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Review

Toward Understanding Research Evolution on Indirect Drivers of Ecosystem Change along the Interface of Protected and Non-Protected Lands

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Abstract: Against a backdrop of rapid environmental degradation and increasing pressures on natural resources, a broad list of innovations has emerged to support the vision of the post-2020 Kunming-Montreal Global Biodiversity Framework and strengthen regional and country-level biodiversity strategies along the interface of protected areas and non-protected lands. The success of these strategies depends in large part on science-informed consideration and approaches to the underlying and indirect drivers of change for natural systems and ecosystem services. This paper aims to inform future strategies and action plans for conservation efforts and sustainable practices globally and regionally, with a specific focus on Latin America's environmental challenges. Bibliometric analysis, covering two decades from 2003 to 2023, focused on global and Latin American research trends related to the indirect drivers of change for natural systems and ecosystem services at the interface of protected and non-protected lands. Through structured analysis, key opportunities for increased collaboration, impact, and research focus are identified, highlighting the need to expand research collaboration strategies and reach, enhance research dissemination through open and equitable innovations, and strengthen capacity to the complex and interrelated challenges underlying accelerated change in natural systems, which affects biodiversity and ecosystem services.

Keywords: indirect drivers of change; natural systems; biodiversity; post-2020 Kunming-Montreal Global Biodiversity Framework; socio-ecological systems; protected areas; conservation; ecosystem services; Latin America; sustainable development

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1. Introduction

Against a backdrop of rapid environmental degradation and increasing pressures on natural resources, the post-2020 Kunming-Montreal Global Biodiversity Framework (GBF) envisions a world where biodiversity is valued, conserved, restored, and wisely used by 2050, maintaining ecosystem services and delivering essential benefits for all people [1,2]. This vision aims to protect ecosystems' integrity, connectivity, and resilience, promote sustainable biodiversity management, and ensure fair benefit-sharing while enhancing ecosystem functions and services for the well-being of both people and the environment [2]. The framework calls for immediate action to stop and reverse biodiversity loss, tackle biodiversity threats, and enhance the sustainability of human–wildlife interactions to create a nature-friendly world that fosters harmony between humans and nature [2]. It focuses on strengthening regional and country-level biodiversity strategies and action plans, advocating for place-based approaches that extend and complement traditional top-down protected area (PA) models and a mainstreaming of biodiversity policy across a wider range of sectors that can affect its success [2,3].

A broad list of innovations has emerged for consideration within local GBF strategies including nature-based solutions (NbS), other effective conservation measures (OECM), area-based conservation, PA buffer zone approaches, biological corridors, and new forms of participative governance, management, and outcomes monitoring [1,3–12]. This expanded focus, along with enhanced monitoring and tracking emphasis, have led to praise for the GBF as being more ambitious, comprehensive, precise, and measurable than prior international biodiversity agreement [1,13,14]. Nevertheless, evaluators have also observed that the GBF's success will depend, to large degree, on finding feasible and equitable solutions for adequate funding, mainstreaming biodiversity policies across relevant sectors, accelerated capacity-building, integration with large-scale and local Climate Change adaptation and mitigation agreements, and effective technology transfer [1,3,13–16]. Thus, continued exploration of the interconnectedness between ecosystems, biodiversity, and human well-being is justified, especially in the context of the innovations that are emerging to complement traditional top-down PA models [17].

For instance, Latin America (LA) is home to approximately 40% of the world's biodiversity and boasts over 8.8 million square kilometers of protected areas [18,19]. Despite these natural riches, the region is confronted with escalating environmental degradation stemming from a complex mix of natural, social, technological, economic, and political factors [18–26]. The integration of science-based policies, strategies, and decision-making processes, along with the innovative approaches prompted by the Global Biodiversity Framework (GBF), hold significant relevance for this region. However, substantial disparities in research funding, capacity building, research output, and knowledge dissemination, in comparison to many European, Asian, and North American nations, impede access to the necessary expertise and resources for informed, science-driven decision-making [27,28].

This study hopes to contribute to the GBF vision for accelerated and equitable capacity building through timely research that can inform global and regional research agendas, strategies, and action plans [2]. It presents bibliometric analysis intended to enrich understanding of how science has approached the indirect drivers of change for natural systems and ecosystem services at the interface of protected and non-protected lands over the two decades between 2003 and 2023.

1.1. Anthropogenic Drivers of Change for Natural Systems and Ecosystem Services

The relationship between science and policy has grown increasingly intricate since the inception of the United Nations Convention on Biological Diversity (CBD) international treaty in 1993 [29]. Understanding and addressing the connections among ecosystems, biodiversity, and human well-being have been central themes in global biodiversity research and policy development. Seminal works such as the 2005 Millennium Ecosystem Assessment (MEA) and the 2019 Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES) Global Assessment Report on Biodiversity and Ecosystem Services have significantly influenced this field [1,30–36]. Anthropogenic (i.e., human-induced) drivers of natural and ecosystem service change are one of the core concepts within both of these works [30–33].

The distinction between direct and indirect drivers of ecosystem change is fundamental in environmental studies [37,38]. Nevertheless, the MEA emphasized the interconnectedness of direct and indirect anthropogenic drivers of ecosystem change, highlighting the complex role these drivers play in shaping natural systems and impacting human well-being [39,40]. Direct drivers, such as land-use change, species exploitation, climate alteration, pollution, and invasive species introduction [33], have been extensively studied, as evidenced by multiple reviews of research trajectories, both at a global level and for distinct regions and ecosystems [20,33,41–44]. In contrast, indirect drivers encompass broader social, economic, political, and technological factors that influence or modify direct drivers of ecosystem change [33]. Factors like socio-economic trends, demographic changes, government policies, and cultural values significantly impact human–nature interactions and ecosystem services [33,41].

The IPBES 2019 Global Assessment Report on Biodiversity and Ecosystem Services built on previous research and understanding of the drivers of natural system change [30,31,36]. The report increased focus on concepts related to the indirect drivers, including the diversity of world views underlying interactions between humans and nature and the many ways in which humans value nature and nature's contributions to people [36]. IPBES emphasized intrinsic, instrumental, and relational values, evolving the MEA's concept of ecosystem services toward a more expansive view of nature's contribution to people (NCP), which embraced a more inclusive and diverse interpretation [1,30–34,36]. Their findings acknowledged the critical role that indirect drivers play in the future of biodiversity and its contributions to human well-being [30,31].

Acknowledging the crucial influence of both direct and indirect drivers on the trajectory of biodiversity and human well-being, researchers have called for a comprehensive research approach to address these drivers [3,30,31]. For example, Cardona Santos et al.'s (2023) study of eight national biodiversity strategies called for continued exploration of indirect drivers of change for natural systems and ecosystem services [3]. The authors presented a range of factors, including the impact of broader social, economic, political, and technological factors; the importance of societal values, behaviors, production, and consumption patterns that contribute to biodiversity loss; the role of collaborative structures, policy designs, and educational campaigns; and the influence of trade practices and technological advancements [3]. Ongoing exploration of both direct and indirect drivers of change for natural systems and ecosystem services is one of the central tenets in sustainability research [3,30,31], informing the development of strategies to conserve biodiversity and promote sustainable human–nature relationships [3,41,43,44].

1.2. The Importance of Improving Understanding of the Indirect Drivers of Change in Nature along the Interface of Protected and Non-Protected Lands

Guerra et al. (2019) highlight the importance of investigating indirect drivers of change related to the interface processes between protected and unprotected areas [45]. Their global study, spanning 1992–2015, revealed significant differences in land cover change rates within and around Protected Areas (PAs). While areas within the World Database of Protected Areas experienced a land cover change rate of 3.91% during the study period, the rate in the areas within a 5 km buffer surrounding these PAs was notably higher at 6.02% [45]. Understanding the factors contributing to these heightened rates of land cover change is crucial, especially in light of the GBF's emphasis on OECMs and area-based conservation strategies for extending the potential of traditional PA conservation approaches [4–10,12,46].

Blanco et al.'s (2020) global review of research related to interface processes between protected and unprotected areas underscored the incomplete understanding of PAs as social-ecological systems. Their study highlights conflicts within and around PAs resulting from challenges related to aligning local conservation efforts with affected communities [47]. Findings emphasized human activities motivated by social, economic, and technological forces. These indirect drivers manifested as road expansion, amenity-based migration, subdivision, urbanization, industrialization, and agricultural expansion (amongst others), in the areas of interface between PAs and surrounding territories [47]. Additionally, they discussed PA governance and relationships with local communities in the context of political and social influences on conservation actions. They identified several future research priorities, emphasizing the importance of integrated research methods that combine social and biophysical data to explore the influence of social, economic, political, and technological factors on conservation policies [47].

1.3. Equitable Access to Resources and Knowledge: The Importance of Understanding the Latin American Context

The GBF promotes equitable and accelerated technical and scientific cooperation, capacity building, and development [17]. It stresses the necessity of adopting strategic and coherent approaches to support the effective implementation of the convention and its protocols, recognizing the challenges faced by many parties, particularly those in developing countries and regions, due to capacity limitations. Consequently, the GBF advocates for enhanced technical and scientific cooperation and the facilitation of research collaboration to ensure the effective generation and utilization of essential scientific and analytical information [17].

LA, which encompasses the entire continent of South America, as well as Mexico, Central America, and the Caribbean islands, occupies a unique position on the global stage, standing out for its exceptional natural wealth that includes approximately 40% of the world's biodiversity, 31% of the world's freshwater resources, and 45% of the world's forests and hosts around 8–9% of the world's population [18–26]. The region's diverse ecosystems, from the Amazon rainforest to the Andean mountains and the Galapagos Islands, are not only home to a vast array of plant and animal species but also provide critical benefits that support human well-being and the global environment [18,19,21]. According to the 2020 Protected Planet Report for the LA and Caribbean region, terrestrial and marine PAs cover more than 8.8 million square kilometers, representing 24% of the terrestrial territory and 18.9% of marine and coastal zones [19].

Nevertheless, LA faces significant challenges due to rapid environmental degradation and mounting pressures on natural resources [18,20–26,44]. One of the shortcomings currently faced by the region involves connectivity between PAs. As of 2020, around a third of the national PA systems in LA and the Caribbean functioned as conservation "islands", without the connectivity required to adequately protect biodiversity and ecosystem services [19]. PA management and governance have also been problematic within the region. Close to 60% of PAs are managed through government top-down systems that tend to be underfunded, non-transparent, and lacking in management effectiveness [3,19]. The rest are under diverse forms of governance (e.g., private, Indigenous peoples, local communities, shared governance) but often lack the legal and operational mechanisms they need to effectively function [19,48]. Additional challenges faced by the region involve integrating Protected Areas (PAs) into broader landscapes and seascapes through coordinated land-use planning, development, and monitoring. Moreover, clear strategies and management processes are needed to identify and integrate OECMs effectively [3,19].

