

Article

Global Trends and Innovations in Forest Ecological Compensation: An Interdisciplinary Analysis

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Abstract: Forest ecological benefit compensation protects the ecological environment, increases enthusiasm among forest ecological builders, protects the legitimate economic interests of forest landowners, and maintains environmental security. In this study, a systematic analysis was conducted on 4062 publications in the field of international forest ecological benefit compensation identified using the Web of Science core collection Science Citation Index Expanded (SCI-E) and Social Science Citation Index (SSCI) databases alongside CiteSpace optical measurement software. The research status and influence of countries were tracked, scientific research institutions and important authors were identified, and interdisciplinary and scientific hotspots were analyzed. The results show that the number of studies in this field has significantly increased over time and has strong development potential. The journals and articles presenting cutting-edge research in this field are all considered highly professional. The selected research is highly interdisciplinary but primarily involves environmental science and ecology. Despite the publication volume of China ranking second among the top 10 countries, its average citation volume was the lowest, indicating the urgent need to increase the international influence of China. Forest biodiversity, ecosystem services, and climate change are current research hotspots in this field. Dynamic changes in forest ecological benefit compensation and the driving forces behind its evolution are of great concern to researchers.

Keywords: forest; forest ecological benefit compensation; biodiversity; forest protection; forest management; climate change



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1. Introduction

Sustainable forestry involves forest resources, such as wood and other raw materials, that are crucial for sustaining human society, including industry and the economy [1–5]. Forest resources also provide essential services such as temperature regulation, water conservation, sequestration, oxygen release, and noise reduction [6]. With increasing social and economic development, forest resources in many parts of the world have been destroyed to varying degrees, bringing forth an urgent need to improve protection strategies and rationalize their use. As a result, forest ecological benefit compensation has become important; however, it possesses various characteristics, such as intangibility, pleiotropy, externality, and public product attributes. In addition, the breadth and ambiguity of its beneficiaries pose challenges that cannot be easily addressed. Forest ecological benefit

compensation is now a topic of widespread concern and has been a continued research focus of governments and scholars worldwide.

Ecological compensation, commonly known as payment for ecosystem services (PES), refers to various systems, policies, or project arrangements in which beneficiaries of ecosystem services compensate service providers to ensure a sustainable supply. Taking the forest as the most suitable object encourages people to maintain the service function of the forest ecosystem with economic means and solves the external problem of forest ecological benefits caused by the failure of market mechanisms [7]. Three primary methods have been used to research forest ecological benefit compensation: forest ecological compensation, forest resource ecological compensation, and forest ecological benefit compensation. Forest ecological compensation and forest resource ecological compensation are synonymous, whereas forest environmental benefit compensation serves a slightly different purpose. Forest environmental benefit compensation emphasizes cost compensation beyond the scope of its obligations when providing ecological benefits to society, whereas forest ecological compensation emphasizes economic responsibility for the consequences of harmful acts on the ecological environment. The concept of forest ecological compensation is more extensive, including compensation for the forest environment, protective inputs to the forest ecological environment, and conservation behavior [8,9], as well as monetary compensation, which refers to environmental benefits generated by forests that cannot be traded.

Forest ecological benefit compensation research began in China during the early 1980s, and earlier in various regions. It included the collection of water resource fees, forestry development and construction funds, and financial subsidies for forestry construction. In the 1990s, China implemented a reform of classified management in forestry that aimed to build an ecologically sustainable forestry industry. The government attached great importance to forest ecological benefit compensation, and related policies were successively introduced. This period of significant development in forest ecological benefit compensation research in China helped achieve a clearer understanding of ecological compensation fees obtained by comparing them with pollution and resource compensation fees. A consensus has been reached on the necessity and feasibility of establishing an ecological benefit compensation system by evaluating the collection scope, standards, basis, methods and approaches, and usage scope of ecological benefit compensation fees, as well as policies and legal frameworks, including fund management measures. In the early 21st century, pilot work for the funds was conducted in 685 counties (units) and 24 national nature reserves in 11 provinces (regions) of China, officially marking the beginning of the implementation of forest ecological benefit compensation policies in China. The establishment of forest ecological benefit compensation funds fundamentally solves the driving forces and mechanisms behind the construction of forest ecological public welfare. Theoretical accumulation and advanced forest ecological benefit compensation theories and methods were introduced during this period.

The international community primarily adopts support methods for forestry development, particularly government support, with the goal of balancing ecological and economic benefits. If preferential policies are implemented for state-owned forest management, subsidies, loan incentives, and tax incentives will be provided for private forest management. Alongside government forestry investments, stakeholders and investors have also become investors in the production of forest ecological services. International, regional, and local research institutions, donors, and businesses, such as the International Forestry Research Center (CIFOR), the International Institute for Environment and Development (IIED), the World Resources Institute (WRI), the International Development Research Center (IDRC), the International Fund for Agriculture and Development (IFAD), the Ford Foundation, the World Wildlife Fund (WWF), and the International Union for Conservation of Nature (IUCN), have actively participated, and seminars and projects related to forest ecological compensation mechanisms and markets have been launched consecutively. International research on forest ecological benefit compensation mainly focuses on the research and

development of various ecological service markets or forest ecological service capabilities based on market methods. The various economic incentive mechanisms that have emerged worldwide have effectively compensated for the ecological benefits of forests, achieving a win–win situation for both the economy and the environment. In most cases, ecological compensation only partially compensates for the costs of appropriate forest management but serves as a catalyst driving forest management in a positive direction.

To date, literature reviews on forest ecological benefit compensation have been limited because it is challenging to establish a connection among the large number of studies and elucidate the current state of forest benefit compensation research from a broader perspective. CiteSpace is a crucial quantitative analytic technique that is frequently used to assess performance in a range of research subjects and may accurately depict the general advancement in a discipline or research field [10–12]. In addition, various types of knowledge graphs can be generated using data mining, information processing, scientific measurements, and graph drawing to present more understandable information to researchers, thus combining visualization techniques with conventional bibliographic analysis [13–15]. In this study, Web of Science data were processed using CiteSpace software to explore international forest ecological benefit compensation research trends. The aim of the study was to elucidate research progress and academic dynamics by tracking the state and impact of research in this field by nation, institution, and author, and to assess the critical interdisciplinary and research hotspots for future studies.

