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Emerging Lines of Research Related to Ecological Compensation Models. A Bibliometric Review Study

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Abstract: There are multiple models of ecological compensation found in the scientific literature; however, these models are directed to particular case studies and consequently show the absence of a universally applicable model. The current ecological crisis requires effective solutions for the consumption of ecosystem components through compensation. From this perspective, this study aims to identify emerging lines of research in the field of ecological compensation from a bibliometric study in the scientific databases of Scopus and Web of Science based on the exploration of 186 articles using VOSviewer software. It is also intended to analyze the identified clusters. The findings allowed the identification of three emerging research trends in this field through cluster grouping: 1) multivariate statistical models for ecological compensation, and 2) models based on compensation accounting and the value of ecosystem services.3 Valuation models for ecological compensation of geographic mapping. After analyzing each of these trends, it is concluded that there is no single model for the universal application of ecological compensation, so it is necessary to build valuation coefficients that allow homogenizing the magnitudes that come from the multiple measurements used in the identified approaches. It is proposed to build standardized and generally accepted ecological compensation models that materialize successful solutions to achieve compensation derived from the use of ecological components in the management of productive, social, and environmental projects.

Keywords: sustainability; ecological compensation; valuation

与生态补偿模型相关的新兴研究方向。文献计量综述研究

摘要：科学文献中存在多种生态补偿模型；然而，这些模型都是针对特定案例研究的，因此缺乏普遍适用的模型。当前的生态危机需要通过补偿来有效解决生态系统成分的消耗问题。从这个角度来看，本研究旨在通过 Scopus 和 Web of Science 科学数据库中的文献计量研究，基于使用 VOSViewer 软件探索 186 篇文章，确定生态补偿领域的新兴研究方向。它还旨在分析已确定的集群。研究结果允许通过集群分组确定该领域的三个新兴研究趋势：1) 生态补偿的多元统计模型，以及 2) 基于补偿核算和生态系统服务价值的模型。3 地理测绘生态补偿的估值模型。在分析了这些趋势之后，得出结论，没有一个普遍适用的生态补偿模型，因此有必要建立估值系数，以使来自已确定方法中使用的多种测量的量级均质化。建议建立标准化、普遍接受的生态补偿模式，实现在生产、社会和环境项目管理中使用生态成分所产生的补偿的成功解决方案。

关键词： 可持续性; 生态补偿; 评估

1. Introduction

Measurement and valuation models for ecological compensation have varied approaches, as they have been developed theoretically and methodologically based on specific case studies. The aim of this study is to identify emerging lines of research on ecological compensation models, drawing from various methods, methodologies, and models that have been developed in case studies and other types of documented research found in the scientific databases Scopus and Web of Science. To achieve this objective, a search was conducted in these databases, and the data were processed and classified using VOSviewer, a free software created by Nees Jan van Eck and Ludo Waltman from CWTS Leiden University, to build and visualize bibliometric networks. These networks belong to scientific journals, researchers, or individual publications, and through text mining, they are used to construct and visualize networks of co-occurrence from texts found in the scientific literature [1]. The number of years consulted ranged from 2015 to 2024. This analysis allowed us to identify several models, methodologies, and methods used for case studies with an ecological compensation approach, given that the problem refers to the ecological deterioration produced by different environmental, social, and economic projects.

In recent years, there has been a growing focus on ecosystem services and ecological compensation in response to widespread environmental degradation. Some institutions and research initiatives have also directed attention to the examination of these concepts within World Heritage Sites [2]. Ecological compensation has been demonstrated to be an effective strategy for addressing conflicts between regional environmental conservation and economic development. Globally, imbalances in patterns and negative effects on ecological benefits have affected the effectiveness of ecological compensation [3].

In this sense, this document is structured as follows. In the first section, each of the networks and links established by the clustering was analyzed, starting with documents by year, most relevant authors, thematic area, most relevant institutions, most relevant countries or regions, references, keywords, emerging research trends by authors, and analysis of the clusters. Finally, an analysis was conducted based on the aforementioned clusters with a deterministic orientation to identify emerging trends related to ecological compensation models.

Similarly, the common element for each group was identified, finding the following trends: (1) statistical models for ecological compensation; (2) models based on compensation accounting and the value of ecosystem services; and (3) valuation models for ecological compensation of geographic mapping.

Finally, some recommendations for future research are provided.

2. Methodology

2.1. Data Sources

Data were extracted from the scientific databases Scopus and Web of Science using the search criteria set out in Table 1.