Given the importance of LA's nature for biodiversity and human benefits, the current challenges faced within the existing PA paradigm of the region, and the GBF vision of equitable access to research and capacity-building, better understanding of the dynamics occurring in the spaces that surround PAs, at a global level and in LA, may help inform action plans and strategies to improve connectivity, shared governance, and OECMs.

1.4. Research Purpose

This study seeks to enhance understanding of how science has addressed social, technological, economic, and political indirect drivers of change for natural systems and ecosystem services along the interface of protected and non-protected lands. The research identifies global trends and examines research patterns for LA institutions and collaborators. By analyzing the dynamics surrounding global and LA PAs, the study may inform GBF strategies for enhancing connectivity, shared governance, and OECMs in the LA region and beyond. Through bibliometric analysis spanning two decades from 2003 to 2023, the study addresses three research questions (RQs):

- RQ1: How has knowledge been disseminated within academic channels over the past two decades?
- RQ2: Which countries, institutions, networks, and authors have contributed to knowledge during this period?
- RQ3: How has research and thinking evolved over the past two decades?

2. Materials and Methods

Bibliometric analysis provides a structured framework to explore scholarly output, collaboration patterns, and research impact, offering valuable insights into how research and knowledge is created, evolves, and is disseminated [28,49–61]. By harnessing bibliometric techniques like citation analysis, keyword mapping, author affiliation network analysis, and trend identification, research can uncover underlying patterns, highlight research themes, and provide a comprehensive overview of the scholarly landscape [51,56]. Drawing on the insights gleaned from prior literature on the significance of bibliometric research in academia, particularly in predicting future research themes and supporting decision-making processes, this methodological approach serves as a powerful tool for elucidating the evolving research landscape and facilitating strategic advancements in the realms of landscape ecology and conservation science [56–62].

Informed by the traditional bibliometric research approach [57,58] and the advice of Donthu et al. [51] and Öztürk et al. [54], the research process for this project involved a five-stage approach, as outlined in Figure 1.

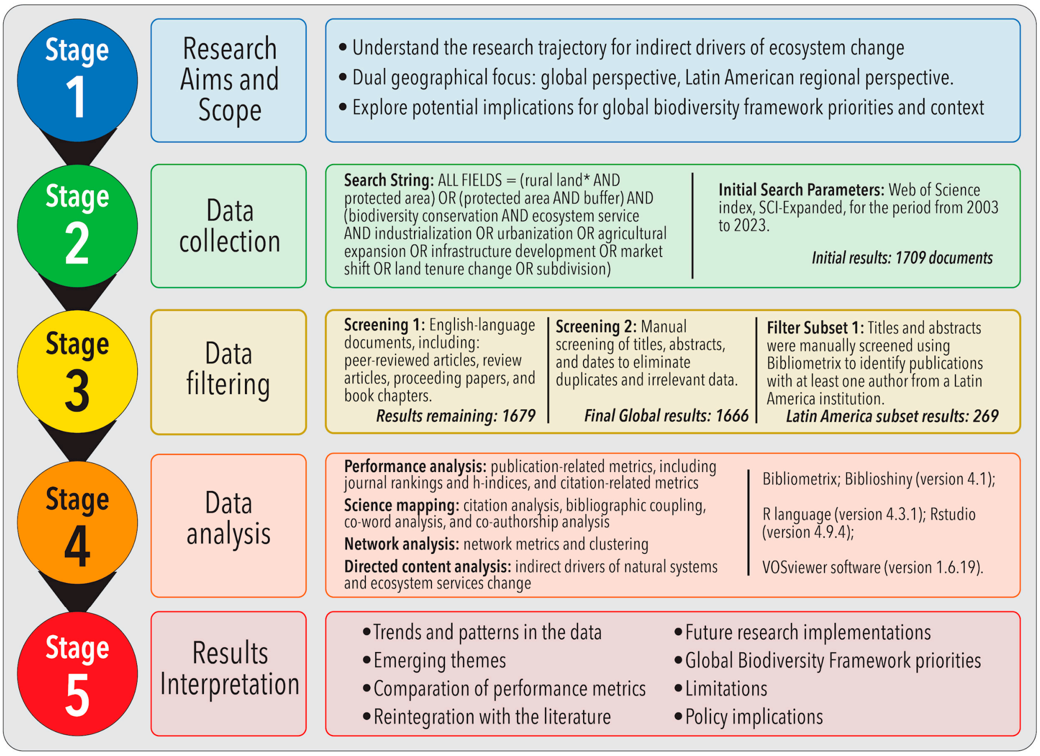


Figure 1. Research design and workflow diagram.

Stage One, "Research Aims and Scope", reviewed existing research and policy to identify research gaps and needs to inform the research aims and scope of the bibliometric approach, as described in Section 1.4 Research Purpose [54].

Stage Two, "Data Collection", operationalized the research aims and scope through an iterative data collection strategy (Figure 1). Following the guidelines proposed by Grames et al. [52], the initial naive search developed for this research was based on the research aims and results of literature reviews [3,30–33,40,47]. Concept groups were then identified, representing the study system (e.g., protected areas, rural lands, buffer zones), interventions (e.g., common social, technological, economic, and political indirect driver manifestations), and outcomes (e.g., biodiversity conservation, ecosystem service).

Next, based on prior experience and literature, an initial list of search terms was developed to fit the concept groups, including keywords like " industrialization", "urbanization", "agricultural expansion", "tourism", "amenity migration", "infrastructure development", "market shift", "land tenure change", "subdivision", "30 × 30," "conservation," "biodiversity", "ecosystem" "ecosystem service", and "natural system". These terms were combined within several pilot search strings and tested using a search of the Web of Science (WOS) platform. Following iterative experiments, the initial search string was modified to reduce ambiguity and better incorporate the concepts of lateral thinking (synonyms) and vertical thinking (different levels of terms) [55,63,64].

The refined, search formula was as follows: ALL FIELDS = (rural land* AND protected area) OR (protected area AND buffer) AND (biodiversity conservation AND ecosystem service AND industrialization OR urbanization OR agricultural expansion OR infrastructure development OR market shift OR land tenure change OR subdivision). In the context of Web of Science, utilizing the "All Fields" search option enables a comprehensive search that encompasses various metadata fields within the database's records. When conducting a search using "All Fields", the search includes fields such as title, authors, abstract, author keywords, Keywords Plus, bibliographic information, cited references, document types, source titles, and addresses and affiliations. This method ensures a thorough exploration of potential locations where the search term may appear, increasing the chances of finding all relevant articles. Additionally, analyzing term frequency or concepts across all fields provides a more comprehensive understanding of research trends while also aiding in pattern detection for broad patterns and trends that may not be apparent when the search is limited to specific fields like the title or abstract [54,65]. Data collection took place in June 2024, utilizing the Web of Science database to ensure article quality [56,62,66] and the "SCI-Expandex" filter, for the period covering 2003 to 2023. This process resulted in the identification of 1709 records.

Stage Three, "Data Filtering", involved two screening stages and the creation of the LA subset. Initial screening focused on identifying English-language articles within the categories of article, review article, proceeding paper, and book chapter, reducing the database to 1679 records. Titles and abstracts were manually screened to eliminate duplicates and irrelevant data [58,59,66]. The search results were exported as complete records in plain text file (.txt) format, containing DOI, authors, titles, publication year and month, journal, author contact information, abstract, and references [54,58]. Following this screening process, a final selection of 1666 publications meeting the inclusion criteria was obtained, representing publications from institutions around the world.

The LA subset was developed by filtering for the publications that included at least one author from an institution in LA, yielding 269 publications [28,49,50,53]. For the purposes of this study, LA consisted of the 29 countries that included the entire continent of South America, as well as Mexico, Central America, and the Caribbean islands whose inhabitants speak one of the Romance languages (i.e., Argentina, Belize, Bolivia (Plurinational State of), Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, French Guiana (department of France), Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Martinique, Mexico, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint-Barthélemy, Saint-Martin, Suriname, Uruguay, and Venezuela (Bolivarian Republic of)) [67].

Stage Four, "Data Analysis", involved performance analysis, science mapping, network analysis, and directed content analysis [28,49–55]. Analysis and visualization of the cleaned dataset employed the Bibliometrix and Biblioshiny (version 4.1) software packages, in conjunction with the R language (version 4.3.1) and Rstudio (version 4.9.4) and VOSviewer software (version 1.6.19). Performance analysis (e.g., publication-related metrics, citation-related metrics, and publication–citation combined metrics) provided insights about the global and LA research constituents. Science mapping (e.g., citation analysis, co-citation analysis, co-word analysis, and co-authorship analysis) illuminated the relationships between these constituents [51]. Network analysis (e.g., network metrics and clustering) helped enrich the prior techniques to understand the relative importance of research institutions, countries, and collaborations [51]. Full text review of the top twenty documents in the global sample, based on total citations, employed directed content analysis techniques to achieve additional insights about the study of indirect drivers of change in natural systems and ecosystem services around PAs over the past two decades [68].

Stage Five, "Results Interpretation", employed the outputs produced through the Bibliometrix and Biblioshiny (version 4.1) software packages, in conjunction with the R language (version 4.3.1) and Rstudio (version 4.9.4) and VOSviewer software (version 1.6.19) [52,57].

Interpretation focused on the trends and patterns in the data including key contributors, influential works, and emerging themes. Comparison of performance metrics across different entities (e.g., researchers, institutions, or journals) facilitated assessment of the relative impact and productivity across the global sample and LA subsets. Then, results were reintegrated with the literature to identify potential implications for future research, global biodiversity framework priorities, and context. Visualization outputs were later adapted, using Adobe Illustrator, to best illustrate the comparative approach of the study. This integrated approach provided a comprehensive overview of research trajectories regarding the indirect drivers of change for natural systems and ecosystem services in areas surrounding PAs.

3. Results

The results presented in this section begin with a brief description of the general sample characteristics, followed by evidence that emerged for the three primary research questions.