2. Data and Methods

2.1. Data Sources

International forest ecological benefit compensation literature was sourced from the Web of Science Core Collection literature search platform. The Science Citation Index Expanded (SCI-E) and Social Science Citation Index (SSCI) databases were selected to ensure that the results were authoritative and representative.

A fuzzy search was conducted using a combination of the theme “forest” and the titles “ecological benefits”, “ecological effects”, and “ecological compensation”. Data were retrieved on 20 March 2022, and a preliminary search of 4562 articles was conducted. Further manual interpretation of the literature titles and summaries was conducted to remove irrelevant articles, resulting in the retention of 4062 articles. Given the accuracy and concentration of the literature, TI = (“forest”) was chosen as the retrieval approach; TS = (“electrical benefits” or “electrical effect” or “eco compensation” or “electrical compensation”) AND Language: (English) AND Literature type: (Article).

The retrieved literature records were exported in the RefWorks format and saved as plain text files. After data conversion and processing using CiteSpace software, they were used to analyze the data samples in the text.

2.2. Methods

CiteSpace is a Java application developed by Chen Chaomei of Drexel University in the United States to visualize literature analysis [16,17]. It may be accessible from pertinent websites and is now one of the most important analytical tools in the field of bibliometric analysis [18] (<http://cluster.ischool.drexel.edu/~cchen/citespace/download/>, for free on <https://citespace.podia.com/download>, accessed on 1 July 2020). This study used Excel combined with CiteSpace (version 5.8 R3, Drexel University, Philadelphia, PA, USA) software to analyze the research institutions, authors, source journals, keywords, and other indicators in the field of international forest ecological benefits research. CiteSpace keyword clustering and keyword emergence analysis were used to identify themes and hotspots in the field. This method is used to mine research topics within a specified time interval for keywords, and keyword saliency detection reflects a sharp increase or decrease in the interest of a professional and can be used to identify research hotspots. The visualization graph created by CiteSpace consisted of nodes and links, with nodes representing authors, research institutions, and keywords; the larger the node, the more articles the corresponding

author or research institution had published. The connections between nodes indicated collaboration between authors or research institutions, with thicker connections indicating closer collaboration.

Researchers may acquire knowledge regarding the current state of a research field in terms of time, institutions and members, keywords, and highly cited publications by utilizing the statistical analysis features of CiteSpace software, which include collaborative network analysis and co-existential network analysis [19,20]. The software parameters were defined as follows: time period = 2009–2022 (years per slice = 1); default selection criteria; trim settings were “Pathfinder” and “Pruning sliced networks”; node type selection: institution, country, keyword, category, reference, cited author, and cited journal; and “trimming the merged network” was set for keyword co-occurrence analysis. Other parameters remained at their preset values.

3. Results

In this study, Excel combined with CiteSpace software was used to explore the research status, hotspots, and development trends of international forest ecological benefits in the form of knowledge graphs. The analysis identified the main journals, authors, and research institutions in this field. By analyzing the temporal changes, clustering, and emergence of keywords, the main research topics were identified and future research trends predicted.

3.1. Literature Characteristics

3.1.1. Text Quantity

Variations in the amount of published literature serve as significant markers of research activity in particular domains [21,22]. From 2009–2021, statistics as of 20 March 2022 were unable to represent the entire year of data; hence, a total of 44 articles published in 2022 were omitted. Research publications on forest ecological benefit compensation showed a continuously increasing trend (Figure 1), indicating that an increased number of scholars are involved in this field of research, that it is rapidly developing, and that it has future potential.

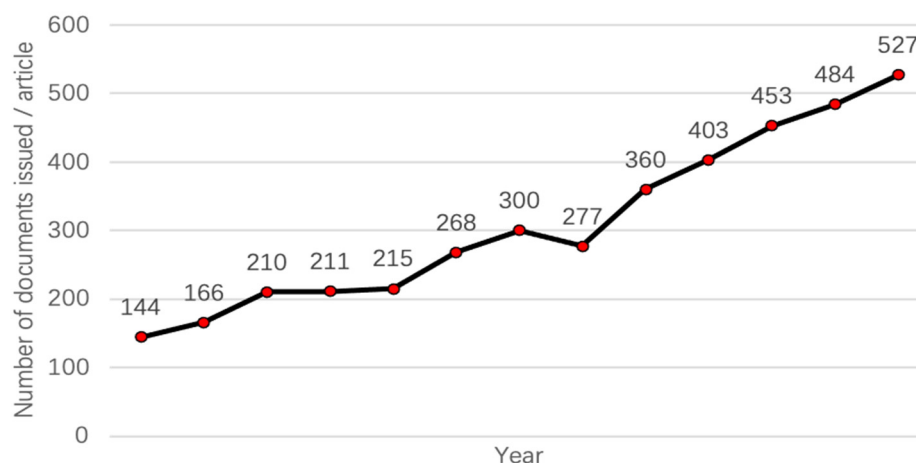


Figure 1. Number of research articles related to forest ecological benefit compensation from 2009–2021.

The number of articles on forest ecological benefit compensation increased overall from 2009–2021 (Figure 1). Interestingly, the number of articles published from 2011–2013 did not change notably, with 210, 211, and 215 articles, respectively. The number of articles published in 2016 showed a downward trend, with 277 articles published, 23 fewer than that in 2015. The number of articles published in 2017 reached 360, with an increase of 83 articles compared with that in 2016 and a growth rate of 30%, which was the highest growth rate from 2009–2021. A rapid growth trend occurred since 2017, and it is predicted that the number of seats will increase.

3.1.2. Primary Journals

Analysis of previous international forest ecological benefit compensation studies identified five journals with the highest citation frequencies and mediation centers (Table 1). The identified journals generally covered a wide range of research areas and had a high concentration of articles.