Table 1 Search criteria for bibliographic selection in scientific literature (compiled by the authors)

Selected criteria	Scopus	Web of Science
Years of consultation	2015–2024	2015-2024
Subject area	-Environmental science -Engineering -Energy -Earth and planetary sciences -Economics, Econometrics and Finance. -Business, Management and Accounting	-Environmental science -Engineering -Science, technology and other topics -Business economics -Biodiversity conservation -Physics
Document type	-Articles -Session document	-Articles
Magazine Selection	-Any type	-Highly cited articles -Review articles -Early Access Articles -Open access articles.
Language	-All languages	-All languages
Terms used for the search	“Ecological AND compensation AND model OR ecocompensation AND in AND projects.”	“Ecological AND compensation AND model OR ecocompensation AND in AND projects.”
Partial result	126 documents	256 documents
Total result	Documents	

2.2. Search Equation in Scopus

“Ecological AND compensation AND model OR ecocompensation AND in AND projects.”

Refinements that modified the search in Scopus:

“Title-abs-key (ecological and compensation and model or ecocompensation and in and projects) and (limit-to (subjarea, “envi”) or limit-to (subjarea, “agri”) or limit-to (subjarea, “soci”) or limit-to (subjarea, “engi”) or limit-to (subjarea, “ener”) or limit-to (subjarea,”eart”) or limit-to (subjarea, “econ”) or limit-to (subjarea, “busi”)) and (limit-to (exactkeyword, “ecological compensation”) or limit-to (exactkeyword, “environmental protection”) or limit-to (exactkeyword, “compensation”) or limit-to (exactkeyword, “sustainable development”) or limit-to (exactkeyword, “ecosystem service”) or limit-to (exactkeyword, “ecology”) or limit-to (exactkeyword, “offset system”) or limit-to (exactkeyword, “economic development”) or limit-to (exactkeyword, “ecosystems”) or limit-to (exactkeyword, “biodiversity”) or limit-to (exactkeyword, “sustainability”) or limit-to (exactkeyword, “project management”) or limit-to (exactkeyword, “ecosystem”) or limit to (exactkeyword, “theoretical model”) or limit-to (exactkeyword, “ecological protection”) or limit-to (exactkeyword, “ecological restoration”) or limit-to (exactkeyword, “eco-offsetting”)).”

WoS search equation:

“Ecological AND compensation AND model OR ecocompensation AND in AND projects.”

“Refine the results for the ecological offset or eco-offset model in projects (All fields) and Highly cited articles (Exclude) and Review article or Early access (Exclude - Document types) and Open access (Exclude) and 2011 or 2012 or 2013 or 2014 (Exclude - Publication years) and Environmental Sciences Ecology or Engineering or Science Technology Other Subjects or Business Economics or Biodiversity Conservation or Mathematics Computational Biology or Physics (Research Areas) and Water Resources or Geosciences Multidisciplinary or Civil Engineering or Geography Physical Environment or Public Occupational Health or Engineering Multidisciplinary or Instruments Instrumentation or Toxicology or Urban Studies or Construction Technology or Building Engineering Electrical Electronics or International Relations or Freshwater Marine Biology (Exclude - Web of Science Categories)”

2.3. Analysis Tools

The VOSviewer software is an important tool for visually representing co-occurrence data in bibliometric maps. Although it does not have the capability to create matrices, it enables visualization. It is a robust tool for visualization, offering label-, density-, cluster density-, and scatter-view options. According to [4], in terms of methodology, a quantitative methodology is used for the construction of bibliometric maps, which requires: a) data collection, b) selection of analysis units, c) calculation of the frequency of co-occurrences, and co-authorships by countries and authors, and d) visualization of the corresponding analysis units in two-dimensional maps [5]. This method enables the implementation of different segmentation algorithms through an improved form of multidimensional scaling, which prevents visualization issues, such as creating circular representations or positioning important terms in the center of the visualizations. The clustering algorithm incorporates multiple resolution parameters determined by the specified configuration values [6].

The method of author concurrence analysis was carried out through the following stages: (1) importing the selected articles in the WoS and Scopus databases, as a result of introducing the search equation into the VOSviewer software. Subsequently, the concurrence by authors, which generates three groups or clusters, identifies homogeneous segments of models, methodologies, and methods of ecological compensation present in the tracking of the referred information. Finally, the positioning and visualization of the data obtained in the bibliometric map are analyzed, in which the relationships between authors are represented in the form of links distributed in nearby points in a multidimensional space. Finally, the results obtained in the generated clusters were interpreted, which allowed for the identification of emerging trends in research on the different forms of instrumentalization in ecological compensation from the implementation of productive, environmental, or social projects.

3. Results

3.1. Publication Propensity

When analyzing the trends and trajectories of research related to ecological compensation models in project execution, the publications contained in WoS and Scopus between 2015 and 2024 were compared, the joint production of these scientific databases was calculated, and the search was refined by eliminating matches, as shown in Figure 1.

