It also includes themes pertinent to the *ecological outcomes* and *ecosystem services* of ANR, emphasizing carbon *sequestration*, *climate change* mitigation, *biodiversity* recovery, and *soil* amelioration. This ecological cluster appears to be a matured core cluster, with its position around the centre of the figure. The mention of the application of ANR in *large-scale* and *landscape* restoration, represented in the second cluster in "blue", seems to be transitional. ANR practices appear to have been mostly implemented on a small or experimental scale rather than on a large scale, particularly by restoration scientists. This may partly explain the lower volume of scientific publications despite the proliferation of the restoration practices. There seems to be a disconnect between restoration

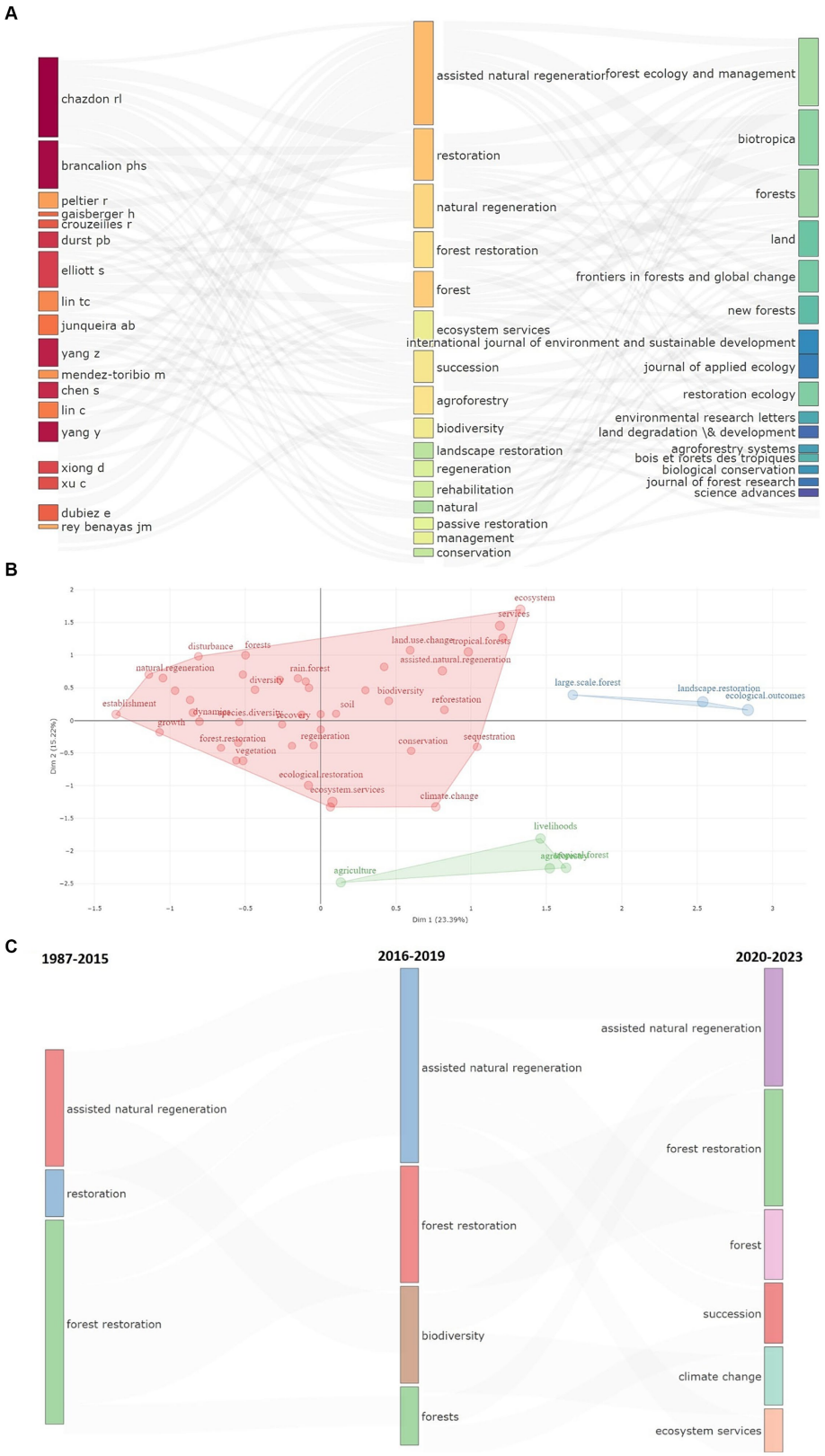

FIGURE 4
(A) Three-field plot connecting some of the main journals, keywords, and authors. **(B)** Multiple Correspondence Analysis (MCA) of high-frequency keywords, and **(C)** thematic evolution in ANR studies. The two-dimensional MCA employs plane distance to demonstrate the similarity between keywords and map the conceptual structure of ANR research. The dimensions represent linear clustering of the keywords, capturing the amount of their variability. Keywords and clusters positioned closest to the centre signify themes that have consistently maintained attention over the period of evolution, while those near the edge depict more limited and transitional themes. Clusters of keywords close to each other in the plot indicate a strong co-occurrence (Aria and Cuccurullo, 2017; Xie et al., 2020). The thematic evolution flowchart is a Sankey diagram where each node signifies a theme, and the node size corresponds to the number of keywords in the theme (Cobo et al., 2011; Xie et al., 2020).

organizations implementing activities on the ground at various scales, potentially including large-scale projects, and restoration and ecological researchers who focus more on observing and experimenting with succession processes in restoration. Bridging this gap is essential to foster improved documentation, exhibition, and research in restoration and ANR fields. This integration can be achieved by encouraging collaboration and knowledge sharing between field practitioners and researchers, creating integrated project databases, and promoting interdisciplinary studies that combine practical implementation with scientific inquiry.

Social outcomes of ANR, such as *livelihood* improvement, appear strongly linked to its implementation in *agricultural* landscapes and *agroforestry*, albeit with limited attention, evident in the third cluster in "green". ANR has the potential to maximize livelihoods more effectively when utilized for establishing agroforestry through FMNR or enrichment planting on agricultural land as a form of farm-level diversification than when primarily implemented as an ecological restoration approach (Wilson et al., 2022).