3.1. General Research Trends

The final global sample for this study consisted of 1666 documents published between 2003 and 2023, drawing on 87,996 reference materials. LA-affiliated collaborators were co-authors for 269 of these documents (16.15%), citing 16,831 references (19.13% of the total reference materials). The dataset documents were distributed through 474 different research outlets (academic journals, publishers, academic conferences, etc.) in several formats, including 1570 peer-reviewed WOS journal research articles, 65 peer-reviewed WOS literature review articles, 26 conference proceeding papers, and 5 book chapters. The LA subset documents were distributed within 151 (31.86%) of the publishing outlets represented in the study. LA-affiliated co-authors participated in 250 peer-reviewed WOS journal research articles, 13 peer-reviewed WOS literature review articles, 5 conference proceeding papers, and 1 book chapter. In total, 927 (55.6%) documents were classified as "open access", meaning that there was no charge or special subscription needed to access their content. Open-access documents were published from 307 of the total 474 publishing outlets (64.76%). One hundred and fifty-three LA subset documents were classified as "open-access" (56.9%). The global dataset garnered a total of 46,489 citations, ranging from 0 to 1076 per article, with a mean of 27.9 citations per article. LA subset documents earned a total of 7214 citations, which represented 15.5% of the overall global dataset citations. These citations ranged from 0 to 422 per article, with a mean of 26.82 citations per article.

A total of 8863 authors, affiliated with institutions from 125 countries, contributed to the documents in the global dataset. On average, there were 5.83 co-authors per document within the global dataset, and more than forty percent (42.32%) of the documents included international collaboration. Higher levels of article collaboration were observed within the LA subset, with 8.7 co-authors per article and international collaboration for close to 60% of the overall number of studies (57.99%). Specifically, the subset articles involved a total of 2226 co-authors, with affiliations spanning 68 countries, including 16 countries located within LA. The majority of authors contributed to a single article (4031, 87.3%), while 587 authors repeatedly collaborated over the study timeframe with contributions to multiple articles.

3.2. Academic Knowledge Sharing and Distribution

Figure 2 illustrates the publication trends for both the global samples and the LA subset from 2003 to 2023. On average, there were 79.33 articles published per year within the global dataset and 12.81 per year within the LA subset. The temporal trends for the global dataset suggest three distinct periods of research activity. An initial exploratory phase spanned the years between 2003 and 2010, during which the annual article gradually crept from 11 in 2003 to 49 in 2010, when the Aichi targets were reached. Subsequently, from 2011 to 2016, there was a notable acceleration in global research output, with annual article numbers ranging between 52 and 92. Most recently, beginning in 2017 and extending through 2023, the number of annual articles surged to between 103 and 188 per year. This level of consolidated focus may coincide with major research efforts, like the IPBES Global Assessment Report on Biodiversity and Ecosystem Services (2019) [30,31], the 2020 Aichi thresholds, and subsequent research to support the development of the GBF [2].

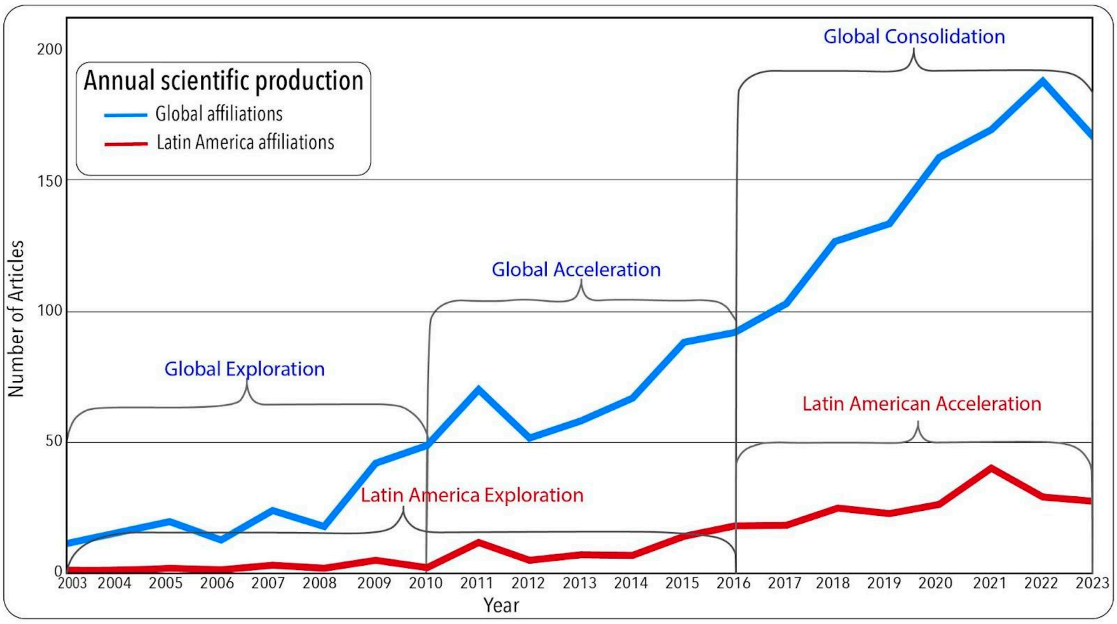


Figure 2. Annual scientific production trends from 2003 through 2023.

In contrast, research growth in the LA subset appeared less robust and pronounced (Figure 2). The first article within the subset was published in 2003, and up to 2008, authors affiliated with LA institutions published fewer than three articles per year. While annual production increased slightly from 2011 to 2015, ranging from five to fourteen articles per year, overall trends suggest a longer exploratory phase in this region of the world. Similar to the global tendencies, there was a peak in production in 2011, following the establishment of the Aichi targets. From 2016 forward, publication numbers steadily increased, with annual production ranging between 18 and 40 articles, suggesting a period of accelerated research attention.

Throughout the study period, the journals that published the highest number of related articles were Sustainability (105 articles), which began coverage around 2014, followed by Landscape and Urban Planning (44 articles), whose coverage began much earlier, in 2004. Biological Conservation and Journal of Environmental Management each published 42 articles, although the Journal of Environmental Management's coverage began in 2003, two years prior to Biological Conservation's initial coverage in 2005. Science of the Total Environment was the fifth most important global journal in terms of coverage, with 37 published articles, beginning in 2010. Although their order within the top five differed, the same top journals in terms of global coverage were also the five highest ranked in terms of impact, with h-indices ranging between 18 and 26, (Figure 3, Table 1).

Sustainability provided the highest coverage for articles within the LA subset, publishing a total of 15 articles between 2008 and 2023. Biological Conservation's coverage in the LA subset began in 2007 and totaled eight articles by 2023, while PLOS One, also with a total of eight articles, began coverage in the LA subset much later, in 2013. Three other journals, Tropical Conservation Science, Journal of Environmental Management, and Journal for Nature Conservation, published a total of seven articles each within the LA subset, beginning in 2011, 2014, and 2017, respectively. The highest-ranking journals with the LA subset were Biological Conservation and the Journal of Environmental Management, with h-indices of 22 and 21, respectively. Tropical Conservation Science (h-index = 7) was ranked lowest in terms of impact amongst the top journals for LA subset production.

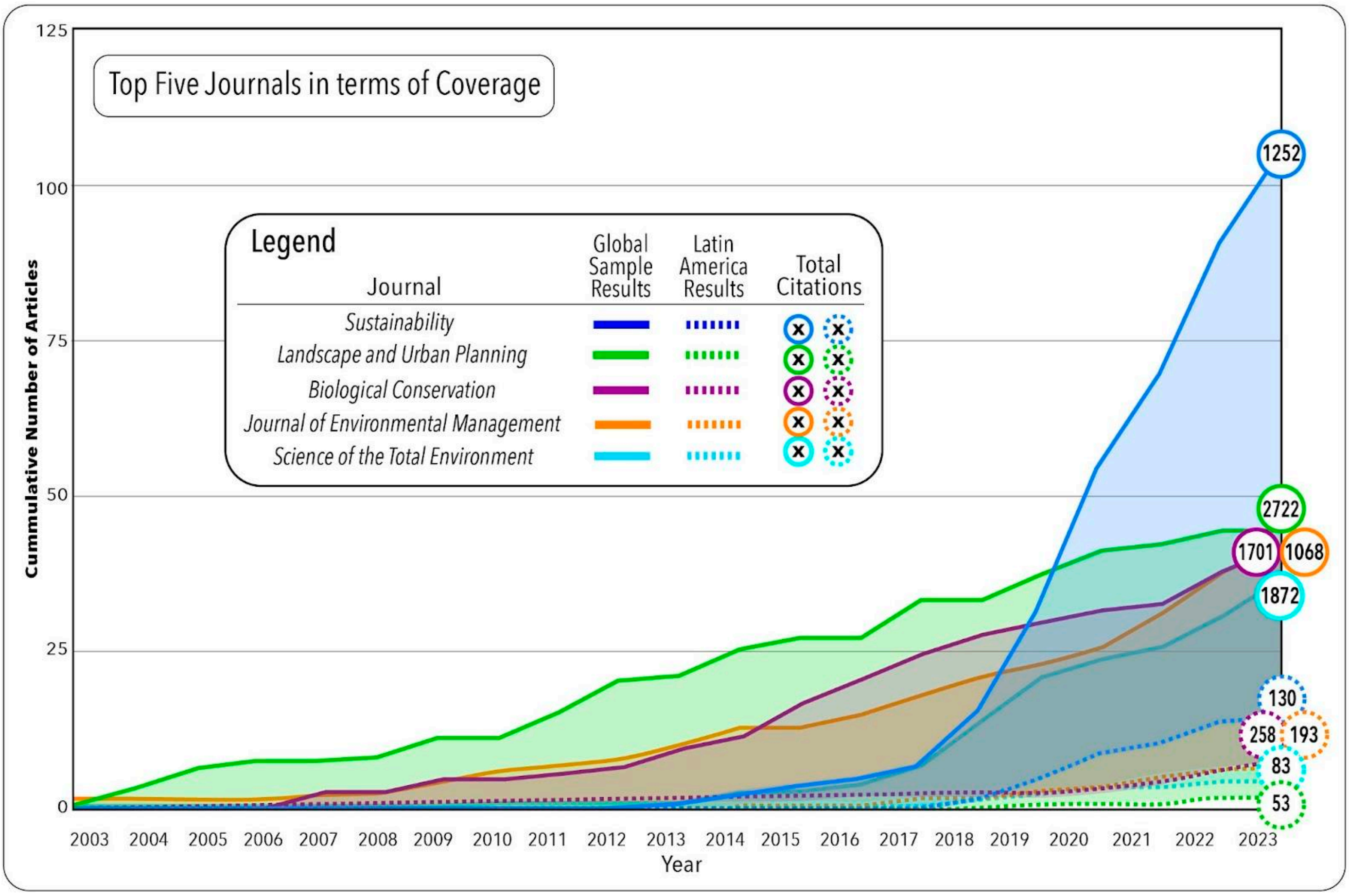


Figure 3. Journal coverage and total citations from 2003 through 2023 for the top five journals in terms of overall publications.