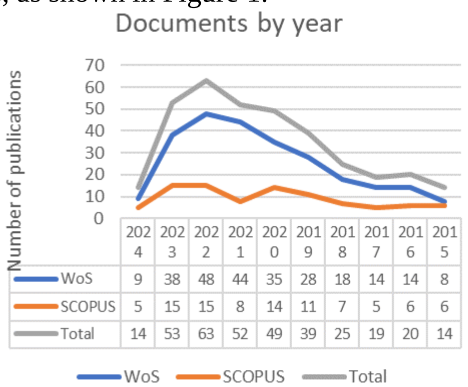

Figure 1. Documents per year (elaborated by the authors)

According to the information analyzed in 2014, Wen [7] was the first author to address the topic of ecological compensation, arguing that this topic does not come from a new concept. In the same year, academic production in the referred area represented only 4%, and this trend remained in single digits until 2019, when the percentage of publications increased to 11%, a trend that continued to rise, reaching its peak in 2022 with 18% production on this topic. However, a decrease of three percentage points is observed in 2023, with 15% of production and 2024, which represents 4% of intellectual production in the first half of the year. Similarly, the growing interest in ecological compensation in the last five years was identified, since its sum represents 77% of the total range delimited for analysis.

3.2. Most Relevant Authors

Borges-Matos is one of the most cited authors in this thematic reference, whose latest publications were written in co-authorship with Maron [8], which reflects the author’s interest in the thematic area of ecological compensation and its importance in the subject. This author, in co-authorship with other authors, reaches 408 citations in the analyzed period from 2015 to 2024. S. W. Broch, in co-authorship, adds 90 citations, followed by M. Zafonte, in co-authorship with a total of 69 citations; X. An, in co-authorship, adds 63 citations; Y. Ren reflects 62 citations; I. Liekens adds 59 citations in co-authorship; I.W. Bull, in co-authorship, adds 57 citations as X. Chu in co-authorship; X. GAO in co-authorship, adds 48 citations, and finally, I. Begés adds 41 citations, as shown in Figure 2.

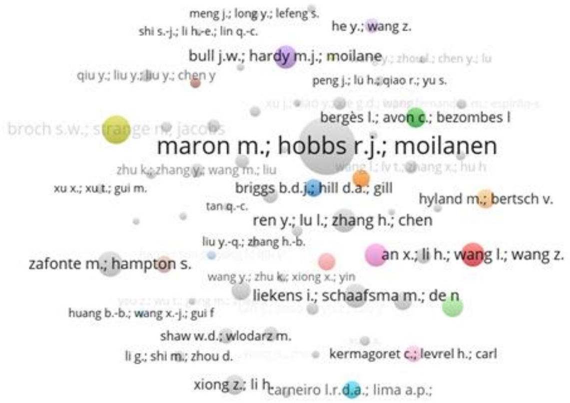

Figure 2 Authors with the greatest relevance in ecological compensation (elaborated by the authors based on VOSviewer))

Maron works on issues related to the biodiversity net gain policy, its design, and the consequences of biodiversity offsetting, forest conservation and restoration, and forest bird communities in Australia [9]. She also collaborates with different people and governmental and non-governmental organizations to achieve the materialization of her line of research in environmental policies and management, applying ecological knowledge to reduce and stop the decline of biodiversity [9].

Richard J. Hobbs, an Australian ecologist from the University of Western Austria, focuses on vegetation management, ecosystem rehabilitation and restoration, and conservation biology [10].

Atte Moilanen works on sustainable conservation solutions in Finland and elsewhere in the world, using the spatial conservation planning software Zonation, which is also used in the implementation of the IBC-Carbon project to examine opportunities to safeguard forest biodiversity, carbon sequestration, and other ecosystem services [11].

The axis of research that unites the three authors in terms of their relevance is their common interest in the conservation of biodiversity and its restoration through intellectual contributions, which have become fundamental references within this research trend.

Thematic area focused on ecological compensation.

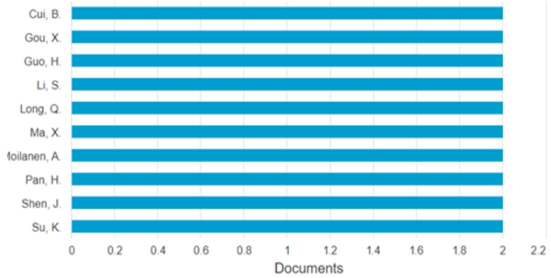

Figure 3. Bar graph of documents by author on ecological compensation models (elaborated by the authors based on Scopus 2023)

The most cited authors are listed in [12].

Table 2. Cited documents by subject area (compiled by the authors)

Subject Area	Scopus	WoS	Total
Environmental science	91	274	365
Agricultural and Biological Sciences Social Sciences	49		49
Social Sciences	25		25
Energy	15	43	58
Engineering	12	88	100
Economics, Econometrics and Finance	8	38	46
Biochemistry, Genetics and Molecular Biology	7		7
Business, Management and Accounting	7		7
Earth and Planetary Sciences	7	24	31
Medication	6		6
Computer Science	5		5
Decision Sciences	4		4
Mathematics	1		1
Multidisciplinary	1		1

Interdisciplinarity from the perspective of environmental, agricultural, biological, and social sciences has a clearly defined objective: facilitating the reappropriation of nature by assessing its ecological potential, which has traditionally been addressed by these fields of knowledge when they refer to the principle of self-management of agrarian societies and the primary productivity of natural ecosystems [12]. However, the science and practice of ecological restoration are increasingly required to compensate for the loss of biodiversity caused by development projects [13]. Ecological compensation as a trend has become very common in various fields of knowledge owing to the imbalance in the development of modern society, economy, and environment, and the increased pressure on the carrying capacity of ecosystems.