The thematic evolution analysis further demonstrates that ANR research themes have experienced development since 2016. The evaluation period was divided into three stages to balance article distribution (Figure 4C). The main ANR keywords have evolved from simple concepts of *restoration* in the initial stage (1987–2015) to broader themes such as *ecosystem services*, *succession*, *biodiversity*, and *climate change* by 2020–2023. Thematic evolution analysis is useful for displaying the direction, understanding the development trajectory, and predicting the evolutionary trends of a research field (Cobo et al., 2011; Xie et al., 2020).

3.4 Collaboration analysis among countries, researchers, and institutions

Research collaboration on ANR studies is promoting more international, rather than regional, interactive engagement and fostering equitable research partnerships. Over 800 authors globally were observed to have contributed to ANR research, the majority of whom have collaborated internationally. This figure is likely an underestimate due to the focused approach used in the search. Although the highest collaboration frequencies were found among some of the most prolific countries, especially Brazil, the United States, Australia, and the UK, research collaboration was common among many other countries (Figure 5A). Scientific exchanges within regions, such as within Africa, show low evidence, but there is a high level of cooperation between developed and developing countries, with countries like Kenya having multiple collaborators in Europe. Some of the main collaborating institutions were the University of Connecticut and the University of the Sunshine Coast (both represented by Chazdon RL), the International Institute for Sustainability (represented by Crouzeilles R), and the University of São Paulo (Brancalion PHS) (Figures 5B,C). The network analysis of some authors leading ANR research revealed that Chazdon RL acts as a central researcher connecting different groups.

Just as tropical landscape restoration and forest recovery is multidimensional (Poorter et al., 2021), ANR and its practices intersect with different sectors, such as forestry, agriculture, sustainable development, conservation, and environment, and thrive in different socio-cultural, economic, and ecological conditions (Chazdon et al., 2023). Highlighting the collaboration dynamics in ANR research could help identify potential for future cooperation and project development among multi-sectoral restoration practitioners on a regional and global scale.

3.5 Global nomenclatures and misconstructions in ANR definitions and application

Assisted Natural Regeneration is described in various ways across the reviewed literature, with certain terms being specific to particular geographical locations. Table 2 summarizes the diverse nomenclatures used for ANR, the awareness of which could enhance the identification, recognition, and adoption of this restoration approach. The terms could help inform a more appropriate and inclusive literature search on the concept in the future. ANR has been described and adopted in accordance with the definitions proposed by FAO, WRI, and ANR Alliance (FAO, 2019; Alves et al., 2022; Chazdon et al., 2023) in most cases.

Other terms used to synonymously describe assisted natural regeneration include *Human-Assisted Natural Regeneration*, *Facilitated Regeneration*, *Managed Natural Regeneration*, *Farmer-Managed Natural Regeneration, Assisted Passive Restoration*, *Passive Restoration*, *Assisted Regeneration*, *Assisted Succession*, and *Accelerated Natural Regeneration*. These terms are associated with specific practices, including the removal of competition from weedy vegetation to regenerating seedlings, restricting disturbances like grazing to natural regeneration, enrichment planting of native trees, gap planting and soil moisture conservation (see Honu and Dang, 2000; Brancalion et al., 2016; Ishtiyak et al., 2016; Palomeque et al., 2017; Lozano-Baez et al., 2019; Li et al., 2021; Kassa et al., 2023). Other common terms for passive plantings of native species to encourage natural regeneration, such as *Enrichment Planting* and *Applied Nucleation* (planting islands or nuclei of native trees while protecting natural regeneration), have been described and applied as ANR (Lozano-Baez et al., 2019; da Cruz et al., 2020; Wilson et al., 2022). Furthermore, Kelly et al. (2021) adopted a new term –*Assisted natural regeneration approach (ANRA)*– to describe natural regrowth protection and management in farmlands and fallows.

Some other studies have misapplied the term ANR, relating it to accelerating forest recovery through high-intensity active ecological tree planting of native species without emphasizing the protection of natural regeneration. For example, Yang A. et al. (2018) considered ANR synonymous with restoration plantings which "aim to restore ecosystem functionality and biodiversity via the planting of native species." In the same vein, Alanís-Rodríguez et al. (2021) related ANR, using the term "*assisted natural/ecological succession*," as an "active restoration" where activities like planting species are undertaken to accelerate ecosystem recovery. Their emphasis was on "reforestation with native species" rather than promoting natural regeneration. This is also the case in the Philippines, where ANR is implemented as a reforestation method under the National Greening Program of the DENR. Native tree seedlings are planted in regular spacings by Peoples Organizations without regard to their effect on facilitating the natural regenerative potential of the recovering areas, deviating from DENR guidelines. Although ANR allows and includes reintroduction of native trees into degraded landscapes through supplemental planting, principal emphasis of interventions should be to protect and enhance naturally regenerating seedlings and promote seed dispersal from sources in native remnant forests adjacent to the restoration areas (Chazdon et al., 2023).