Table 1. Mainly co-cited journals.

Cited Journal	No. of Citations	Cited Journal	Intermediary Centrality	No. of Citations
Forest Ecol. Manag.	39,269	Quaternary Sci. Rev.	0.05	2045
Ecology	39,011	Ecol. Econ.	0.04	6751
Science	39,607	Global Environ. Chang.	0.04	3908
Ecol. Appl.	29,786	Anal. Ecological. Comm.	0.04	1449
Nature	28,846	Biota Neotrop.	0.04	623

The top three journals cited were Forest Ecology and Management, Ecology, and Science (Table 1), indicating that these journals are at the forefront of international forest ecological benefit compensation research. Quaternary Science Review, the most mediated journal, showed that studies on forest environmental benefit compensation are generally published. The results also indicated that the high volume of citations in journals does not correspond exactly and completely with the high number of publications.

3.2. Interdisciplinary Examination

Recent technological advancements have caused academic boundaries to be dismantled and rebuilt, and interdisciplinary study is now widely acknowledged as a means of advancing science and technology [23]. To investigate the interdisciplinary status of field knowledge linked to forest ecological benefit compensation, this study involved building a multidisciplinary network based on the Web of Science database and integrating it with an interdisciplinary co-occurrence analysis diagram (Figure 2).

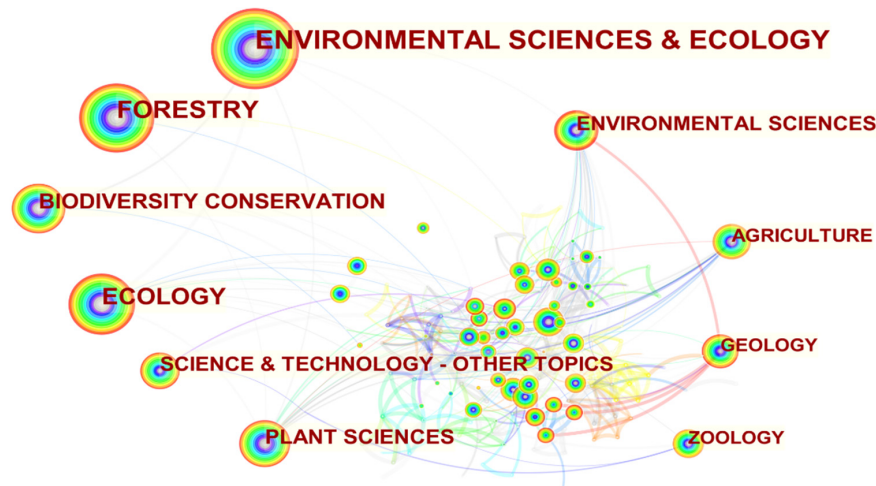


Figure 2. Discipline co-occurrence map from the WOS database. Note: From the color of the innermost circle to the color of the outermost circle, it represents the increase in year, the same in the figures below.

Forest ecological benefit compensation research primarily involves disciplines such as immunological sciences and ecology, forestry, biodiversity conservation, ecology, science and technology, and other topics such as plant sciences and environmental sciences, including agriculture, geology, and zoology, which showed strong intersectionality (Figure 2). Environmental sciences, ecology, and forestry had the highest number of publications.

From the centrality of each index, environmental sciences had the highest centrality with a value of 0.31, and ecology had a value of 0.21, indicating that most research in this field has been within these two disciplines; they are hub nodes of diverse fields, as seen by their tight ties to other disciplines.

3.3. Examination of Prominent Research Nations, Research Centers, and Authors

3.3.1. Principal Research Countries

The publication results, total number of citations, and average number of citations of the top 10 countries in the field of international forest ecological benefit compensation research are shown in Table 2.

Table 2. Top 10 countries in terms of the number of articles on forest ecological benefit compensation-related research.

Country	No. of Articles	Total No. of Citations	Average No. of Citations
USA	1234	32,095	26.01
China	574	7070	12.32
Brazil	441	9411	21.34
Canada	352	6845	19.45
Germany	311	7356	23.65
Australia	237	6803	28.70
Spain	212	5086	23.99
England	200	7163	35.82
France	187	4765	25.48
Mexico	167	2867	17.17

The United States published the most articles (1234) in the field of forest ecological benefit compensation, followed by China (574). The top three countries in terms of absolute citation indicators were the United States, Brazil, and Germany. For the average citation indicator, the United Kingdom was highest (35.82), followed by Australia (28.70) and the United States (26.01). Despite China ranking second among the 10 countries in terms of the volume of published articles, it performed poorly in terms of the average number of citations and was ranked lowest with an average citation indicator of 12.32, indicating that the influence of China in this field could be improved.

The collaborative network atlas was used to assess the volume of papers on forest ecological benefit compensation research published in various countries worldwide (Figure 3).

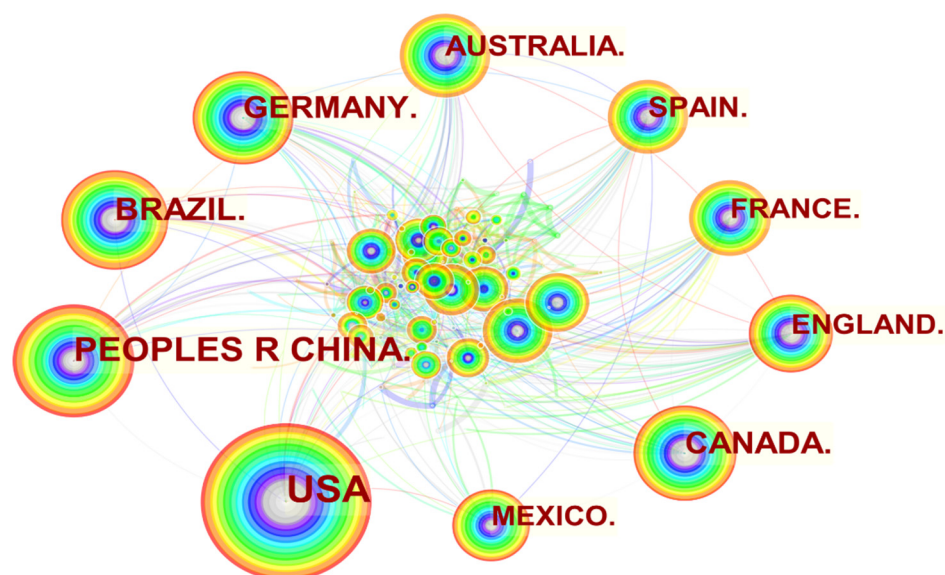


Figure 3. National collaborative network of research on forest ecological benefit compensation.