However, the various approaches used to quantify ecological compensation standards differ significantly [14]. In this sense, quantitative assessment as a common element to the areas of knowledge focused on ecosystem protection and forms of compensation have been used to determine the status and trends of biological, physical, or chemical/radiological conditions; carry out environmental impact assessments; take corrective actions in case of remediation failure; manage ecosystems and wildlife; and evaluate the effectiveness of remediation, restoration, and long-term management.

Various disciplines are involved in ecological assessment, including biologists, conservationists, foresters, restoration ecologists, ecological engineers, economists, hydrologists, and geologists.

Because ecological assessment forms the basis of many different types of environmental management, it seems reasonable to integrate management options to achieve economies of time, energy, and cost. Integration and iteration between these disciplines is only possible with ongoing interactions among practitioners, regulators, policymakers, and others [15].

These reasonings induce the generation of a hypothesis on the subject:

H1: Interdisciplinarity is essential to address the complexity of ecological compensation models, considering the analysis factors necessary to base effective solutions to their detriment.

3.3. Most Relevant Institutions by their Citations

The results of the relevancy analysis of institutions are given in Figures 4 and 5, and Tables 3 and 4.

Figure 4. Most relevant institutions in ecological compensation research (elaborated by the authors)

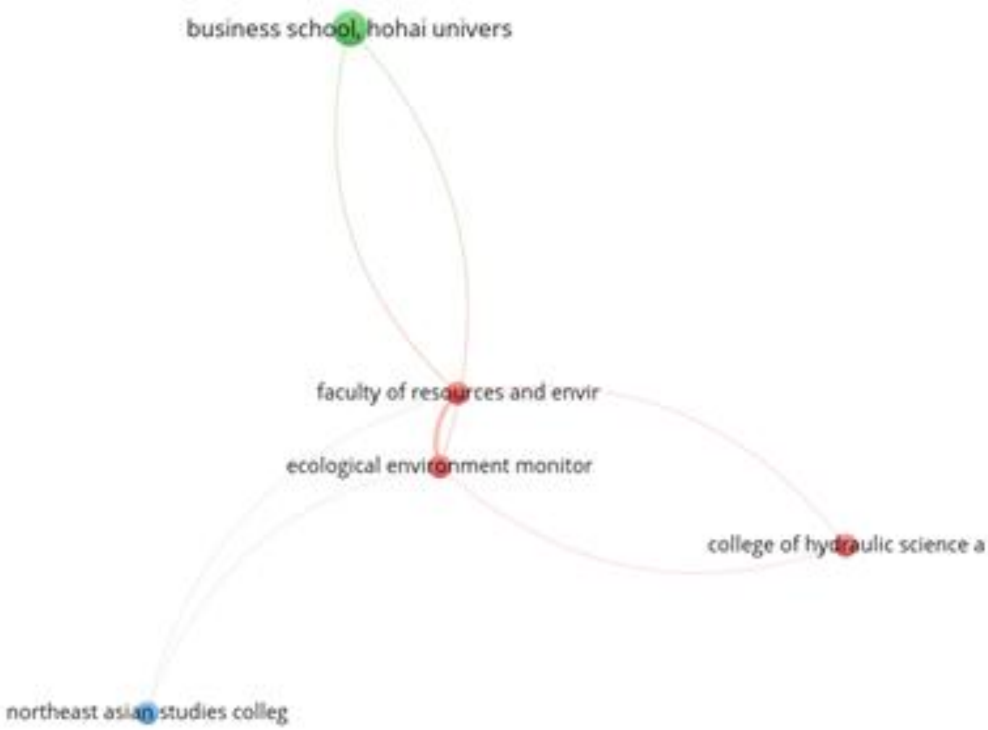

Figure 5. Most relevant institutions by total links (elaborated by the authors)

Table 3. Relevant institutions in ecological compensation research (compiled by the authors)

Organization	Documents	Cited
Business School, Hohai University, Nanjing, 211100, China	5	143
College of Humanities and Development Studies, China Agricultural University, Beijing, 100193, China	2	4
College of Hydraulic Science and Engineering, Yangzhou University, YangZHOU 225009, China	2	27
Ecological Environment Monitoring Center Station of Hubei Province, Wuhan, 430071, China	2	27
Faculty of Resources and Environmental Science, Hubei University, Wuhan, 430062, China	2	19
Institute of Ecological Civilization, Jiangxi University of Finance and Economics, NanCHANG 330013, China	3	24
Institutes of Science and Development, Chinese Academy of Sciences, Beijing, 100190, China	3	24
Northeast Asian Studies College, Jilin University Changchun 130012, China	2	22
School of Economics and Management Changsha University of Science and Technology, China	2	5
School of Electrical and Information Engineering, Changsha University of Science and Technology, China	2	5
Stake Key Laboratory of Hydrology Water Resources and Hydraulic Engineering Nanjing.	2	9
University of Chinese Academy of Sciences Beijing 100049, China	2	22