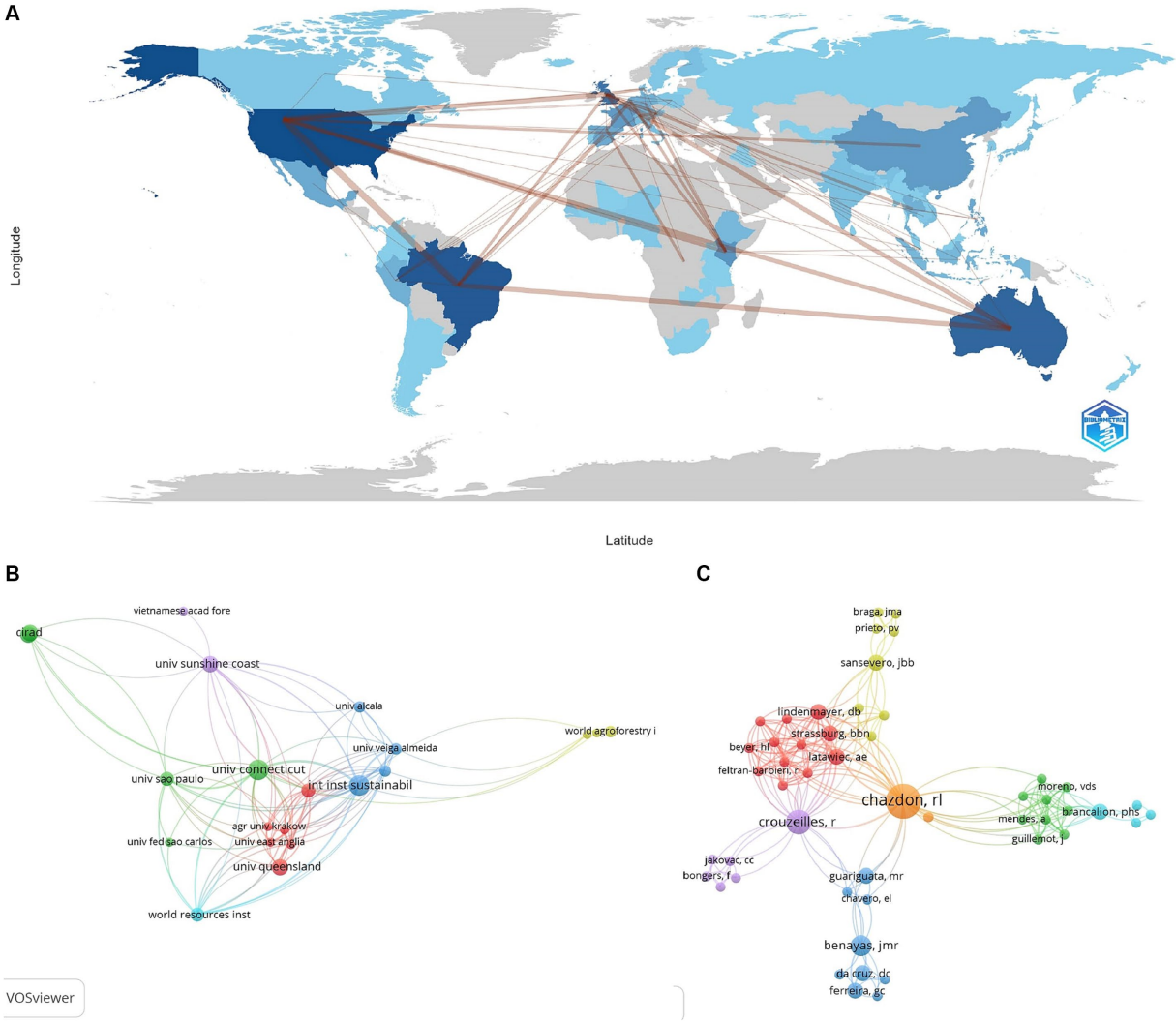

FIGURE 5
The network map of some of the top collaborative **(A)** countries, **(B)** institutions, and **(C)** authors for ANR research. Each node represents a(n) country/author/institution, with its size directly correlating to the total frequency of collaboration. The lines connecting two countries or authors or institutions signify their collaborative relationships, with the thickness of the line indicating the number of collaborative articles (i.e., collaborative frequency or strength) (Van Eck and Waltman, 2010; Waltman et al., 2010; Zhang et al., 2020).

3.6 Common interventions of assisted natural regeneration

More than 20 restoration activities and interventions have been applied across various spatiotemporal and socio-ecological contexts in the implementation of ANR, exhibiting geographical trends in their prevalence. Appropriately integrating these interventions, adapted to the ecosystem conditions, is crucial for effective recovery. The most common interventions identified across the ANR core studies ($n = 44$) were weed control around natural regenerants through slashing or cutting and installing physical fences or exclosures, each applied in approximately 40–48% of the total studies. Other major interventions include enrichment planting with native species, climber removal, firebreak, grass pressing, FMNR, and residues retention (Figure 6). In terms of their spatial patterns, while interventions like manual weeding and fencing were widespread across all regions, the latter was most prominent in Latin America-Caribbean and Africa, where grazing is a major degradation agent. FMNR is most predominant across Sub-Saharan African countries like Niger and Mali. Retention of residues and other soil amendment practices are prevalent in East Asian countries like China and Japan (Supplementary Table S2). Adapting Chazdon et al. (2023), these interventions are classified into three groups—tree, site, and landscape—based on the spatial scale of implementation (see Supplementary Table S3). Some interventions are applicable to individual trees, while others are implemented across sites or entire landscapes. Tree-based and site-based methods emerged as the most prevalent interventions.

3.6.1 Weed control around natural regenerants

The most common interventions in ANR aim to protect and manage natural regeneration in the site or across the landscape, including controlling and removing weedy vegetation like ferns, grasses, or shrubs around natural regeneration inhibiting their growth (see Carandang et al., 2007; Palomeque et al., 2017; Do et al., 2019). Wilson

TABLE 2 Different terms used to describe assisted natural regeneration worldwide.