Table 1. Top 20 journals, ranked by the number of global publications, with total citations, h-index scores, and comparative information for the Latin America subset.

Journal Name	Global Articles	Total Global Citations	LA Articles	Total LA Citations	h-Index
Sustainability	105	1252	15	130	18
Landscape and Urban Planning	44	2722	2	53	26
Biological Conservation	42	1701	8	258	22
Journal of Environmental Management	42	1068	7	193	21
Science of the Total Environment	37	1866	5	83	20
PLOS One	33	838	8	215	15
Ecological Indicators	31	1031	1	3	16
Biodiversity and Conservation	30	980	6	350	16
Forest Policy and Economics	24	491	2	25	14
Conservation Biology	23	2157	2	323	18
Remote Sensing	23	420	1	10	10
Forests	23	279	0	0	10
Landscape Ecology	21	730	3	207	16
Environmental Management	20	476	5	117	13
Environmental Conservation	19	682	4	110	14
Environmental Monitoring and Assessment	19	331	0	0	9
Global Ecology and Conservation	19	308	1	42	11
Journal for Nature Conservation	19	279	7	80	11
Scientific Reports	18	484	2	112	9

Note: The h-index [69] is a quantitative indicator used to assess the quantity and quality of academic output. A higher value indicates a greater impact of the journal in the field.

3.3. Research Contributors, Affiliations, and Network

At a country-level, researcher collaboration occurred through three interconnected clusters (Figure 4). The red cluster demonstrated the strongest levels of collaboration, particularly involving the USA, UK, Germany, and Australia. These countries collaborated with other red cluster researchers from various Asian and African countries, as well as the LA country of Peru. The main red cluster countries (USA, UK, Germany, Australia) often interacted with countries situated in the blue cluster, including China, Canada, Switzerland, South Africa, and Brazil. Within the blue cluster, the highest levels of collaborations occurred between researchers from China, Brazil, and Switzerland. Additionally, blue cluster collaborations extended to countries around the world, including Canada, the Netherlands, India, several African countries (Kenya, South Africa, Ethiopia, and Ghana), and various LA countries (Mexico, Argentina, Chile, and Colombia). The third cluster (green) centered around Spain, reaching across Europe and beyond. Cluster participants included researchers from Nordic countries (Sweden, Norway, and Finland), Central and Eastern European countries (Hungary, Poland, Romania, Czech Republic, and Russia), other European countries (France, Italy, Portugal, and Greece), and Middle Eastern countries (Turkey and Iran).

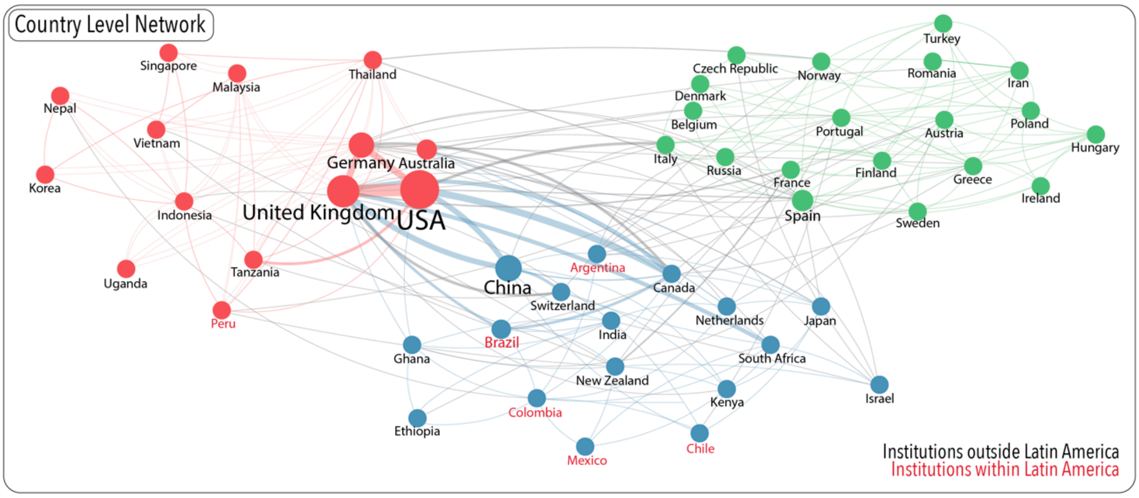


Figure 4. Interrelated clusters of the country-level cooperation network. Different node colors indicate different clusters. Latin American countries are labeled with red text.

Figure 5 shows where the 1666 articles in the global dataset were authored, based on the country affiliations of the corresponding authors. Of the 8863 researchers in the dataset, authors from 91 out of 125 countries (representing 72.22% of the total) acted as corresponding authors. The top affiliations for corresponding authors were from the USA (236 articles, 14.17%), China (233 articles, 14%), and the UK (149 articles, 8.9%). In the dataset, authors from Latin America (LA) were corresponding authors for 186 articles (11.16%), with the majority (62.37%) affiliated with institutions in Brazil (116 articles, 6.96%).

Global dataset authors were affiliated with 1748 different institutions from 125 different countries worldwide (Table 2). Among these, 28 institutions from 14 countries in Asia, Europe, and the Americas had 25 or more author affiliations in the global dataset. For example, the Chinese Academy of Sciences (CAS) had 149 affiliations, the University of California System in the USA had 49 co-author affiliation instances, and the French National Center of Scientific Research (CNRS) had 47 instances. Several LA institutions featured prominently, including the University of São Paulo (Brazil) with 36 affiliation instances, the National Autonomous University of Mexico with 33 instances, and the Argentine National Scientific and Technical Research Council (CONICET) with 25 instances.

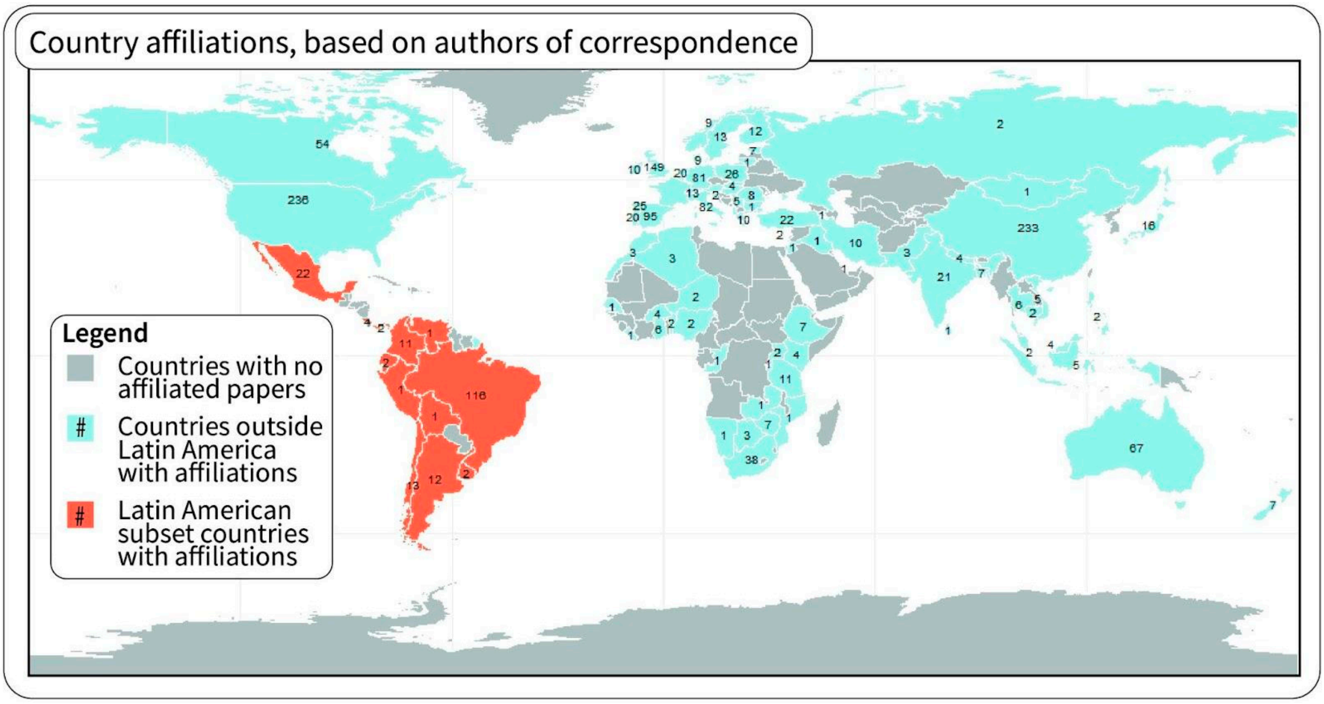


Figure 5. Global distribution of country affiliations for the articles, based on authors of correspondence and number of articles per country.

Table 2. Co-author institutional affiliation instances within the global dataset.

Rank	Institution	Document Affiliations
1	Chinese Academy of Sciences (CAS)	149
2	University of California System, USA	49
3	French National Centre for Scientific Research (CNRS)	47
4	Wageningen University and Research, Netherlands	45
5	Spanish National Research Council (CSIC)	43
6	United States Department of the Interior	42
7	University of Gottingen, Germany	39
8	University of British Columbia, Canada	38
9	University of Oxford, England, UK	37
10	Chinese Academy of Sciences Institute of Geographic Sciences and Natural Resources Research (IGSNRR, CAS)	36
11	State University System of Florida, USA	36
12	University of São Paulo (USP), Brazil	36
13	CGIAR Global Research Partnership	34
14	National Autonomous University of Mexico (UNAM)	33
15	University of New England in Maine, USA	33
16	Helmholtz Association of German Research Centers	31
17	University of Queensland, Australia	31
18	Swedish University of Agricultural Sciences	30
19	University of Chinese Academy of Sciences (UCAS)	29
20	French National Research Institute for Sustainable Development (IRD)	28
21	Chinese Ministry of Agriculture and Rural Affairs	28
22	United States Geological Survey	26
23	University of Florida, USA	26
24	Autonomous University of Madrid, Spain	25
25	Beijing Normal University, China	25
26	Argentine National Scientific and Technical Research Council (CONICET)	25
27	French National Research Institute for Agriculture, Food and Environment (INRAE)	25
28	UK Center for Ecology and Hydrology (UKCEH)	25

Six interconnected collaboration clusters emerged, involving 50 global institutions (Figure 6). The largest cluster (purple) involved 16 institutions from France, England, Netherlands, Germany, Spain, Denmark, and Portugal, with a focus on relationships with the French National Center for Scientific Research (CNRS) and connections to LA through the National Autonomous University of Mexico (UNAM). The second largest cluster (red) consisted of 10 institutions from the USA and Brazil, centered around relationships with the University of California System. A diverse group of nine institutions collaborated within the third cluster (green), including universities from Germany, the USA, Canada, South Africa, Finland, and Argentina's National Council of Scientific and Technical Researchers (CONICET). The fourth cluster (light blue) involved collaborations between French and Australian institutions, centered around the French National Research Institute for Sustainable Development (IRD) and the French Agricultural Research Center for International Development (CIRAD). Five Chinese institutions formed the orange cluster through connections with the Chinese Academy of Sciences. Finally, there was a smaller cluster (blue), comprised of three institutions from Australia and the USA.