As of 20 March 2022, the color of the outer ring of each node in Figure 3 corresponds to the total number of publications (the same below). The results showed that forest ecological benefit compensation research primarily occurred in 10 countries: the United States, China, Brazil, Canada, Germany, Australia, Spain, England, France, and Mexico (Figure 3; Table 2). European countries have conducted more research and had more influence in this field than any other region, as four of the top 10 countries are European.

3.3.2. Major Research Organizations

The publication volume, total citation volume, and average citation count for the top 10 scientific research institutions in international forest ecological benefit compensation research are shown in Table 3.

Table 3. Top 10 research institutions in terms of number of articles on forest ecological compensation benefits.

Research Institution	Country	No. of Articles	Total No. of Citations	Average No. of Citations
US Forest Serv.	United States	218	5474	25.11
Chinese Acad. Sci.	China	203	3618	17.82
Univ. Nacl. Autonomia Mexico	Mexico	82	1102	13.44
Univ. São Paulo	Brazil	80	2449	30.61
Swedish Univ. Agr. Sci.	Sweden	77	1837	23.86
Univ. Chinese Acad. Sci.	China	69	631	9.14
Univ. British Columbia	Canada	59	1246	21.12
Oregon State Univ.	United States	57	1358	23.82
Beijing Forestry Univ.	China	48	417	8.69
No Arizona Univ.	United States	48	709	14.77

The global ranking of the top 10 scientific research organizations had an average of 94.1 articles published; however, only two scientific research institutions have published more than the average number of papers, namely the US Forest Service in the United States, which ranked first with 218 articles, and the Academy of Sciences, a Chinese institution located in China, which ranked second with 203 articles (Table 3). The US Forest Service, the Chinese Academy of Sciences, and the University of São Paulo ranked first, second, and third, respectively, among scientific institutions based on total citation metrics. In terms of average citations, the University of São Paulo in Brazil reached 30.61, followed by the US Forest Service in the United States with 25.11; the Swedish University of Agricultural Sciences in Sweden ranked third, with 23.86, and Oregon State University in the US ranked fourth, with 23.82. The Swedish University of Agricultural Sciences was thus only 0.04 units higher than the Oregon State University in the US.

Regardless of the total number of citations, total number of publications, or average number of citations, the scientific research institutions in the United States were at the forefront, indicating their enormous scientific research potential. Despite the University of São Paulo in Brazil only publishing 80 articles, the total number of citations was 2449 and the average number of sources was 30.61, ranking first, indicating that Brazilian scientific research institutions have had a significant influence in the field of forest ecological benefit compensation research.

As seen in Figure 4, this study also investigated the amount of literature on forest ecological benefit compensation by national scientific institutes using collaborative network atlases.

Universities constituted a relatively high proportion of the institutions studying forest ecological benefit compensation (Figure 4). Among the top 10 scientific research institutions with several articles, seven were universities (National Autonomous University of Mexico, University of São Paulo, University of the Chinese Academy of Sciences, University of British Columbia, Oregon State University, Beijing Forestry University, and Northern Arizona University).

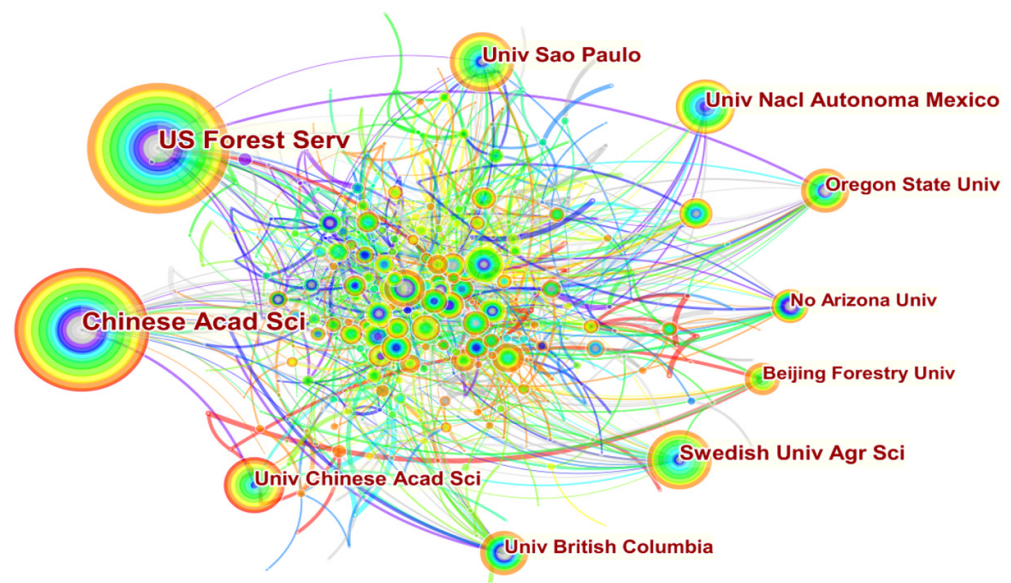


Figure 4. Collaboration network diagram of research institutions related to forest ecological benefit compensation.

3.3.3. Main Authors

Table 4 and Figure 5 present the attributes of the top 10 authors and their research teams in the field of worldwide forest ecological benefit compensation research.

Table 4. Top 10 authors of research related to forest ecological benefit compensation.