Table 4. Institutions by total links and citations (compiled by the authors)

Organization	Documents	Citations	Total links
Institutes of Science and Development, Chinese Academy of Sciences, Beijing, 100190, China	2	27	188
Faculty of Resources and Environmental Science, Hubei University, Wuhan, 430062, China	2	27	188
School of Economics and Management, Changsha University of Science and Technology, Changsha, 410114, China	2	5	66
School of Electrical and Information Engineering, Changsha University of Science and Technology, Changsha, 410114, China	2	5	66
Institutes of Science and Development, Chinese Academy of Sciences, Beijing, 100190,	3	24	24

Continuation of Table 4

Business School, Hoai University, Nanjing, 211100, China	5	143	20
University of Chinese Academy of Sciences, Beijing, 100049, China	2	22	13
State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing Hydraulic Research Institute, Nanjing, 210029, China	2	9	11
College of Hydraulic Science and Engineering, Yangzhou University, YangZHOU 225009, China	2	18	6
Northeast Asian Studies College, Jilin University, Changchun, 130012, China	2	22	2
College of Humanities and Development Studies, China Agricultural University, Beijing, 100193, China	2	4	0
Institute of Ecological Civilization, Jiangxi University of Finance and Economics, NanCHANG 330013, China	2	19	0

The institution considered relevant from this bibliographic review is the Business School of Hohai University, which directs its research projects related to environmental issues through the Institute of Environmental Accounting and Asset Management of Hohai University, formerly known as the Institute of Asset Management, founded in November 2001. Its main research directions are the following environmental accounting, environmental economics, water resources, economics and technical management, investment management, financial accounting, quantitative economics theories, and valuation methods.

3.4. Most Relevant Countries and Regions

In the early 1990s, China was largely arid, with forest cover accounting for only 14% of its total surface area because of abusive agricultural practices, inappropriate political decisions, and migration patterns, as well as uncontrolled commercial activity that resulted in natural disasters. Towards the end of the 20th century, this situation led the Chinese government to initiate actions aimed at caring for and conserving the environment. In this sense, previous programs in this direction with successful results are the Three-North Shelterbelt Forest Program; the project on afforestation, research, planning, and forest development in the Northern Region; the natural forest protection project; the slope land conversion program; and finally, the Grain for Green program [16].

In environmental damage lawsuits, China has focused too much on "punishing" violators and neglected the value of ecological restoration of the environment. Article 1234 of the 2021 Civil Code of China provides important institutional guidelines for ecological environment restoration and sustainable development in China [17]. China outperforms other emerging economies in the race of economic growth but has remained the most polluting economy in the past decades. This requires academic attention because it is one of the largest emitters of emissions, reaching 3 tons (billions) due to economic reflection [18].

Countries' relevance in terms of ecological compensation research is shown in Table 5 and Figure 6.

Table 5. Most relevant countries by documents and citations on ecological compensation research (compiled by the authors)

Country	Documents	Citations
China	104	839
United States	6	531
France	5	71

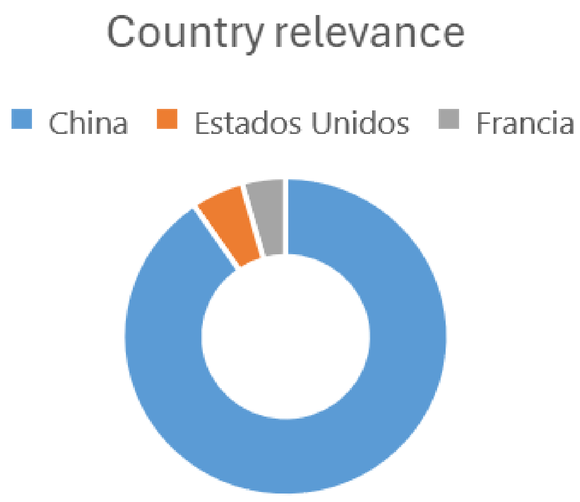

Figure 6. Most relevant countries in ecological compensation research (elaborated by the authors)

3.5. Co-Citation by References

Figure 7 and Table 6 show frequency of co-citation by references of studies on ecological compensation.