Citation	Nomenclature	Specific description	Geographical reference
FAO (2019, p. 5)	Assisted Natural Regeneration (ANR)	Any set of restoration strategies and interventions based on natural regeneration that aim to enhance and accelerate the recovery of native forests.	Global
Alves et al. (2022, p. 2)		"A collection of approaches [which] seek to remove human-caused environmental disturbances, such as deforestation and fire, in order to facilitate and accelerate the regeneration process."	
Chazdon et al. (2023, p. 9)		A set of restoration strategies that utilize a spectrum of approaches and interventions designed to enhance and accelerate the recovery of ecosystems by overcoming specific barriers, with the primary emphasis of restorative actions on natural regeneration.	
Li et al. (2021, p. 5)	Human-Assisted Natural Regeneration	"…removing the dense herbaceous layer and litters to allow the naturally fallen seeds to approach the soil…and decrease the impact of interspecific competition and enhances seedling emergence and survival."	China
Honu and Dang (2000, p. 76)		Removing weedy vegetation like *Chromolaena odorata* and all other non-tree plants manually to release the tree seedlings.	Ghana
Standards Reference Group SERA (2021, p. 8)	Facilitated Regeneration	"Where the removal of causes of degradation is insufficient to allow spontaneous regeneration, active interventions can often foster natural regeneration from *in-situ* propagules (e.g., soil seed banks or buds) or from recolonisation."	Australia
Wilson et al. (2022, p. 13)	Managed Natural Regeneration	"Protection from disturbance + marking and monitoring regenerants + weeding or silvicultural treatments (thinning) if necessary."	Global
Etongo et al. (2016, p. 8)	Farmer-Managed Natural Regeneration (FMNR)	"Also known as assisted natural regeneration, FMNR is the protection of indigenous tree species in the Sahel so that they can regenerate naturally to maturity."	Sahelian Africa
Lozano-Baez et al. (2019, p. 4)	Assisted Passive Restoration (APR)	"…encouragement of regenerating individual native trees and shrubs by manual and chemical control of invasive grasses [and] enrichment plantings with native tree species…in patches without natural regeneration."	Brazil
Brancalion et al. (2016, p. 859)	Passive Restoration (PR)	"Site isolation from human-mediated disturbances and, when necessary, encouragement of regenerating individuals of native trees and shrubs by manual or chemical control of invasive grasses. Enrichment plantings with late-successional tree species in low diversity regenerating forests were also included in this category."	Brazil
Kassa et al. (2023, p. 3)	Assisted Regeneration (AR)	"…restricting livestock grazing activities and harvesting of woody plant species…[and] allowing freely fallen woody species collection…to improve seedlings' growth."	Ethiopia
Palomeque et al. (2017, p. 645)	Assisted Succession	"…removal of competing herbaceous ground vegetation [to] accelerate forest recovery."	Ecuador
Ishtiyak et al. (2016, p. 1013)	Accelerated Natural Regeneration	"A simple…technique for converting degraded forest areas to more productive ones…[through] cleaning, gap planting, and soil moisture conservation."	India
Wilson et al. (2022, p. 13)	Enrichment Planting (EP)	"…[supplemental] planting of native trees + maintaining seedlings to increase regenerating forest health."	Global
Wilson et al. (2022, p. 13)	Applied Nucleation (AN)	"Protection + planting native "tree islands" or rows of trees to encourage regeneration between; maintaining planted trees and sometime regenerating trees."	Global
Kelly et al. (2021, p. 14127)	Assisted Natural Regeneration Approach (ANRA)	"…protecting and managing natural regrowth (shoots) produced by the stumps of trees and shrubs in the fields and fallows."	Mali
Yang A. et al. (2018, p. 72-73)	Naturally assisted regrowth forest/ Assisted natural forest regrowth	Planting of fast-growing native species in a small number to facilitate colonization by a wider number of species.	Indonesia
Alanís-Rodríguez et al. (2021, p. 2)	Assisted Ecological Succession	"…where restoration activities are undertaken to accelerate the recovery of the ecosystem, like planting [native] species to accelerate recovery in an assisted natural succession."	Mexico

et al. (2022) termed this procedure as "Managed Natural Regeneration". Various weed control methods are employed in different ANR contexts, depending on the composition and severity of the competing vegetation, available resources, and intended efficiency. For instance, reducing competition to regenerants from herbaceous vegetation for water, light, and nutrients by weed pressing or lodging, slashing, or

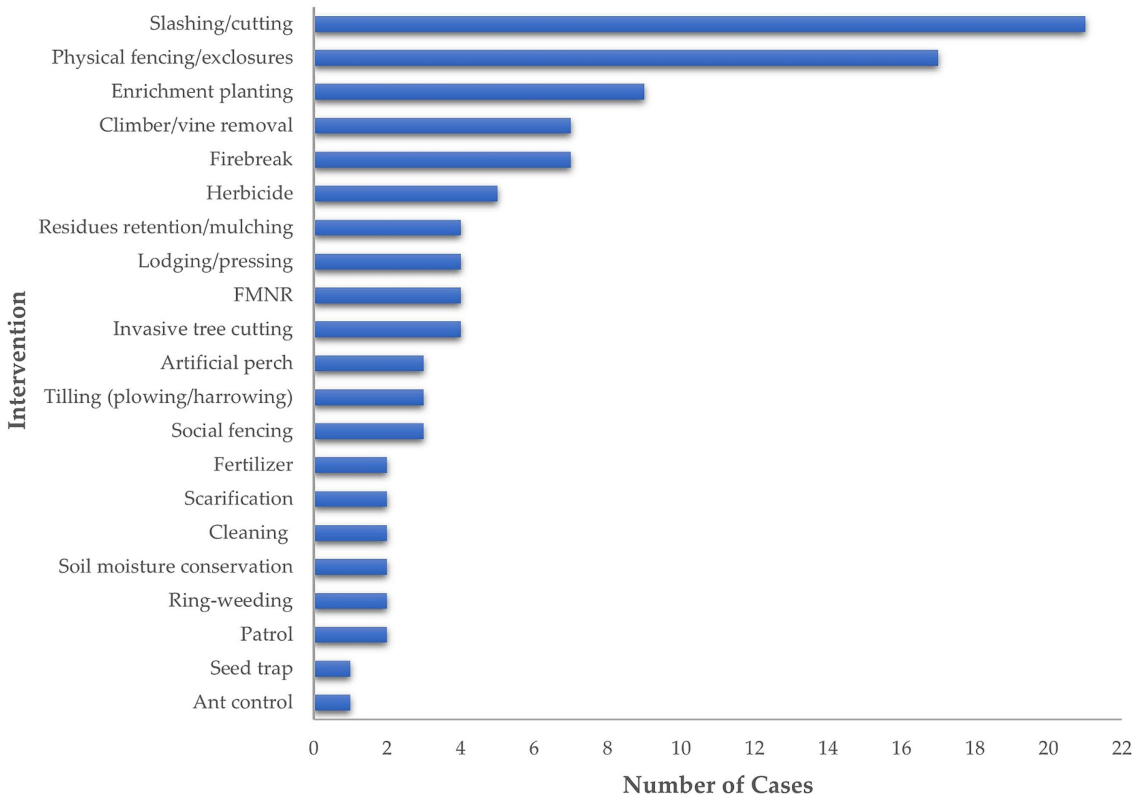

FIGURE 6
Different interventions identified as ANR approaches (number of cases = 47; number of studies = 44).

pulling grasses is a prevalent ANR technique across degraded *Imperata* grasslands and watersheds in the Philippines (Friday et al., 1999; Dugan et al., 2003; Shono et al., 2007; César et al., 2014). The residues from slashing or lodging contribute to natural regeneration's growth rates by enhancing soil nutrients, improving soil quality, and retaining moisture (Carandang et al., 2007). Another approach involves controlling abundant pioneers or invasive trees to improve the light conditions for the regenerants (Swinfield et al., 2016). Chemical control of invasive grass around naturally regenerating seedlings is also defined as an ANR intervention, applied in restoration sites in Brazil and across Southeast Asia as an alternative to active plantings (Terry et al., 1996; Rezende and Vieira, 2019; Viveiros et al., 2021). However, the effectiveness of weed control in accelerating the recovery of degraded forestlands varies based on the choice of weeding methods, degradation status, and time since implementation (Tulod and Abanda, 2016; da Cruz et al., 2020).