Author	No. of Articles	Institution	Country
Kris Verheyen	24	Ghent University Department of Environment Professor	Belgium
Arshad Ali	13	School of Ecological and Environmental Sciences, East China Normal University, Shanghai, China	China
Pedro H.S. Brancalion	12	University of São Paulo	Brazil
Guillaume Decocq	10	Jules Verne University of Picardie	UK
Carlos A. Peres	9	School of Environmental Sciences, Univ. of East Anglia, Norwich, Norwich, UK	UK
Hong S. He	9	School of Natural Resources at the University of Missouri-Columbia, 203 ABNR Building, Columbia, MO 65211, USA	US
Brian J. Palik	9	USDA Forest Service, Northern Research Station, USA	US
Anthony W. D'Amato	9	Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington, VT, USA	US
Bart Muys	8	Department of Earth and Environmental Sciences, Katholieke Universiteit Leuven	Belgium
Milton Cezar Ribeiro	8	Department of Ecology, São Paulo State University (UNESP), Rio Claro, Brazil	Brazil

Of the principal authors, Kris Verheyen from Belgium ranked first with 24 articles. Three times this number of articles were from China, Brazil, the United Kingdom, and the United States.

Five primary research teams in this field were identified, and their effects were more significant and the research results were more prominent, as illustrated in the collaborative network diagram for authors shown in Figure 5.



Figure 5. Collaborative network diagram of forest ecological benefit compensation study authors.

Every node in Figure 5 represents one author; the more prominent a node, the more articles it represents. Cooperation between authors is shown by the connection between the nodes, whereby the stronger the cooperative relationship, the thicker the link. With 571 authors and 400 pooled threads, the author collaboration network depicted in Figure 5 reflects a sizable researcher population and diverse spectrum of collaborative contacts in the International Forest Eco-Benefit Compensation Study. The network analysis revealed the presence of five main research teams, whose partners and fields of study are as follows:

1. With 24 publications, the Kris Verheyen research team (circled in blue in Figure 5) had the largest number of publications. Authors with the most intimate ties and collaborations included Kris Verheyen, Guillaume Decocq, and Bart Muys. It is evident from the color of the links between the nodes that the collaboration between these three authors was most active in 2015 and 2019. Verheyen et al. concentrated on the effects of climate change, land, and forest biodiversity [24–27].
2. More than 13 publications were published by the Arshad Ali research team, with a primary focus on biomass from forests. This research team did not produce any publications in 2018 and reached their zenith in 2019 with the release of five publications. The research team of Arshad Ali is orange in Figure 5, suggesting that they had been active over the last 2 years based on the color of the outer ring of the nodes generated in the collaborative network of authors. The fact that three articles in 2021 and one in 2022 were published lends credence to this. This suggests that more in-depth study and exploration of the topic of forest ecological benefit compensation are anticipated from the research team of Arshad Ali in the future [28–30].
3. The Pedro H. S. Brancalion (yellow circles in Figure 5) research team published 12 papers; however, they did not produce any publications after 2019. The main research direction of the Pedro H. S. Brancalion team was forest and landscape restoration [31].
4. The Carlos Peres research team (green circle area in Figure 5) published nine articles. Their primary research direction was the impact of deforestation on biodiversity [32–34].
5. The Brian J. Palik and Anthony W. D’Amato (orange circles in Figure 5) research team did not have the highest number of published articles. Team network nodes were closely connected, indicating that the team cooperation network was mature, independent, and closely related. The research directions of this team included forest regeneration, forest plant communities, and forest timber management [35,36].

However, the team did not produce any publications after 2020 and will follow up on this study.

3.4. Literature Cited for Analysis

Literature co-citation is used to measure the relationships between publications, which refers to situations when two or more articles are cited by one or more articles at the same time [37–40]. This is an established method used to measure the degree of relationship between publications. The citation frequencies can help to identify research hotspots and trends to a certain extent [41,42]. In addition, the number of sources should be considered as a factor affecting the importance of an article. In summary, exploratory literature should be cited when investigating the research dynamics of forest ecological benefit compensation. Table 5 and Figure 6 illustrate that the top five articles totaled seven, taking into account the centrality of the referenced literature.

Table 5. High frequency of co-citation in the literature on forest ecology benefit compensation.

Total No. of Citations	Centrality	Year	Country	Title
731	0.14	2008	New Zealand	“Plantation forests and biodiversity: oxymoron or opportunity?”
3	0.13	2021	Finland	“Site types revisited: Comparison of traditional Russian and Finnish classification systems for European boreal forests”
329	0.13	2013	USA	“vegan: Community Ecology Package”
339	0.11	2014	USA	“Second growth: The promise of tropical forest regeneration in an age of deforestation”
3867	0.11	2011	USA	“A Large and Persistent Carbon Sink in the World’s Forests”
2	0.11	2016	USA	“Second growth: the promise of tropical forest regeneration in an age of deforestation”
0	0.11	2013	USA	“Managing Forests and Fire in Changing Climates”