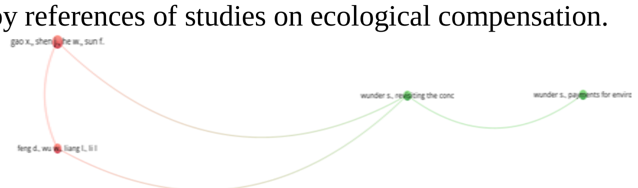

Figure 7. Co-citation by references of research on ecological compensation (elaborated by the authors)

Table 6. Co-citation by references (compiled by the authors)

Co-citation by citation of authors	citations	Total links
Feng et al. [19].	3	3
Gao et al. [20]	5	3
Wunder [21]	3	3
Wunder [22]	3	1
Costanza et al. [23]	3	0
Reid et al. [24]	5	0
Qin et al. [25]	3	0

The co-authorship of these citations is based on the ecological compensation approach, which relates to payments for ecosystem and environmental services. There is a considerable challenge to achieving the Sustainable Development Goals (SDGs) of ending poverty and maintaining ecosystem functions in rural areas, largely because the livelihoods of rural people depend heavily on fragile ecosystems. China has ambitions to solve this problem by enacting economic stimulus policies such as ecological compensation. for ecological protection, and payment for ecosystem services [26].

Case studies that corroborate this claim include the Grain for Green Program, the world's largest payment for ecosystem services, and over the past 20 years, the Chinese government has implemented in stages that have deeply affected socio-ecological benefits, such as the Loess Plateau in China, one of the regions with the most severe soil erosion and the most fragile areas [27]. At present, China has established a compensation system for the ecological benefits of forests and has increased the management and protection of natural and public welfare forests [27]. Payments for ecosystem services were designed to reduce the impact of human activities on eco-sensitive areas. These programs often adopt economic incentives and command-control strategies for ecosystem restoration and compensation [28].

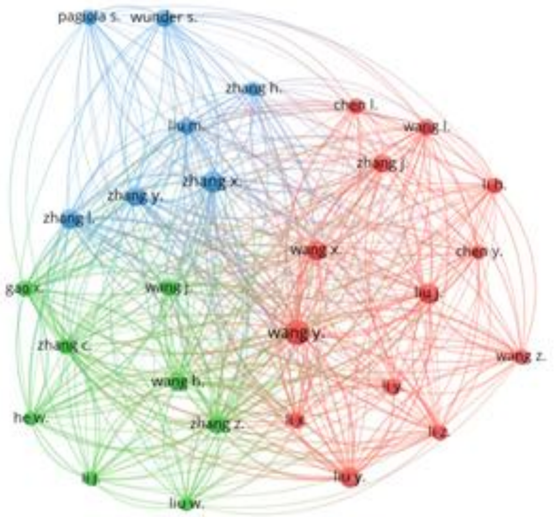

Figure 8. Correlation of authors by reference (elaborated by the authors)

Table 7. Correlation of authors by references (compiled by the authors)

ID	Author	Citation	Total links
1115	Chen L. [29], [70]	23	275
1151	Chen Y. [30], [41], [43]	22	407
2251	GAO X. [20], [31]	28	904
2789	HE W. [20], [31]-[32]	21	702
3928	LI H. [33]-[34]	25	460
3939	LI J. [38]-[39]	21	482
3983	LI X. [40]-[46]	27	720
3992	LI Y. [42], [47]-[49]	28	496
4000	LI Z. [31]	25	605
4125	LIU J. [50]-[51]	41	673
4143	LIU M. [52]	26	619
4161	LIU W.	20	458
4175	LIU Y. [53]-[59]	41	867
5306	PAGIOLA S. [60]	25	
7360	WANG H. [42], [57], [61]-[62]	33	808
7370	WANG J. [31], [34], [63]-[64]	28	676
7383	WANG L. [49], [65]-[66]	27	590
7410	WANG X. [46], [48], [61], [67]-[68]	39	771
7426	WANG Y. [38], [44], [59], [67]-[71]	68	1542
8217	ZHANG H. [18], [36], [58], [72]-[73]	22	351
8226	ZHANG J. [72], [75]-[78]	34	594
8233	ZHANG L. [45], [63], [72]	38	873
8263	ZHANG X. [20], [26], [29], [31], [64]-[65], [78], [100]	49	1214
8273	ZHANG Y. [14], [44], [66], [70], [72], [76], [79]-[82]	40	921
8284	ZHANG Z. [2], [20], [64]	35	1096

3.6. Keywords

The keywords have the purpose of making the content communicable and recoverable for the scientific community to which it belongs or for those to which it is transversal in an interdisciplinary way [81]. They could well guide the trend in topics related to ecological compensation, as presented in the articles consulted in the scientific databases WoS and Scopus. China is highlighted with 266 links, a situation that is jointly reflected in the analysis carried out in the country with the greatest relevance in this field of knowledge (Figure 9, Table 8).