3.6.2 Fencing and area exclosures

Another set of common ANR interventions, termed "Protecting Regenerating Forests" (Wilson et al., 2022), aims to protect regenerating sites from disturbances like grazing and unsustainable extraction, such as timber or fuelwood felling and land clearing. This synthesis reveals that about 45% of ANR studies considered fencing, area enclosures, or livestock exclusions as primary techniques for facilitating natural recovery. Alves et al. (2022) also identified fencing, among six other ANR interventions, as a predominant approach for curbing grazing activities, with around 38% of cases (i.e., 9 out of 24 projects) employing this method. Fencing in assisted regenerating sites involves physical installations or social fencing. Physical fencing has been used to overcome recruitment limitations and improve soil quality, seedling density and survival, tree growth, species richness, forest structure, and biomass in various ecosystem types globally (Negussie et al., 2008; Mir et al., 2022). Social fencing, a collaborative approach by local land users and restoration practitioners, is likewise widely considered an ANR technique across tropical regions (Tamba et al., 2021; Wilson et al., 2022). An example is Mountain Closure in China, which communally prohibits grazing, logging, and agricultural activities within degraded mountainous forested areas, allowing natural forest recovery (Zhang et al., 2016). Additional methods to exclude grazing include tethering, collecting grass as fodder, direct stocking rate management, or controlled grazing to promote tree growth by reducing grass competition or fertilizing (Evans et al., 2015; Wilson et al., 2022).

3.6.3 Enrichment planting with native species

In some cases, enrichment planting is needed to accelerate the canopy closure of the regenerating area while supplementing the diversity and ecosystem function. Enrichment planting of seedlings of forest-native species that are absent in a restoration site or landscape to increase the abundance of species with ecological, cultural, and/or economic importance is one of the commonest ANR interventions globally (Alves et al., 2022; Nasam et al., 2022; Kassa et al., 2023). Among the 44 studies included in this systematic review, 21% of them implemented targeted supplemental planting to improve biodiversity, carbon storage, or even to promote the productive functionality of the

degraded areas, especially in selectively logged or logged-over secondary forests or recovering areas that lack enough later-successional species and seed sources (Brancalion et al., 2016; Suzuki et al., 2021; Alam et al., 2022). This finding somewhat aligns with Alves et al. (2022) who reported that at least 50% of the examined cases ($n = 24$) enriched natural regeneration using plantings of native trees. Although it is undefined to what degree reintroduction through enrichment planting could fall out of the scope of ANR, most ANR implementers hold an inclusive stance on the appropriateness of integrating reintroduction approaches into ANR components as long as these practices enhance natural regeneration (Chazdon et al., 2023).

3.6.4 Fire protection

Recurring fires play a critical role as agents of disturbance and degradation impeding natural successional processes, eliminating woody regrowth, and inhibiting forest recovery (Chazdon and Guariguata, 2016). In the Philippines, for instance, forest restoration and reforestation face significant challenges due to frequent fires resulting from burning fire-climax or fire-prone *Imperata* and *Saccharum* grasslands (Shono et al., 2007; Ancog et al., 2016). These grasslands have often replaced forested cover and persist due to swidden cultivation practices. Escapes of fires used in land preparation for swidden farms pose a threat to adjacent reforestation and regenerating areas (Rebugio et al., 2007). Naturally regenerating forests are susceptible to fires, necessitating interventions to protect them and foster regrowth survival. One widely adopted intervention involves establishing firebreaks or fire lines around restoration sites and landscapes, as demonstrated in various ANR case studies and projects (Shono et al., 2007; Alves et al., 2022; Elliott et al., 2023; Ssekuubwa et al., 2023). To incentivize local communities to maintain these firebreaks, cultivation of the areas with food crops is encouraged (FAO, 2019). In this review, firebreaks emerged as a priority in nearly 20% of the studies. Additional strategies employed to control or prevent fires around regenerating areas include social awareness campaigns, patrolling, and controlled burning (Shoo and Catterall, 2013; Wilson et al., 2022; Ssekuubwa et al., 2023).

3.6.5 Integrated approaches

Measures like fencing, exclusion, weeding, and fire protection vary in effectiveness for restoring natural diversity and ecological functions, depending on factors such as land use degradation type, history, intensity, and competition from other vegetation. This highlights the need for integrated ANR approaches (Terry et al., 1996; Negussie et al., 2008; Tulod and Abanda, 2016). Recognizing that tropical forest trees often face dispersal and establishment limitations (Holl, 2012), strategies aimed at mitigating herbaceous vegetation can be combined with those aimed at enhancing propagule supply rather than using either strategy in isolation (Shoo and Catterall, 2013). The latter category includes installing artificial perches, retaining residues as a natural seed source, and enrichment planting (Scott et al., 2000; Yang Y. et al., 2018). Tree recovery in highly disturbed rainforest areas in Queensland and abandoned pastures in Ecuador was further enhanced when exclosures or manual slashing were combined with controlled herbicidal treatments or enrichment planting, respectively (Palomeque et al., 2017; Uebel et al., 2017). Combining retention and mulching of logging residues on the degraded forest floor with conservation of resprouts at a high-density enhanced soil quality and forest regeneration in Alberta and across China (Cirelli et al., 2016; Wei et al., 2022; Xu et al., 2022). In three-year-old post-mining restoration sites in Brazil, relying solely on resprouts from residues was ineffective and needed to be complemented with enrichment planting (da Cruz et al., 2020). Restoring degraded dry forestlands can also be facilitated by combining area exclosures with soil moisture conservation structures like soil and stone bunds (Eshetie et al., 2021).