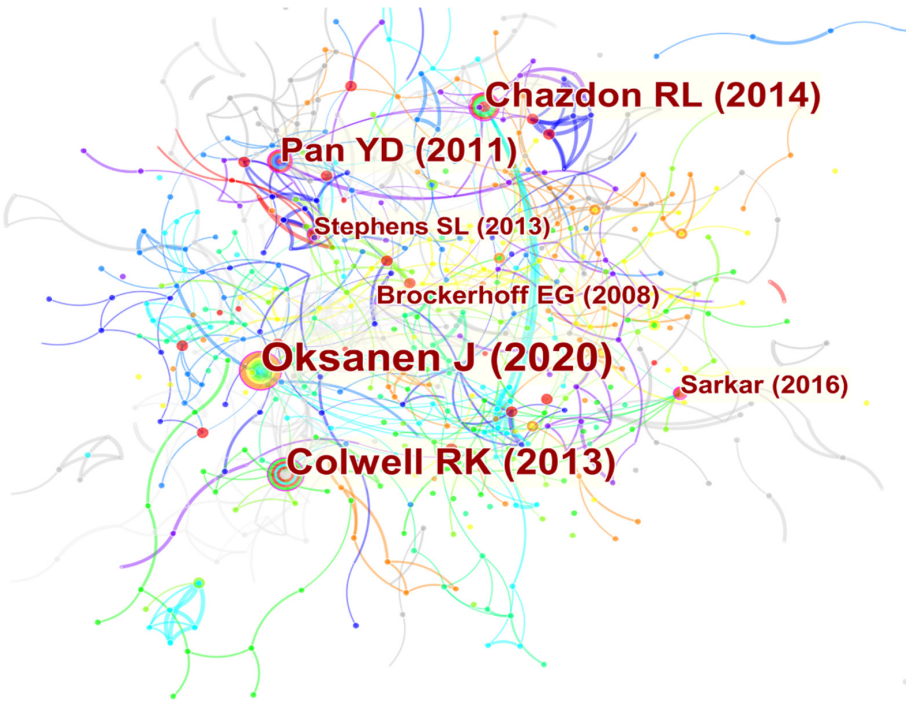


Figure 6. High frequency co-citation literature chart of related research on forest ecological benefit compensation.

Combining the data in Table 5 from a central order perspective indicated that the top three countries were New Zealand, Finland, and the United States, and that the most prominent centrality was 0.14, based on the 2008 New Zealand scholar EG Brockerhoff's "Plantation forests and biodiversity: oxymoron or opportunity?", which mainly investigated the issues of biodiversity conservation, deforestation, and forest management.

In conjunction with Figure 6, co-citations at high frequency were considered and the results in order of central size showed that RK Colwell from Finland came in second place: "Site types revisited: Comparison of traditional Russian and Finnish classification systems for European boreal forests", published in 2021 [43]. This article provides a significant review of forest types and forest species. In third place was J Oksanen from the United States, with "vegan: Community Ecology Package", which focuses on planted forests and biodiversity, published in 2013. The centrality of the remaining four articles was also strong, with a value of 0.11. The literature indicated that scholars have focused on the topic of "forest biodiversity".

3.5. Analysis of Research Hotspots

3.5.1. Co-Occurrence of Keywords

Keywords generally reflect the research direction and scientific interest of an author, show a high degree of condensation, and reflect the key research direction and content of an article. Keywords can be used to quickly browse and directly and efficiently understand the research objectives, methods, content, views of the author, and other useful information [44–50]. Consequently, examining the frequency of keywords in the literature is essential for debating research hotspots in a certain topic as well as their evolution and modifications [51–56].

The primary study emphasis of this area was measured and a significant word co-occurrence network diagram of forest ecological benefit compensation research was produced using the keyword co-occurrence analysis feature in CiteSpace software (Figure 7). Figure 7 shows only the keywords that appeared ≥ 316 times when setting the threshold. The nodes represent keywords and the size of the node represents the frequency of keyword occurrence; the larger the node, the higher the occurrence, and the thicker the line, the higher the frequency of occurrence between the two keywords.

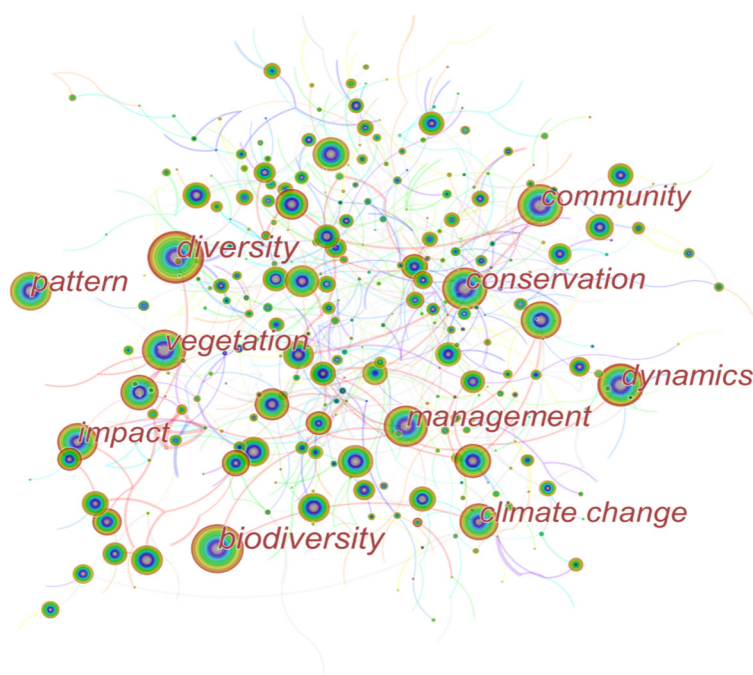


Figure 7. Keyword co-occurrence network diagram for forest ecological benefit compensation.

The keywords with ≥ 316 occurrences were diversity (580), biodiversity (537), conservation (419), management (408), vegetation (385), dynamics (372), patterns (370), communities (336), impact (320), and climate change (316) (Figure 7). Owing to their high frequency, these keywords were regarded as virtual nodes in the network. These critical nodes covered the main contents of international forest ecological benefit compensation research. First, starting from “forest biodiversity”, “how to protect”, and “how to manage”, scholars have carried out research on forest ecological benefit compensation around these starting points. Second, scholars set “forest growth pattern”, “ecosystem services”, “communities”, “climate change”, and “impacts” as the main research directions. Third, the “dynamics” keyword comes into view. It is predicted that scholars will pay more attention to the dynamic changes in forest ecological benefit compensation or in the research impetus to promote the evolution of forest ecological benefit compensation.

A cluster analysis of the keywords used for forest ecological benefit compensation research is shown in Figure 8 to help elucidate the related words with a higher degree of correlation.