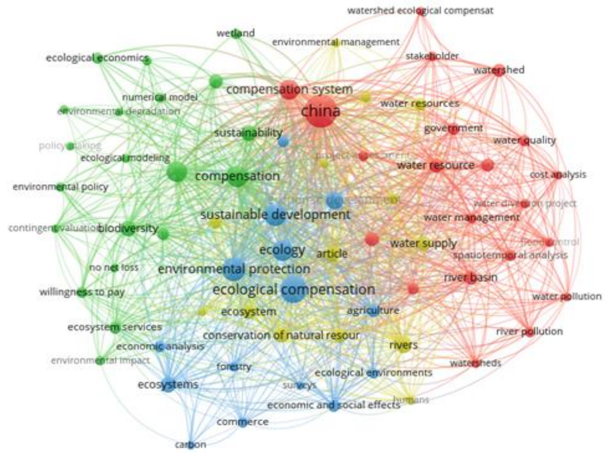

Figure 9. Keywords related to ecological compensation in articles (elaborated by the authors

Table 8. List of keywords referenced in the articles analyzed (compiled by the authors)

Keyword	Occurrences	Total link strength
Biodiversity	16	56
China	67	286
Compensation	30	149
Compensation system	26	86
Conservation of natural resources	14	121
Ecological compensation	47	152
Ecology	28	132
Economic and social effects	10	63
Economic development	20	97
Economics	10	67
Ecosystem service	28	130
Environmental protection	34	183
Rivers	17	123
Sustainability	15	74
Sustainable development	30	144
Water resource	12	72
Water resources	10	72
Water supply	13	116

3.7. Cluster Study Generated by Co-occurrence of Authors in Publications Referring to Ecological Compensation

3.7.1. Cluster 1. Multivariate Statistical Models for Ecological Compensation

The first cluster consists of a grouping or classification of models tending towards some form of ecological compensation based on multivariate statistical methods that are used for case studies, where it is possible to extract data that have some relationship and that fit some type of statistical response that is required to be obtained, based on parameters that fit the model to the data and identification of properties to mitigate statistical errors.

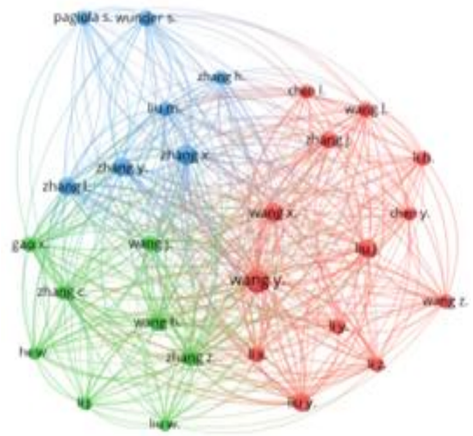

Figure 10 Co-occurrence of authors in the study of ecological compensation (elaborated by the authors)

3.7.2. Cluster 2. Models Based on Compensation Accounting and the Value of Ecosystem Services

The second cluster grouped scientific writings on models based on accounting for compensation and the value of ecosystem services. From the economic and ecological perspective, the use of calculations based on use and non-use values is observed, consisting of establishing whether the value is clearly given by biodiversity in a direct way, and how it benefits economically; while non-use values determine cultural values that produce economic benefits to measure the value of ecosystems and calculate some forms of compensation based on this valuation, which can be economic or ecological, with the first one predominating [82]. These models provide elements of analysis for land management decision-making that safeguards these services and optimizes human well-being.

3.7.3. Cluster 3. Valuation Models for Ecological Compensation of Geographical Mapping

The third cluster compiles valuation models for ecological compensation of geographic mapping. These allow the identification of the spatial distribution of ecosystem services and the changes experienced over a period of time in order to monitor the natural resources contained in the delimited area and the flow of services, and to plan and manage the territory [83]. It is to some extent related to cluster 2, because these models are also used to quantify ecosystem resources and guide the communication of decision makers. Promoting Sustainable Policies.

3.8. Cluster Analysis

This study highlights the important aspects of ranking in relation to ecological compensation models in Scopus and WoS articles. The first method analyzes the relationship between the average and dispersion of data; however, its limitations in handling specific types of data make it difficult to obtain accurate solutions. The second group categorizes models based on accounting and economic valuations of ecosystem services. The third group of studies focuses on assessing the value of ecological compensation through land mapping and monitoring. However, the calculation and conversion of different land types have been debated. There is a need to establish evaluation bases to standardize the measurements of ecological compensation models.

Considering that this research applies the documentary technique, one of its strengths is the use of the VOSviewer software tool, providing credibility to the formation of clusters, given the coherence of the criteria grouped in each of them, which allowed us to identify the emerging trends in ecological compensation research with credibility and efficiency. However, it is identified in this evaluation exercise that a weakness of this study is that the grouping of recent documents with relevant contents and that can set trends, are classified under general criteria in the established clusters.

On the other hand, this study made it possible to verify the hypothesis put forward on interdisciplinarity as a fundamental factor in addressing the complexity of ecological compensation models, considering the analysis factors necessary to base effective solutions to ecological detriment. In this way, fields of knowledge in the exact sciences, such as statistics and engineering, and social sciences, such as accounting, were identified.