3.7 Cross-context application of ANR in ecological restoration, forest management, and integrated land management

There is ample evidence for the broad applicability and alignment of ANR with various modes of restoration, sustainable land management, and forest stand management across several tropical ecosystems and biomes (see Supplementary Table S2 for details). ANR interventions are most commonly implemented in the context of ecological restoration for recovering native ecosystems, biodiversity, and ecosystem functionality in degraded forestlands, shrublands, grasslands, pasturelands, watersheds, and corridors (Shono et al., 2020; Chazdon et al., 2023). Over 84% of the reviewed studies had specific ANR interventions implemented or experimented as an ecological restoration (ER) approach (Figure 7). Area exclosures, removal of competition from grasses, shrubs, and weeds, with or without enrichment planting with native species and creating artificial perches or seed trapping have been adopted to recover native tree density, species abundance, richness, diversity, forest structure, and myriads of ecosystem services in abandoned croplands, pasture fields, thornscrubs, post-mining sites and denuded forestlands across different tropical eco-regions. Approximately 34% of these ER articles also intersected with the forest regeneration and management (FRM) context, where assistance is given to facilitate natural regeneration and recovery and improve the stands of existing forested cover, often within the context of enhancing sustainable timber production.

ANR strategies aligning with the FRM context were identified in half of the studies, with about 14% exclusively centred on it. These interventions, including liana cutting, vine cutting, prescribed burning, fire control, fertilizer application, liberation by girdling or applying herbicides to control invasive tree species, and enrichment plantings, assist recovery in post-logging forests or post-agriculture secondary forests (Shoo and Catterall, 2013; Do et al., 2019; Stone et al., 2020; Wills et al., 2022). They aim to promote the establishment of the natural regeneration of usually scarce commercial local species, with better survival, growth, and adaptability to variable environmental conditions. ANR in the form of gap opening has been employed to accelerate the recruitment, growth, and density of native seedlings in logged-over rainforests in Southeast Asia, and it has been used to convert *Pinus* forests to native forest ecosystems in Brazil and Sri Lanka (Tuomela et al., 1996; Ashton et al., 1997; Coelho et al., 2021; Baul et al., 2023).

Other prominent approaches identified as ANR in forest management seek to improve edaphic conditions for natural regrowth and promote understory initiation after logging without having to sow seeds or plant seedlings. These techniques include soil harrowing (Rezende and Vieira, 2019), soil scarification (Negussie et al., 2008; Yamazaki and Yoshida, 2020), soil screening (Suzuki et al., 2021), topsoil replacement (Yoshida et al., 2023), litter transposition (Guerra et al., 2020), and residues retention (Xu et al., 2022). Residue retention

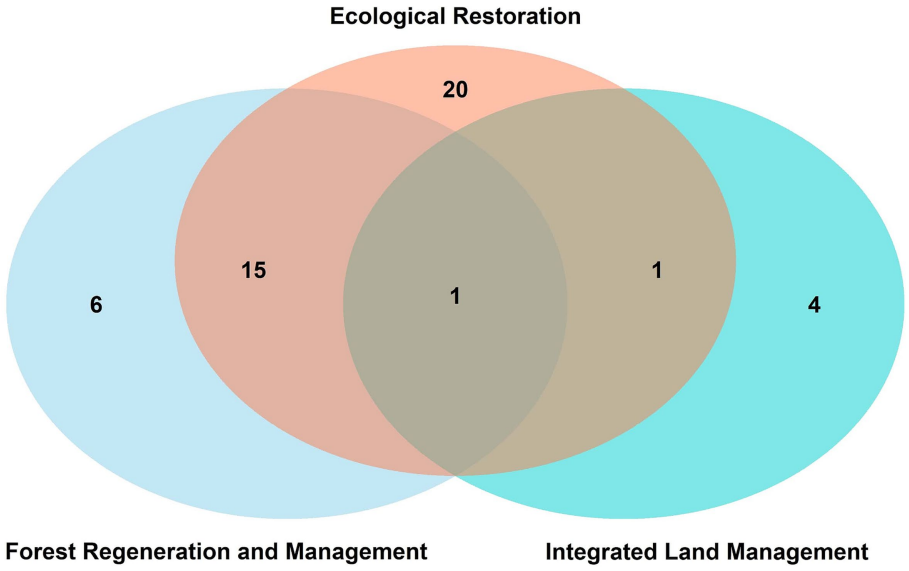

FIGURE 7
Distribution of ANR studies and interventions by implementation contexts (no. of studies = 44; total no. of cases = 47).

alone helped to recover and conserve resprouts at a density of over 6,000 seedlings per hectare in a logged-over forest in Fujian Province, outweighing active planting capacity and associated ecosystem benefits (Yang Y. et al., 2018).

The third context involves the regeneration of trees on farms and rangelands, aligning with Integrated Land Management (ILM), which aims to simultaneously facilitate food production, biodiversity conservation, ecosystem provision, and rural livelihoods (Estrada-Carmona et al., 2014). ANR interventions exemplifying this context include FMNR and on-farm tree planting. These encompass the protection, and management and planting of native multipurpose tree species, respectively, in agricultural and pastoral landscapes to improve productivity and livelihoods while conserving tree diversity and mitigating climate change effects (Brancalion et al., 2016; Reij and Garrity, 2016; Boukary et al., 2023). Approximately 14% of the analyzed studies fall under this modality, mainly in Sahelian Africa, where FMNR originated and is extensively practised. However, it is essential to note that the limited number of articles on ILM in this study does not imply its restricted application or research, as indicated by the synthesis of 30 studies with FMNR intervention by Chomba et al. (2020). Only a few studies have self-identified the intervention as ANR, while in some other cases, authors tried to distinguish them, as seen in Chomba et al. (2020). This study's findings confirm the wide applicability of ANR in various modes of restoration, sustainable land management, and forest stand management.