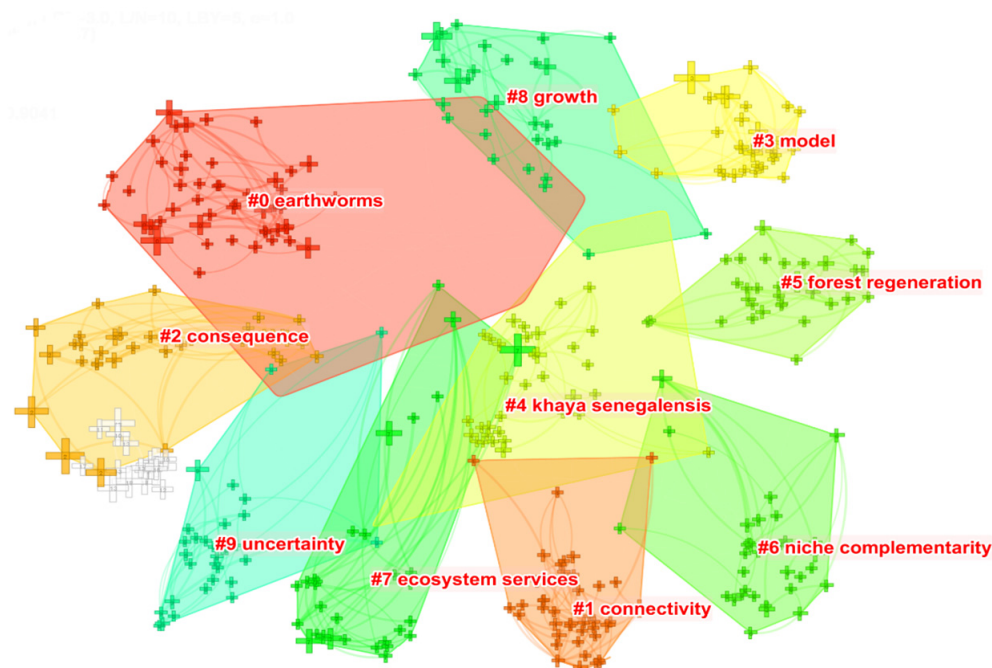


Figure 8. Keywords cluster diagram of forest ecological benefit compensation.

The keywords for forest ecological benefit compensation research could be clustered into ten categories: earthworms, connectivity, consequence, model, *Khaya cenogenesis*, forest regeneration, niche complementarity, ecosystem services, growth, and uncertainty (Figure 8). They were sorted from 0–9, with a smaller number indicating that the cluster contained more keywords. Multiple closely related words formed each cluster, in which keywords were explicitly used in “Cluster Explorer” using the logarithmic likelihood rate (one of the cluster label word extraction algorithms) algorithm to produce the keyword co-occurrence network cluster table (Table 6).

In Table 6, the newly formed cluster name is in the network, generally the primary keyword; however, in the CiteSpace software, it is a cluster of keywords closely related to the algorithm. It then selected the member in the same cluster group with the highest tracing value by assigning a value to each keyword and labeled the member after determining that it was representative of the category, thus forming a new cluster name. In particular, the average contour value of clustering in the network needs to be given more attention because it represents the quality of the clustering results. Generally, when clustering is reasonable, the average contour value of clustering is >0.5 ; when clustering is convincing, the average contour value of clustering is >0.7 .

Table 6. Top 10 clusters of studies related to forest ecological benefit compensation.

Serial Number	Cluster Name	Average Profile Value	Keywords
#0	Earthworms	0.893	earthworms; population; community; indirect effects; species richness
#1	Connectivity	0.867	connectivity; tropics; habitat amount; stable isotope; time series
#2	Consequence	0.942	consequence; urban sprawl; nutrient dynamics; tree diversity; fragmented landscape
#3	Model	0.830	model; ndvi; richness; conservation; landscape ecology
#4	Khaya senegalensis	0.940	khaya senegalensis; ntfp; tropical trees; matrix models; system
#5	Forest regeneration	0.941	forest regeneration; non-timber forest products; plant–plant interaction; socio-ecological system; tree mortality
#6	Niche complementarity	0.844	niche complementarity; soil nutrients; evergreen broadleaf forest; roe deer; community-weighted mean
#7	Ecosystem services	0.913	ecosystem services; payments for ecosystem services; management; economic valuation; policy
#8	Growth	0.922	growth; availability; pine; 2; generalized linear models
#9	Uncertainty	0.819	uncertainty; risk; diversification; last glacial maximum; null models

The average contour value of clustering was much larger than 0.7 in the top 10 forest ecological benefit compensation studies, as indicated by the pertinent data in Table 6. As a consequence, the suggested clustering findings can be considered persuasive. This can also be used to verify whether it is correct to select forest environmental benefit compensation as the title of the article, such as #0 clustering: “earthworms” contained research topics mainly on earthworms, population, community, indirect effects, and species richness. Evidently, these topics are all related to the theme of the ecological environment, and the fragment under the other nine types of clustering labels can be used as an analogy.

3.5.2. Burstiness Keywords

Burst detection may be used to investigate transient and developing trends and provide a precise visualization analysis based on the length of popular themes in both domestic and international academic domains. It can also be utilized as a sign of high activity in the study field. The node with the highest keyword prominence and the most evident research orientation is the node that must be taken into account in the study. After considering the sudden characteristics of CiteSpace, the intensity maps of 10 keywords from 2009–2022 were drawn, similar to Figure 9. Among them, “strength” is on behalf of the power of the sudden. Beyond that, the beginning represents the year of impulsive start, the year of premature termination is presented at the end, and red represents the year when the keywords were prominent.

“Dispersibility” was the term with the greatest outbreak intensity value of 8.57 from 2009–2022; this term suddenly emerged in 2011 and was then terminated in 2014 (Figure 9). The actual context of this period is that the United Nations had designated 2011 as the International Year of Forests, with the theme of “Forests for the People”, which aimed to arouse public awareness of environmental protection, promote activities such as forest protection, development, and management on a global scale, and give full play to the critical role of forests in fostering sustainable economic and social development. Taking forests as the research object, the essential role of ecological filtering and dispersal limitations in species coexistence is discussed.