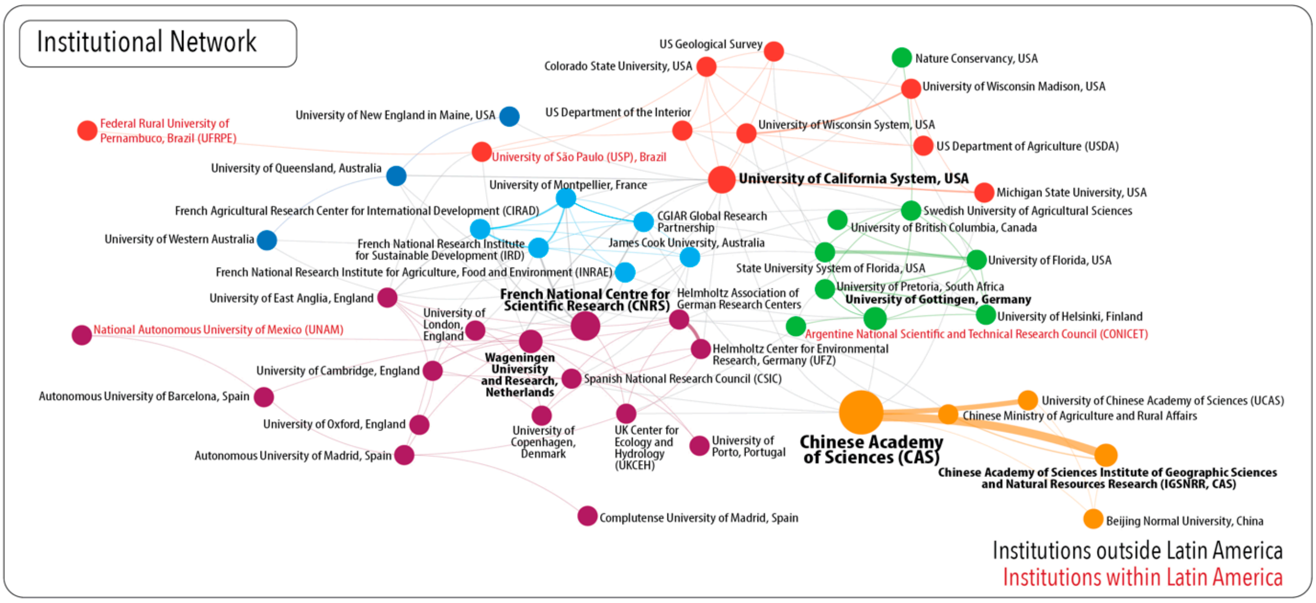


Figure 6. Interrelated clusters of the institutional collaboration network. Different node colors indicate different clusters. Latin American countries are labeled with red text.

3.4. Evolving Research Themes and Findings

Keyword analysis for the global dataset identified key areas of research focus, documenting their emergence and temporal evolution (Figure 7). Analysis used a minimal threshold of five mentions within the author keywords of the papers, mapping a total of 34 keywords [70]. The earliest trend topics that met the established thresholds reached their first quartile year (Q1) in 2009, meaning 25% of the dataset publications for 2009 were associated with keywords like "landscape ecology", "urban planning", or "forestry". In 2010, another set of Q1 keywords emerged, including "development", "environmental policy", and "environment". The most enduring keywords, as determined by the length of time between their Q1 and Q3 years, were "fragmentation", "rural development", "environmental policy", and "landscape ecology", which all spanned a period of 11 years. Other enduring themes included "conservation planning", "South Africa", "attitudes", and "forestry", with ten-year spans. The most frequently mentioned keywords were "protected areas" (116 papers), "conservation" (78 papers), "biodiversity" (60 papers), "ecosystem services" (58 papers), and "deforestation" (49 papers). Apart from concepts like "conservation" or "biodiversity conservation" and "protected areas", which could be considered as indirect drivers of change, the most frequent keywords related to indirect drivers were "urbanization" (32 papers),"sustainability" and "sustainable development" (24 papers each), "human–wildlife conflict" (23 papers), "agriculture" (23 papers), "management" (22 papers), "rural development" (13 papers), and "conservation planning". Noteworthy emerging concepts, based on their Q1 years, included "endangered species" (Q1 year: 2021), "land cover change" (Q1 year: 2020), and three keywords, "landscape planning", "spatial planning", and "invest model", which all reached their Q1 years in 2019.

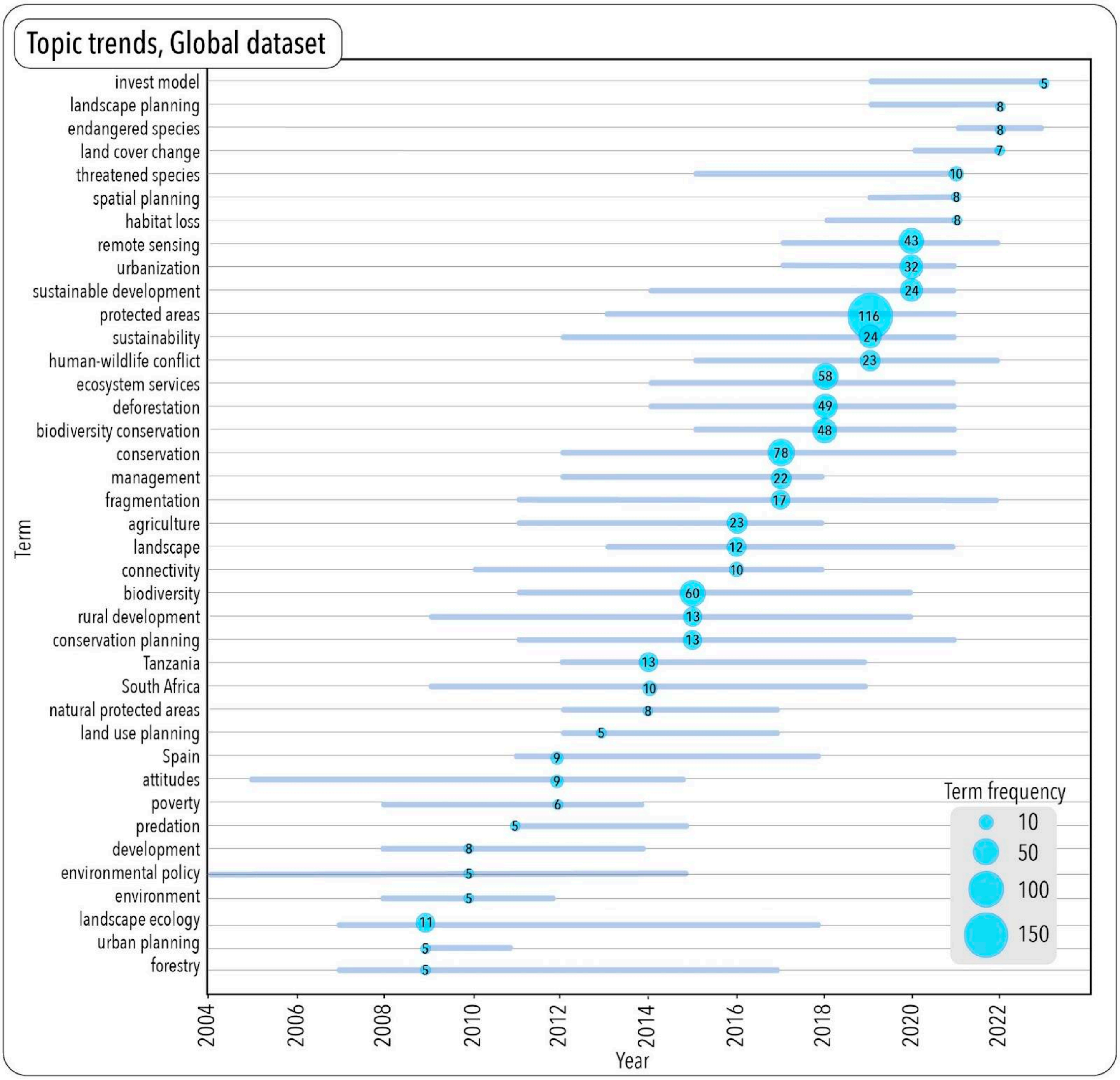


Figure 7. Trend topics and evolution for the global dataset, based on author keywords.

The same minimal threshold of five keyword mentions was applied within the LA subset, resulting in the identification and mapping of 12 keywords [62]. As illustrated in Figure 8, the earliest trend topics that met the minimal threshold of five papers included "fragmentation", "Colombia", "biodiversity", and "conservation", which reached their first quartile years between 2010 and 2015. The most enduring topics within the LA subset were "fragmentation", which spanned from Q1 to Q3 over 12 years, and both "conservation" and "biodiversity conservation", which each had Q1 to Q3 spans over seven years. Among the frequently mentioned topics were "protected areas" (28 papers), "deforestation" (28 papers), "conservation"(20 papers), and "biodiversity conservation" (14 papers). Other than "conservation", "biodiversity conservation", and "protected areas", the only term that could be considered an indirect driver of change within the LA subset was "management", with five mentions. Emerging concepts or topics gaining relevance among LA researchers included "ecosystem services" (Q1 = 2018), "Cerrado", which is a large tropical savanna ecoregion in eastern Brazil (Q1 = 2018), and "natural regeneration" (Q1 = 2018).