3.8 Cost analysis of ANR

Although ANR is acknowledged as a low-cost method for restoring degraded tropical forestlands, potentially offering benefits over conventional tree planting, its relative cost varies considerably and can be influenced by socioeconomic, ecological, and technical factors. Table 3 summarizes cost analyses from nine studies across nine tropical countries, adjusted for inflation to country-specific 2023 values. About 42% of cases ($n = 12$) used spatially explicit methods based on secondary financial datasets, while others relied on experimental economic analysis or expert estimates. The cost elements considered in implementing ANR typically include establishment, management, and opportunity costs (Molin et al., 2018; Wills et al., 2022). Establishment costs encompass direct expenses for fencing, weeding, constructing firebreaks, fertilization, patrolling, vine cutting, and covering the materials, transport, and labour involved. Additional management costs, covering annual maintenance, monitoring, and other transaction costs, are usually included for three years post-establishment to facilitate regenerant establishment (Dugan, 2011; Evans et al., 2015). Opportunity costs, often overlooked, are demonstrated through land rental costs for alternative agricultural activities like livestock and crop production or differences between their prices and forested land prices (Evans et al., 2015; Nunes et al., 2017; Molin et al., 2018).

Adjusted, estimated average ANR costs across countries varied, reflecting diverse restoration contexts, intervention types, and national economic conditions, including purchasing power and international currency exchange. These costs ranged from as low as US$57/ha in Niger to over US$14,000/ha in Laos, with a mean average of about US$1,263/ha, excluding Laos' extreme costs due to high inflation rates. It is important to note that this analysis did not aim to directly compare costs across countries given the factors above, but rather to reveal possible average costs of specific ANR practices within distinct contexts and countries.

Some comparative studies of ANR with active planting have projected substantial cost savings for ANR. For instance, ANR up to US$90.6 billion in the Brazilian Atlantic Forest compared to tree planting (Crouzeilles et al., 2020), or a 19–34% reduction in costs relative to other restoration scenarios (Molin et al., 2018). ANR demonstrated economic viability by doubling the potentially restored area at an average cost of US$776 million over 20 years through resprout protection and control of invasive species (Nunes et al., 2017). Restricting livestock grazing from native pastures through

TABLE 3 Cost analysis of ANR practices in tropical countries, and other original research articles used as the core evidence base for ANR interventions, costs, and contexts.

Average Cost (US$/ha)*	Country	Intervention	Ecosystem type	Analysis method	Context ***	Citation
57	Niger	FMNR: resprouts thinning & protection	Farmlands	Expert estimate	ILM	Reij and Garrity (2016)
101	Malaysia	Vine cutting, selective cutting of undesired species	Logged-over forest	Experimental	FRM	Elliott et al. (2023)
146**	Australia	Fencing	Native pastures	Spatial	ER	Evans et al. (2015)
448	Thailand	Firebreaks, patrols & grass pressing	Open woodland	Experimental	FRM, ER	Elliott et al. (2013)
719	Philippines	Firebreaks, weed pressing, 500 regenerants/ha	Open weedy sites	Experimental	ER	Dugan (2011)
815	Cambodia	Firebreaks, vine cutting. 6,950 regenerants/ha	Dense scrub	Experimental	ER	Elliott et al. (2023)
1,686	Brazil	Resprout protection (fencing) and weeding. 50–75 regeneration favourability range	Abandoned pasturelands with grasses	Spatial	ER	Nunes et al. (2017)
1,911	Tanzania	Vine/grass cutting; herbs/shrub cutting; lantana removal; firebreak	Degraded forest/savanna	Spatial	FRM, ER	Wills et al. (2022)
1,933	Brazil	Fencing, weeding and fertilization; enrichment planting. 41–70% regeneration probability	Abandoned croplands and pastures with grasses	Spatial	ER	Molin et al. (2018)
2,762	Thailand	Firebreaks, ring-weeding. 974–3,000 regenerants/ha	Open weedy sites	Experimental	ER	Elliott et al. (2023)
3,321	Brazil	Exclosures, facilitating seed supply from remnant forests (perches)	Abandoned agricultural and pasture lands	Spatial	ER	Crouzeilles et al. (2020)
14,607	Lao PDR	Firebreaks, vine cutting. 5,000 regenerants/ha	Dense scrub	Experimental	ER	Elliott et al. (2023)

*adjusted for inflation to country-specific 2023 values. **break-even carbon price (in US$/$tCO_2e$). ***Contexts or modalities of ANR interventions are categorised into three: FRM means "Forest regeneration and management", ER represents "Ecological restoration", and ILM stands for "Integrated land management".

fencing could sequester up to twice as much carbon as environmental plantings at lower carbon prices (Evans et al., 2015). Brancalion et al. (2019) indicated that ANR interventions, including clearing around naturally establishing trees and enrichment planting of native species that do not colonize regenerating sites, are over 80% less expensive than direct seeding and seedling planting in Brazilian biomes.

Estimated (comparative) costs and cost-effectiveness are influenced by time, land use history, opportunity costs, and implementation risks. ANR's relative cost-effectiveness is challenged by higher opportunity costs associated with passive restoration methods compared to active plantings, impacting forgone agricultural and pastoral land benefits, profitability from forestry and forest products, and landowner compensation and incentives (Shoo and Catterall, 2013; Molin et al., 2018; Ruggiero et al., 2019). The temporal dimension, land use types, restoration objective/benefits, and maintenance and opportunity costs can interact and challenge ANR's cost-effectiveness. This is seen in the reduction of carbon farming project durations in Australia (Evans et al., 2015) and Tanzania (Wills et al., 2022) and the impact of land opportunity costs, prominently in mechanized agricultural landscapes (Molin et al., 2018). Long-term risks and considerations, including uncertain restoration outcomes, slow growth and succession, and encroachment, may also limit ANR's comparative benefits and returns (Tamba et al., 2021).