Top 10 Keywords with the Strongest Citation Bursts

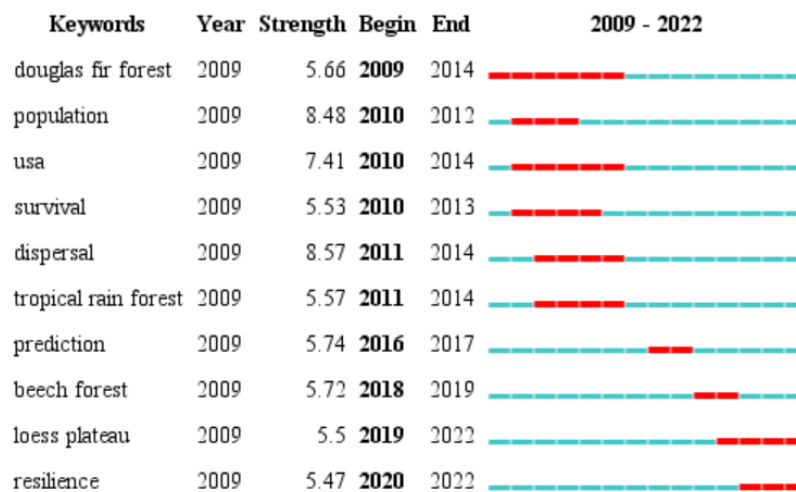


Figure 9. Burst of keywords related to forest ecological benefit compensation (2009–2022).

Excessive emphasis has also been placed on terms such as “Douglas fir forest”, “population”, “USA”, “survival”, “tropical rain forest”, “prediction”, “beech forest”, “Loess Plateau”, and “resilience”. Although the level of surprise is >5 , research on forest ecological benefit compensation has continuously been improving. Currently, the focus given to the remaining terms has decreased, with the exception of “resilience” and “Loess Plateau”, which have continued to receive attention.

Lastly, since 2019, the term “Loess Plateau” has continued to garner considerable attention and high burst intensity. As the world continues to warm, increasing attention is being paid to the regulatory functions of terrestrial ecosystems in response to climate change [57–61], among which increasing vegetation has been vigorously promoted as an effective method of climate change mitigation [62–65]. The ecological environment of the Loess Plateau has been severely damaged by human activities. Consequently, there have been numerous studies on habitat management in the Loess Plateau, increasing the frequency of this keyword.

4. Discussion

The essential characteristics of global forest ecological benefit compensation literature were analyzed and interdisciplinarity, research strengths, and research hotspots were identified. The results were then used to derive the following recommendations for this field of research:

- (1) Forest ecological benefit compensation research involves multiple disciplines and has strong intersections, particularly in the fields of environmental science and ecology, which serve as interdisciplinary hubs. A large amount of research has focused on the quantitative evaluation and measurement models of forest ecological benefit compensation, as well as the interaction and superposition effects of forest ecological benefits. Therefore, the relevant disciplines should be used to strengthen cooperation and communication in this field to promote progress in theoretical and practical research on forest ecological compensation.
- (2) In the context of frequent human activities and prominent ecological and environmental issues, protection and management of forest biodiversity has become urgent and must be addressed by the academic community and government departments of various countries. Actively protecting and effectively managing forest biodiversity is an important global task that is required to maintain ecological balance and facilitate sustainable development. All governments, academic institutions, communities, and people in every nation must engage in this. Promoting research on the

dynamic shifts and important motivators of forest ecological benefit compensation, such as mitigating the effects of climate change and desertification, should also receive particular emphasis.

- (3) Although the CiteSpace software used in this study has been widely used in bibliometric research, some issues remain, such as the inability to distinguish between the first and corresponding authors. Interdisciplinary modeling of forest ecological compensation may be accomplished through the use of machine learning. This will yield valuable insights into solving challenging social ecological restoration issues. Hence, forest ecological benefit compensation should be investigated using machine learning and large data mining techniques in the future.

The objective bibliometric examination of literature data served as the foundation for this study, and the findings are consistent, reliable, and mostly unaffected by empiricism. Hence, the results have theoretical importance and value, and will aid in clarifying the dynamics of the research and advancing knowledge in the subject of forest ecological benefit compensation.

5. Conclusions

The study used the SCI-E and SSCI databases from the Web of Science core collection as sample data sources and CiteSpace visualization software to draw a knowledge map of international forest ecological compensation research from 2009–2022. A systematic and detailed analysis was conducted of the basic characteristics of the literature, interdisciplinary intersections, countries, institutions, authors, co-citations, and hotspots. Future directions were discussed based on the analysis of the international development trends in this field.

Internationally, research on ecological issues began as early as the 1960s, while China established a special fund in the early 21st century for the development of forest ecological benefit compensation policies, indicating the commencement of formal research. Therefore, research in this field began later in China; however, in recent years, progress has been significant and is currently in a period of rapid development. By analyzing the research status of international forest ecological compensation, it was found that: (1) within the scope of quantitative statistics, Kris Verheyen from Belgium had the most publications, and the other authors were predominantly from China, Brazil, the United Kingdom, and the United States. Five primary research teams were identified. The Kris Verheyen team published the most articles, followed by teams led by Arshad Ali, Pedro H. S. Brancalion, Carlos A. Peres, Brian J. Palik, and Anthony W. D’Amato; (2) overall, cooperation between most international research institutions was relatively close, although cross-national collaboration was the lowest. From a temporal perspective, collaborative relationships between research institutions primarily formed in the early 21st century.

Analysis of the research topics on international forest ecological compensation revealed that: (1) from the perspective of temporal changes, forest biodiversity, forest growth patterns, ecosystem services, communities, and climate change have always been important research hotspots in international forest ecological compensation research. (2) The results of keyword clustering analysis indicated that the international research hotspots have focused on forest regeneration, niche complementarity, and ecosystem services, covering most areas of forest ecological benefit compensation research. Research on international forest ecological compensation has had wide coverage and a certain breadth and depth; however, there has also been an imbalance in various research fields. (3) The results of keyword emergence analysis indicated that the forefront of future international research on forest ecological benefit compensation may lie in environmental filtering, species coexistence, ecological restoration ability, and other aspects of forest ecological benefit compensation.

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