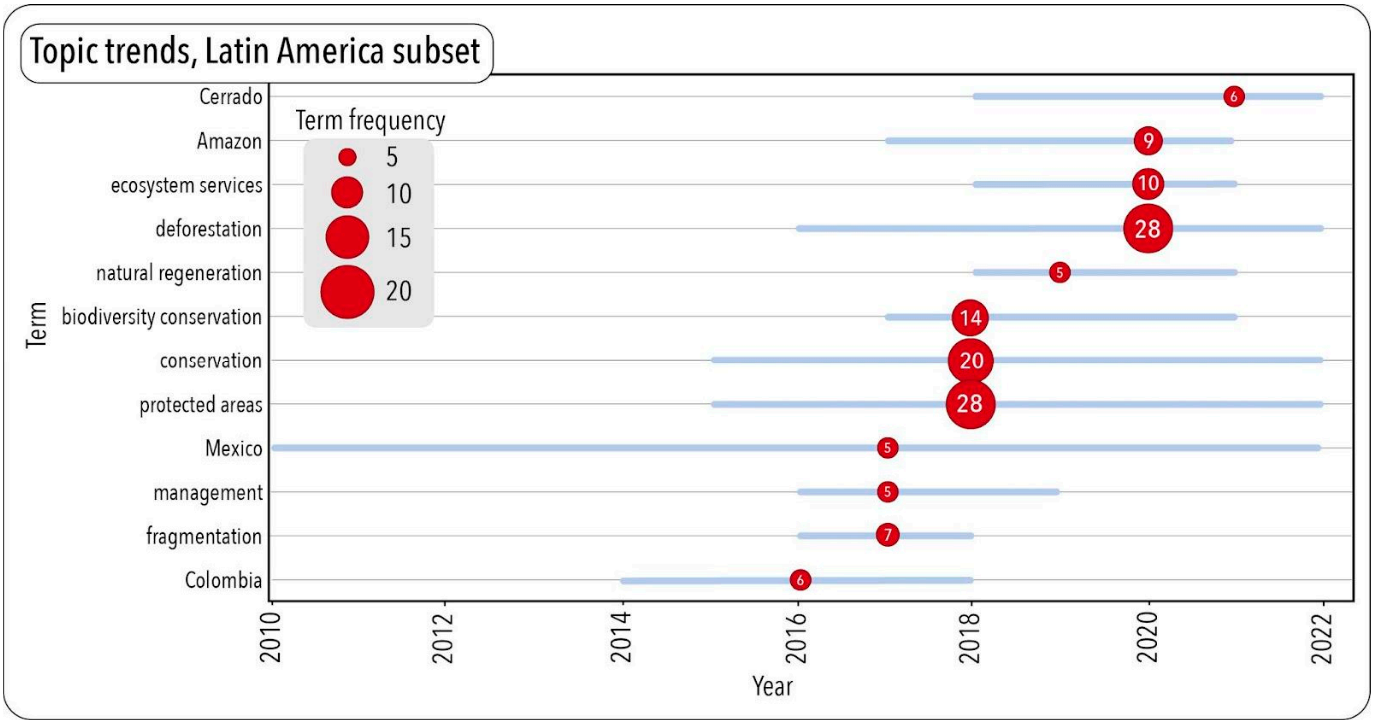
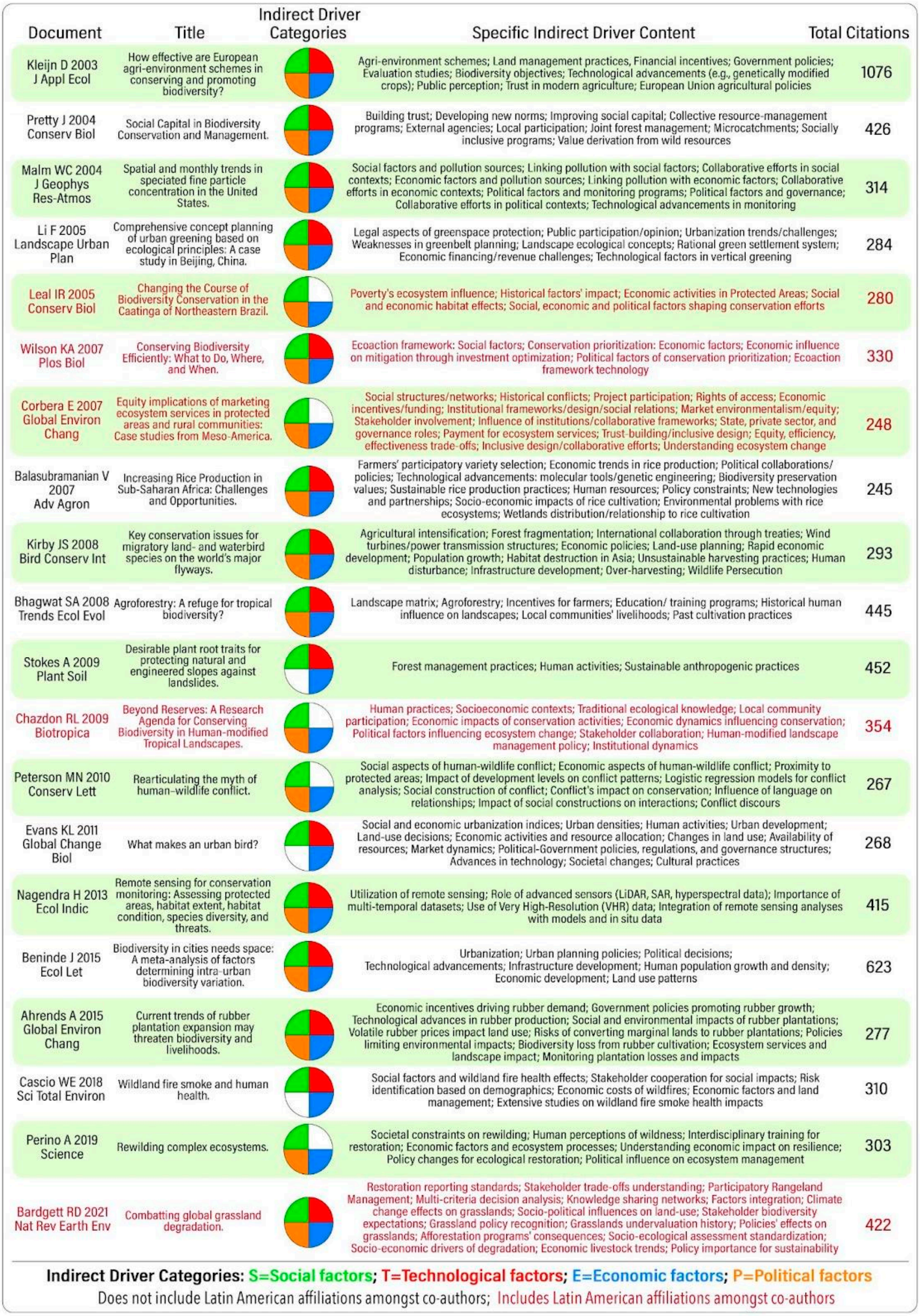


Figure 8. Trend topics and evolution for the Latin American dataset, based on author keywords.

Together, the 20 articles with the highest level of impact, as measured by total citations, represented 7632 (16.42%) of the 46,477 total global dataset citations. These articles spanned the years between 2003 and 2021, with two from 2004, 2005, 2008, 2009, and 2015 and three in 2007. Five of the articles (25%) included co-authors with LA affiliations, including institutions in Brazil, Chile, Costa Rica, El Salvador, Nicaragua, and Mexico.

The 20 highest-impact papers examined factors influencing changes in natural and ecosystem services, with a focus on social, economic, technological, and political drivers (Figure 9). These papers covered a wide range of specific indirect drivers, including agri-environmental schemes, pollution's social and economic impacts, urban greenspace planning, poverty's effects on ecosystems, market influences on land use, socio-economic aspects of wildland fires, human perceptions and behaviors affecting stakeholder engagement, and policy implications. Three recent articles stood out for their significant impact on research, as evidenced by their high citation counts: W.E. Cascio's 2018 paper on human health and wildland fire smoke (310 citations) [71], Perino et al.'s 2019 article on rewilding complex ecosystems (303 citations) [72], and Bardgett et al.'s 2021 publication on combating global grassland degradation (422 citations) [73].