3.9 Socio-economic benefits of ANR

ANR has the potential to contribute to rural livelihoods and socio-economic development across all contexts, albeit to varying degrees. FMNR is a notable ANR approach known for generating substantial socio-economic benefits, by fostering woody vegetations in crop fields and providing a range of timber and non-timber products to farmers. Assisted woody trees and shrubs play a crucial role in household economies, as farmers utilize them for local consumption or for sale (Belem et al., 2017). Firewood, charcoal, and other Non-Timber Forest Products (NTFPs) like wild leafy vegetables,

fodder, nuts, fruits, and medicinal products are commonly derived from assisted natural resprouts (Reij and Garrity, 2016; Chomba et al., 2020; Tiétiambou et al., 2020). Kpolita et al. (2022) reported that local farmers in the Central African Republic conserve and manage regenerating woody species in their parcels for utility for edible caterpillars, sawn timber, firewood, charcoal, and pharmacopoeia. In the Sahel region, commercializing NTFPs and timber from native trees conserved through FMNR initiatives, such as shea (*Vitellaria paradoxa*), African whitewood (*Triplochiton scleroxylon*), locust bean (*Parkia biglobosa*), baobab (*Adansonia digitata*), wild coffee (*Guiera senegalensis*), substantially contributes to household cash incomes (Binam et al., 2015; Reij and Garrity, 2016; Kpolita et al., 2022). Increased returns from forest products, attributed to effective protection of regenerating areas by fencing in Burkina Faso, contributed up to 23% of farmers' total gross profit and helped alleviate poverty (Belem et al., 2017).

When ANR is implemented for ecological restoration in fire-disturbed landscapes, it involves creating firebreaks often planted with cash and food crops, offering economic benefits to local restoration practitioners while contributing to the maintenance of the firebreaks. Such practices are viable incentives to encourage people to protect the restoration areas (Wilson et al., 2022). In other instances, remnant trees in restoration areas can provide shade for economic plants, as seen in ANR restoration projects in Brazil, where yerba mate (*Ilex paraguariensis*) – a native tea plant – and Brazil nut (*Bertholletia excelsa*) were cultivated under the shade of protected trees for income generation for local communities (Alves et al., 2022; Chazdon et al., 2023). Lastly, the overarching goal of ANR in the regeneration and management of logged-over forests is typically to facilitate stock recovery for timber and pulp production, carbon sequestration and offset projects, and other commercial purposes. Retaining residues and removing weeds in a logged-over forest in China increased tree stock density to 4,500 stems per hectare (Yang Y. et al., 2018). Simulations by Tamba et al. (2021) found that area exclusion or enrichment planting could help regenerate a degraded dry forest in Ethiopia, with potential returns of up to 30,000–50,000 USD over 25 years.

4 Opportunities for future research in ANR

Despite the recent increase in ANR research, relatively less emphasis has been placed on the social aspects of these diverse restoration interventions. Figure 4B highlights that the ecological outcome of ANR has received more research attention. Social and economic themes, such as *livelihoods*, have only recently gained attention, albeit with limited prevalence across most ANR research. This finding aligns with Uriarte and Chazdon (2016) who identified relative economic and livelihood outcomes of passive restoration interventions, as well as their trade-offs and synergies with ecological outcomes, as key research gaps in incorporating (assisted) natural regeneration into tropical FLR. Assessing the true economic value of ANR benefits, which mostly entail environmental/ecological services rather than timber and non-timber products with existing clear market prices, is often a challenge. Common barriers to the adoption, sustained implementation, and expansion of ANR in local communities include opportunity costs for productive land uses and land or tree tenure insecurity (Wilson et al., 2022; Chazdon et al., 2023). Addressing these socio-economic challenges requires dedicated research efforts.

Recent concerns and the growing need for research emphasize the importance of justifying the cost-effectiveness and carbon potential of ANR, along with assessing effective policies and legal frameworks, governance structures, financial and incentivization mechanisms, and efficient monitoring systems to foster ANR (Uriarte and Chazdon, 2016; Chazdon et al., 2020a). Adequately tracking and facilitating communication regarding the additionality of socio-ecological impacts of ANR implementation requires dedicated research. Therefore, use of diagnostic tools to effectively identify and map target areas for ANR, and incorporating ANR into FLR spatial prioritization frameworks are crucial (Uriarte and Chazdon, 2016). These gaps present opportunities for future research directions that could promote ANR mainstreaming into large-scale ARR and FLR projects.

5 Limitations

This study's language scope was limited to English, and the search terms employed may have lacked the sensitivity or flexibility needed for absolute precision. Despite these constraints, the study adopted an inclusive approach by incorporating various document types and utilizing two databases – Web of Science and Google Scholar. This strategy aimed to broaden the scope of literature coverage, address the inherent weaknesses of each database, and enhance the overall significance of the findings (Ekundayo and Okoh, 2018; McNicholas et al., 2022). Bibliometric studies may face challenges in recognizing emerging themes and recent research focus due to the low frequency of appearing keywords (Ekundayo and Okoh, 2018). To mitigate this limitation, the study complemented the bibliometric analysis with more narrative systematic review. This mixed-methods approach aimed to minimize bias in content judgement and avoid the inadvertent exclusion of important results (Ramanan et al., 2020).

6 Conclusion

The bibliometric analysis spanning from 1987 to 2023 highlights the growing global recognition of Assisted Natural Regeneration (ANR) as a versatile restoration strategy. ANR research is gaining momentum globally, challenging historical tendencies within the restoration and scientific community to overlook the outcomes of restoration methods centred around natural regeneration (Chazdon et al., 2021). This is evident in initiatives such as the recent Pará state revegetation plan (Government of Pará, 2023) and newly developing restoration concessions within Brazil's National Forest System, where ANR constitutes a substantial component.

The literature synthesis revealed diverse ANR publications by hundreds of international authors, reflecting multidisciplinary engagement and signaling expectations of rapid future development. Brazil leads in ANR research and implementation, underscoring active involvement by low- and middle-income countries in ecological restoration. Despite a relative paucity of emphasis on crucial socio-economic aspects such as livelihoods and policies, the systematic review identified a variety of less-intensive ANR interventions aligning with forest regeneration and management, ecological

restoration, and integrated land management, offering both social and ecological benefits. Common interventions include weed cutting, fencing, firebreaks, climber or vine removal, and enrichment planting, with observed geographical trends. There is considerable variability in the costs of ANR, averaging US$1,263/ha, influenced by factors such as time, land use history, type of interventions, and the consideration of long-term maintenance, opportunity costs and associated risks in the cost evaluation.

Author contributions

TO: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. RC: Conceptualization, Investigation, Supervision, Validation, Writing – review & editing. LO: Funding acquisition, Supervision, Validation, Writing – review & editing. NG: Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing. JH: Funding acquisition, Supervision, Validation, Writing – review & editing.

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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.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2024.1412075/full#supplementary-material

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