Document	Title	Specific Indirect Driver Content	Total Citations
Kleijn D 2003 J Appl Ecol	How effective are European agri-environment schemes in conserving and promoting biodiversity?	Agri-environment schemes; Land management practices, Financial incentives; Government policies; Evaluation studies; Biodiversity objectives; Technological advancements (e.g., genetically modified crops); Public perception; Trust in modern agriculture; European Union agricultural policies	1076
Pretty J 2004 Conserv Biol	Social Capital in Biodiversity Conservation and Management.	Building trust; Developing new norms; Improving social capital; Collective resource-management programs; External agencies; Local participation; Joint forest management; Microcatchments; Socially inclusive programs; Value derivation from wild resources	426
Malm WC 2004 J Geophys Res-Atmos	Spatial and monthly trends in speciated fine particle concentration in the United States.	Social factors and pollution sources; Linking pollution with social factors; Collaborative efforts in social contexts; Economic factors and pollution sources; Linking pollution with economic factors; Collaborative efforts in economic contexts; Political factors and monitoring programs; Political factors and governance; Collaborative efforts in political contexts; Technological advancements in monitoring	314
Li F 2005 Landscape Urban Plan	Comprehensive concept planning of urban greening based on ecological principles: A case study in Beijing, China.	Legal aspects of greenspace protection; Public participation/opinion; Urbanization trends/challenges; Weaknesses in greenbelt planning; Landscape ecological concepts; Rational green settlement system; Economic financing/revenue challenges; Technological factors in vertical greening	284
Leal IR 2005 Conserv Biol	Changing the Course of Biodiversity Conservation in the Caatinga of Northeastern Brazil.	Poverty's ecosystem influence; Historical factors' impact; Economic activities in Protected Areas; Social and economic habitat effects; Social, economic and political factors shaping conservation efforts	280
Wilson KA 2007 Plos Biol	Conserving Biodiversity Efficiently: What to Do, Where, and When.	Ecoaction framework: Social factors; Conservation prioritization: Economic factors; Economic influence on mitigation through investment optimization; Political factors of conservation prioritization; Ecoaction framework technology	330
Corbera E 2007 Global Environ Chang	Equity implications of marketing ecosystem services in protected areas and rural communities: Case studies from Meso-America.	Social structures/networks; Historical conflicts; Project participation; Rights of access; Economic incentives/funding; Institutional frameworks/design/social relations; Market environmentalism/equity; Stakeholder involvement; Influence of institutions/collaborative frameworks; State, private sector, and governance roles; Payment for ecosystem services; Trust-building/inclusive design; Equity, efficiency, effectiveness trade-offs; Inclusive design/collaborative efforts; Understanding ecosystem change	248
Balasubramanian V 2007 Adv Agron	Increasing Rice Production in Sub-Saharan Africa: Challenges and Opportunities.	Farmers' participatory variety selection; Economic trends in rice production; Political collaborations/ policies; Technological advancements: molecular tools/genetic engineering; Biodiversity preservation values; Sustainable rice production practices; Human resources; Policy constraints; New technologies and partnerships; Socio-economic impacts of rice cultivation; Environmental problems with rice ecosystems; Wetlands distribution/relationship to rice cultivation	245
Kirby JS 2008 Bird Conserv Int	Key conservation issues for migratory land- and waterbird species on the world's major flyways.	Agricultural intensification; Forest fragmentation; International collaboration through treaties; Wind turbines/power transmission structures; Economic policies; Land-use planning; Rapid economic development; Population growth; Habitat destruction in Asia; Unsustainable harvesting practices; Human disturbance; Infrastructure development; Over-harvesting; Wildlife Persecution	293
Bhagwat SA 2008 Trends Ecol Evol	Agroforestry: A refuge for tropical biodiversity?	Landscape matrix; Agroforestry; Incentives for farmers; Education/ training programs; Historical human influence on landscapes; Local communities' livelihoods; Past cultivation practices	445
Stokes A 2009 Plant Soil	Desirable plant root traits for protecting natural and engineered slopes against landslides.	Forest management practices; Human activities; Sustainable anthropogenic practices	452
Chazdon RL 2009 Biotropica	Beyond Reserves: A Research Agenda for Conserving Biodiversity in Human-modified Tropical Landscapes.	Human practices; Socioeconomic contexts; Traditional ecological knowledge; Local community participation; Economic impacts of conservation activities; Economic dynamics influencing conservation; Political factors influencing ecosystem change; Stakeholder collaboration; Human-modified landscape management policy; Institutional dynamics	354
Peterson MN 2010 Conserv Lett	Rearticulating the myth of human-wildlife conflict.	Social aspects of human-wildlife conflict; Economic aspects of human-wildlife conflict; Proximity to protected areas; Impact of development levels on conflict patterns; Logistic regression models for conflict analysis; Social construction of conflict; Conflict's impact on conservation; Influence of language on relationships; Impact of social constructions on interactions; Conflict discours	267
Evans KL 2011 Global Change Biol	What makes an urban bird?	Social and economic urbanization indices; Urban densities; Human activities; Urban development; Land-use decisions; Economic activities and resource allocation; Changes in land use; Availability of resources; Market dynamics; Political-Government policies, regulations, and governance structures; Advances in technology; Societal changes; Cultural practices	268
Nagendra H 2013 Ecol Indic	Remote sensing for conservation monitoring: Assessing protected areas, habitat extent, habitat condition, species diversity, and threats.	Utilization of remote sensing; Role of advanced sensors (LiDAR, SAR, hyperspectral data); Importance of multi-temporal datasets; Use of Very High-Resolution (VHR) data; Integration of remote sensing analyses with models and in situ data	415
Beninde J 2015 Ecol Let	Biodiversity in cities needs space: A meta-analysis of factors determining intra-urban biodiversity variation.	Urbanization; Urban planning policies; Political decisions; Technological advancements; Infrastructure development; Human population growth and density; Economic development; Land use patterns	623
Ahrends A 2015 Global Environ Chang	Current trends of rubber plantation expansion may threaten biodiversity and livelihoods.	Economic incentives driving rubber demand; Government policies promoting rubber growth; Technological advances in rubber production; Social and environmental impacts of rubber plantations; Volatile rubber prices impact land use; Risks of converting marginal lands to rubber plantations; Policies limiting environmental impacts; Biodiversity loss from rubber cultivation; Ecosystem services and landscape impact; Monitoring plantation losses and impacts	277
Cascio WE 2018 Sci Total Environ	Wildland fire smoke and human health.	Social factors and wildland fire health effects; Stakeholder cooperation for social impacts; Risk identification based on demographics; Economic costs of wildfires; Economic factors and land management; Extensive studies on wildland fire smoke health impacts	310
Perino A 2019 Science	Rewilding complex ecosystems.	Societal constraints on rewilding; Human perceptions of wildness; Interdisciplinary training for restoration; Economic factors and ecosystem processes; Understanding economic impact on resilience; Policy changes for ecological restoration; Political influence on ecosystem management	303
Bardgett RD 2021 Nat Rev Earth Env	Combatting global grassland degradation.	Restoration reporting standards; Stakeholder trade-offs understanding; Participatory Rangeland Management; Multi-criteria decision analysis; Knowledge sharing networks; Factors integration; Climate change effects on grasslands; Socio-political influences on land-use; Stakeholder biodiversity expectations; Grassland policy recognition; Grasslands undervaluation history; Policies' effects on grasslands; Afforestation programs' consequences; Socio-ecological assessment standardization; Socio-economic drivers of degradation; Economic livestock trends; Policy importance for sustainability	422

Figure 9. Indirect driver content within the 20 highest-cited papers, listed chronologically. Note: Citations for the 20 highest-cited papers: [71–90].

4. Unpacking Research Prospects and Challenges

This research conducted a bibliometric analysis covering two decades from 2003 to 2023 with the goal of improving understanding of how science has addressed the social, technological, economic, and political factors influencing change in natural systems and ecosystem services along the interface of protected and non-protected lands, both on a global scale and with a focus on the LA region. Through improved understanding of scientific trends and research evolution, we hope to further the GBF vision of equitable access to research and capacity-building and identify opportunities for improving knowledge dissemination, collaboration, and alignment with the GBF.

4.1. Opportunities for More Intentional Academic Knowledge Sharing and Distribution

With respect to academic knowledge sharing and distribution, the top 20 journals, in terms of article coverage, shared a common emphasis on environmental issues and conservation. Based on their expressed aims and scopes, some of the journals, including Sustainability, Journal of Environmental Management, Environmental Management, Forest Policy and Economics, Global Ecology and Conservation, and Environmental Conservation, seemed especially interested in and supportive of research associated with the indirect drivers of natural system change. For example, the Journal of Environmental Management's aims and scope focus on environmental systems and improving environmental quality. This journal mentioned an interest in papers focused on "social, economic and policy aspects of environmental management" [91]. Similarly, the aims and scope for Forest Policy and Economics declared a focus on:

> *"peer-reviewed policy and economics research related to forests, forested landscapes, and forest-related industries… welcom[ing] contributions from other social sciences and humanities perspectives that make clear theoretical, conceptual and methodological contributions to the existing state-of-the-art literature on forests and related land use systems." [92]*

Other journals were less clear about their interest in research addressing the indirect drivers of environmental change. For example, while the journal Science of the Total Environment declared an interest in multidisciplinary approaches, it emphasized a focus on natural sciences, stating that "papers of social science in nature on economics, sociology, psychology, political science, policy, planning and/or management" were beyond the scope of consideration [93]. This stance was surprising, considering their coverage of topics like ecosystem services, environmental impacts, and health implications of agriculture, forestry, and land use. All of these topics are indirectly influenced by social, technological, economic, and political factors. Thus, Science of the Total Environment's reluctance to consider social science-driven approaches may warrant reevaluation, particularly if these approaches can enhance our understanding of how indirect drivers contribute to changes in natural systems and ecosystem services [40].

The GBF objectives for accelerated and equitable capacity building, timely research, and science-based decision making require strengthened interfaces between science, government, and community [1–3,17]. Academic research journals can contribute to these objectives in several ways, beginning with an intentional review of their aims and scopes, to more clearly align and support sustainability research, policy, and practice, especially related to the GBF. Journals can also contribute through intentional practices related to open access and open science, which support accelerated research dissemination and broader access to high-quality, peer-reviewed research [17]. For example, our study results demonstrated that more than half of the dataset documents were freely distributed via open-access formats. These tendencies support the equitable data-sharing and capacity building emphasized in the GBF.

In particular, the MDPI journal Sustainability emerged as the leading journal in terms of subject coverage for both the global and LA datasets (Figure 3, Table 1). Sustainability is committed to open access and open science principles and offers unique features such as the acceptance of research proposals and ideas, the option to deposit supplementary materials containing detailed calculations and experimental procedures, and consideration of manuscripts aimed at a broader audience, particularly those stemming from publicly funded research projects. Moreover, the journal's rapid expansion in research coverage and dissemination over the past decade provides access to a wide range of research perspectives and advances. For example, the journal's primary aim encourages researchers to publish detailed accounts of their experimental, computational, and theoretical research across a wide range of disciplines, including natural and applied sciences, engineering, economics, social sciences, and humanities. While the overall and average article citations for Sustainability articles were lower than some of the other journals (see Figure 3, Table 1), their approach aligns with their overarching goal of fostering scientific understanding and enabling predictions and impact assessments related to global change and sustainability.

Several other notable strategies were observed among the top twenty journals in terms of their relevant subject-matter coverage. For instance, within their aim and scope statements, both Biological Conservation and Global Ecology and Conservation refer to associated open-access publications, encouraging consideration of these outlets for research dissemination. The journal PLOS One articulates its mission as a collaborative journal community dedicated to advancing science for the betterment of society both presently and in the future. Established with the goal of expediting scientific progress and showcasing its significance, PLOS One advocates for the publication of all robust scientific research, emphasizing the importance of broad discoverability, extensive dissemination, and unrestricted accessibility. The journal Global Ecology and Conservation functions as an international open-access scientific journal specializing in ecology and conservation biology. The journal disseminates articles across a wide spectrum of disciplines contributing to the fields of ecology and conservation, encompassing studies related to terrestrial, marine, or freshwater organisms and ecosystems.

Moving forward, clearer collaboration between the GBD and relevant journals may provide a relevant path to accelerate and enhance technical and scientific cooperation, encouraging research collaboration to effectively generate and utilize relevant scientific and analytical information. For example, Special Issues in academic journals provide a valuable opportunity for exploring and sharing focused research topics. Journals such as Forest Policy and Economics, Global Ecology and Conservation, Biodiversity and Conservation, and Sustainability, amongst others, all feature Special Issue practices that enhance scholarly discourse on specific subjects. These Special Issues are typically led by guest editors and undergo a rigorous editorial process to ensure quality and relevance. The papers included in Special Issues are prominently displayed on dedicated webpages or within special print editions and can be developed in "open access" formats that make them easily accessible to readers and researchers.

4.2. Focused Attention to Supporting Research Collaboration through the Purposeful Expansion of Networks

The global research productivity trends that emerged in this research revealed a considerable increase in relevant research output over the years, reflecting growing consideration and coverage of underlying factors of natural and ecosystem change in the areas surrounding PAs, which can advance understanding of social, technological, economic, and political indirect drivers. Higher levels of collaboration within the LA subset documents and noticeable increases in research coverage over the last decade suggest the importance and potential for networks and alliances to increase and accelerate research understanding and capacity within this region.

Nevertheless, the study revealed disparity in LA research productivity and impact as compared to other regions of the world. For example, just more than half of the 29 LA countries included in the study showed participation within the dataset publications (Brazil, Mexico, Argentina, Chile, Colombia, Peru, Ecuador, Bolivia, Costa Rica, Panama, Uruguay, Venezuela, El Salvador, Guatemala, and Paraguay). Of these, Brazil was the most prominent, ranking fourth amongst the 125 countries that appeared in the study, with

552 total citations and 116 instances of Brazilian-affiliated corresponding authors. Other LA institutions within the top twenty included Mexico, Argentina, and Chile.

The country-level and institutional research analyses in the study (refer to Figures 4 and 6; Table 2) underscore the need for more focused consideration of how LA countries and institutions participate within networks and groups. Results suggested that LA countries may not be as integrated within these networks as institutions from other regions, such as North America, China, Europe, and Australia. Specifically, at the country level (Figure 4), within the red country network cluster, Peru was situated in the periphery of the cluster, with a lower prominence as compared to the core actors, such as the USA, UK, Germany, or Australia. None of the LA countries participated within the green country-level network cluster, which was predominantly populated by European countries and centered around Spain. This is somewhat surprising considering the centrality of Spain within this network and prior findings related to European research collaboration with LA in the area of biodiversity [94]. LA countries were most active within the blue country cluster, where Brazil, Argentina, and Colombia all clustered fairly close in relation to China and Switzerland. Although more peripheral, Mexico and Chile also appeared.

At an institutional level, six institutions stood out in terms of co-author institutional document affiliations (Table 2) and their bridging roles within the interrelated institutional clusters (Figure 6). These included the Chinese Academy of Sciences, the French National Center of Scientific Research (CNRS), the University of California System in the USA, the Wageningen University and Research in the Netherlands, the University of Gottingen in Germany, and the Chinese Academy of Sciences Institute of Geographic Sciences and Natural Resources Research (IGSNRR, CAS). These institutions had 149, 49, 47, 45, 39, and 36 document affiliations, respectively, and also played prominent bridging roles within the orange, red, purple, and green institutional networks clusters (Figure 6). This suggests their significance as key research centers in the field, combined with strong levels of centrality and cohesion building within their respective networks.

LA institutional presence within these networks tended to be less cohesive and close. For example, the National Autonomous University of Mexico, with 33 document affiliations in the dataset, was located at the periphery of the purple cluster with minimal structural cohesion. Being located at the periphery of a network can indicate a lower level of influence, communication, or interaction with other institutions within the network [95–97]. Within the red institutional network cluster, the University of São Paulo (USP), in Brazil, which had 36 institutional affiliations, mapped much more centrally; however, the Federal Rural University of Pernambuco, Brazil (UFRPE), with only three document affiliations, was situated much more peripherally in relation to the centrality of the University of California system. The orange cluster was limited to institutions in China, reinforcing the strength and centrality displayed by the Chinese Academy of Sciences (CAS). The University of Gottingen, in Germany (39 document affiliations), demonstrated slightly more prominence within the green institutional network cluster, although institutions tended to be more equally distributed in this cluster as compared to others. With the exception of the Nature Conservancy, all of the institutions within this cluster, including Argentina's National Scientific and Technical Research Council (CONICET), were situated fairly closely around the University of Gottingen.

The importance of biodiversity and PAs in the LA region, combined with mounting environmental pressures and degradation, merits a higher level of research attention along the protected–unprotected land interface [98–100]. Increased and intentional focus on developing regional, international, and interinstitutional collaboration could help this region of the world to advance understanding and improve regional GBF strategies.

4.3. Evolving Research Themes and Findings

Over the past several decades, increasing emphasis has been placed on understanding and connecting the indirect anthropogenic factors that drive natural and ecosystem service change along the interface of protected and unprotected lands. The MEA (2005) included purposeful consideration of these factors within their scenarios [35], and other authors have expanded attention and consideration within subsequent scenarios [41]. More recently, the IPBES 2019 Global Assessment Report on Biodiversity and Ecosystem Services emphasized the need for more nuanced and situational understanding of the intrinsic, instrumental, and relational values that humans have for nature [30,31]. The 2023 study by Cardona Santos et al. echoed these calls, underscoring the importance of this understanding to inform national biodiversity strategies [3].

The evolving themes and research advances that surfaced in the present study suggest positive momentum in this area. For example, topic trends analysis demonstrated a wide range of indirect driver consideration in connection with the overarching theme of PAs (Figures 7 and 8). Over time, these topics have evolved, suggesting an increased appreciation of the interrelated nature of drivers and the complex interactions that they provoke. For example, early research reflects attention toward broad themes of environmental policy and urban planning, slowly advancing to consider underlying factors like poverty, development, and attitudes. Around 2015, research on biodiversity, rural development, and conservation planning suggested a shift toward more focused consideration of the protected–unprotected interface. From this time forward, topic trends reflected a more nuanced consideration of social, technological, economic, and policy-related factors. Topic trends expanded focus across agriculture, deforestation, human–wildlife conflicts, sustainable development, and urbanization. Most recently, topics seem to reflect increasingly interrelated social-ecological themes and prescriptive and systems-focused approaches. Topic consideration, like remote sensing, spatial planning, habitat loss, land cover change, landscape planning, and, most recently, the InVEST model, a tool used in natural systems and biodiversity planning to assess and evaluate the value of ecosystem services provided by natural landscapes, seems to support a growing research sophistication and interdisciplinary thinking at the interface of protected and non-protected lands [101]. More frequent mention of the InVEST concept is particularly interesting. InVEST stands for Integrated Valuation of Ecosystem Services and Tradeoffs. This model helps decision-makers understand the benefits that ecosystems offer (e.g., clean water, habitat provision, carbon sequestration, and recreation opportunities) and how these benefits can be maintained or enhanced through effective land use planning and management practices [101]. While this same trend toward more nuanced and interrelated treatment of indirect driver concepts and systems change was not apparent within the LA subset topic trends (Figure 8), concepts like ecosystem services have gained in prominence in recent years. More purposeful consideration of how themes are evolving might foster an accelerated cross-application of newer tools, like the InVEST model, within the LA region. Further, an in-depth review of these tools and their impact on research and planning is warranted, extending beyond the capabilities and purpose of bibliometric analysis to achieve a richer understanding of their potential and limitations with respect to indirect drivers of natural and ecosystem service change along the interface of protected and non-protected lands.

Examining the top 20 highest-cited papers of the dataset helped clarify the evolution and durability of indirect driver themes. The earlier papers amongst this group focused on the interactions between indirect factors of change (e.g., social capital, poverty, agri-environmental incentives) and planning, governance, and conservation technology. Around 2009, these concepts began to be combined through research that addressed topics at the interface of social, economic, technological, and political drivers. For example, the 2009 article by Chazdon et al., which included significant LA collaboration, represents an important early work that explicitly recognized the importance of a spectrum of human practices and contexts in the areas that surround PAs [85].

Over time, research treatment of indirect drivers has continued to build on and reflect a more integrated comprehension of the broader social, economic, and political factors. For example, Perino et al.'s recent 2019 article in Science has garnered over 303 citations, ranking 12th in impact amongst the global dataset [72]. Entitled "Rewilding complex ecosystems", the article advocated for rewilding as a pathway to biodiversity goals, stress-ing the importance of understanding how ecosystem processes are shaped by societal, economic, and political influences and emphasizing the need to consider human perceptions of wilderness in restoration initiatives. The authors call for interdisciplinary training for scientists and practitioners to enhance comprehension of the broader factors impacting ecosystem resilience and restoration and highlight the need for policy changes to prioritize ecological restoration efforts [72].

Perhaps the best illustration of research evolution is reflected by the most recent high-impact article, from Bardgett et al., (2021), which has already garnered 422 total citations and the 6th place rank amongst the 20 most impactful dataset papers [73]. With co-authors from the United Kingdom, France, Germany, Switzerland, Brazil, India, and China, this paper provides a clear example and benchmark for scientific approaches to the indirect drivers of change for natural systems and ecosystem services in areas surrounding PAs. The article, "Combatting global grassland degradation", links global grassland degradation with CBD biodiversity agendas and the Sustainable Development Goals, recommending mainstreamed restoration policy and standardized assessments of conditions that take ecosystem service valuation and demand into consideration. Multi-Criteria Decision Analysis (MCDA) is presented, through real-world examples, as a tool for integrating local communities in collaborative learning and decision-making. This methodology helps stakeholders achieve shared understanding by facilitating trade-offs discussions, helping to navigate conflicts arising from differing restoration preferences. The authors highlight the need for global policy recognition of grasslands and their value for ecosystem services. The authors also advocate for global exchanges and collaboration around knowledge sharing and research innovation. Their five-step approach is a clear example of the potential of a focused, science-based approach to global biodiversity restoration and conservation, based on a profound consideration of the underlying indirect drivers of natural system change [73].

Continued evolution of research is necessary to support and inform regional GBF strategies, especially given the importance being placed on innovative approaches that can complement and extend the reach of traditional, top-down PA systems. The success of nature-based solutions (NbS), other effective conservation measures (OECM), area-based conservation, PA buffer zone approaches, biological corridors, and new forms of participative governance, management, and outcomes monitoring is likely to depend on the capacity to understand and influence social, technological, economic, and political factors along the interface of protected and non-protected lands [1,3–9,11,12,46].

4.4. Study Limitations

This study has several limitations that should be acknowledged. Firstly, the research was conducted in English and focused on publications indexed in the Web of Science (WOS) database, potentially overlooking valuable research published in other languages or regional journals. This language bias and limited access to international publishing platforms may result in the underrepresentation of LA research in global bibliometric analyses, potentially skewing the understanding of ecosystem issues in the region.

Secondly, the exclusion of publications beyond the WOS core database could have resulted in the omission of influential articles. Future research endeavors should consider incorporating other databases such as Scopus and ResearchGate to include a more comprehensive selection of relevant papers for analysis. Additionally, a significant portion of practical research in this field may be disseminated through public and private reports as well as government documents. Subsequent studies should explore methodologies to identify, access, and analyze these sources, as they represent important contributions to interdisciplinary and transdisciplinary perspectives.

Also, while bibliometric analysis enabled better understanding of the research trajectories, the directed content-analysis of the top twenty most impactful articles conducted within the research facilitated a more complete understanding of ways in which indirect drivers manifested within the literature. Thus, future research may need to consider how leveraging artificial intelligence (AI) technologies for rich text research could improve the potential for researchers to deepen understanding and uncover hidden patterns and relationships within these large bodies of work and within the full-text documents that make up this and other bibliometric datasets [102].

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