3.8.1. Cluster 1 Multivariate Statistical Models for Ecological Compensation

The utilization of statistical analysis in studying ecosystems has become firmly established as a basis for implementing new methods intended to enhance the quality of life. It is crucial to bear in mind that the objective of statistical science is to offer an impartial foundation for examining issues in which available data diverges from direct causation [84].

The problems identified with multivariate statistical methods in ecology impact not only the handling of data, but also the formulation of research inquiries. Those in the field of eco-compensation rely on multivariate analysis to investigate the interconnectedness of variables, although these methods are predominantly used for description. Although statistical inference can be conducted, it can only approximate roles, processes, causes, influences, and strategies, similar to univariate analysis, in the absence of experimentation [85].

In addition to the number of variables, another obstacle in these analyses is the problem of multicollinearity in model building. This concerns the existence of a linear correlation among the predictor variables, which creates the possibility of non-unique parameter estimation and leads to an erroneous association between the explanatory and response variables. Consequently, the proposed hypothesis cannot be reliably estimated or tested [86].

The challenges associated with the limitations of multivariate approaches must be considered when modeling ecological compensation, particularly concerning the protection of ecosystems in project development. The choice of method is crucial for obtaining high-quality results; therefore, it is essential to understand its advantages and technical context [87].

3.8.2. Cluster 2 Models Based on Compensation Accounting and the Value of Ecosystem Services

Biodiversity compensation is a strategy created to facilitate biodiversity improvements and counterbalance the lasting effects of development projects on biodiversity [88]. Nonetheless, uncertainty remains regarding the precise placement of restoration sites and whether the inherent benefits of a compensatory area can adequately fulfill the requirements of individuals amidst ecological decline [89]. In light of these conditions, with the ongoing worldwide need for ecological resources surpassing ecosystem capabilities, it is essential to anticipate future alterations in supply, usage, and ecological carrying capacity. This is necessary to enable well-informed choices regarding sustainable land utilization and ecological stability [90].

Evaluating the value of land assets is a crucial first step for effective resource management and addressing the discrepancy between availability and need. Despite the widespread use of land, there is currently no universally accepted set of accounting procedures to assess its value in project planning [91]. However, the extended exergy accounting method is widely used as a thermodynamic approach to evaluate the structure and functioning of a societal system. This method enables an unbiased evaluation of the impact of human activities on sustainable development and broader ecosystems, revealing the interplay between a country’s socioeconomic advancement and the natural environment [92].

Furthermore, alternative methods of compensatory accounting have surfaced, such as the energy ecological footprint. This metric quantifies the ecological effects of energy usage, and serves as a critical measure for evaluating sustainability [93]. Measuring the ecological impact at a regional level presents a complex problem for scientists when assessing the services provided by ecosystems. Nonetheless, it is essential for local policymakers to create effective and practical strategies to facilitate sustainable regional growth [94].

However, the quantification of material movements is another approach used by different nations, akin to national bookkeeping, but in physical terms, tracking the movements of materials coming into and going out of a particular economy to gauge the tangible aspect of a society's consumption. Currently, it is being implemented by several European Union countries and some nations in the Americas because of the inadequacy of GDP in assessing the economic and environmental viability of a country [95].

The energy accounting method, also referred to as the energy method, is based on the thermodynamics of different energy sources, resources, and human labor. It systematically converts these factors into solar energy equivalents, which represent the useful energy of a specific type used in the processes involved in the production of a product or service, whether directly or indirectly. This method quantifies the quality of various forms of energy, such as sunlight, water, fossil fuels, and minerals. The theoretical foundation of the energy methodology is based on the recognition of these distinctions, drawing from the principles of thermodynamics, general systems theory, and systems ecology [96]. Taking into consideration natural resources is a crucial requirement for the balanced progress of both humanity and the environment and for promoting positive relationships between the economy and the natural world [97].

Similarly, there has been a significant rise in the need to evaluate the value of ecological goods and services, considering the growing environmental concerns worldwide. Agreements and contracts concerning the provision and requirements of ecosystem services are proliferating in different parts of the world, along with the imposition of strict regulations on free market pricing [98].

Consequently, the evaluation of ecosystem health reflects the state of the local ecological environment and acts as a thorough measurement for assessing the durability and equilibrium of urban ecosystems [99]. Assessment of ecosystem services (ESV) is an essential measure used to evaluate the benefits that ecosystems provide to humans. However, there is presently a deficiency in a cohesive and uniform method for quantifying the value of ecosystem services [100].

Hence, the validation of ecosystem service calculations remains a pending issue for both economists and ecologists. This is because values are based on abstract concepts given the intangible nature of ecological services. As a result, comparing model-based estimates with tangible measurements from the real world is impractical because the latter are often very difficult to conduct [101].

3.8.3. Cluster 3 Valuation Models for Ecological Compensation of Geographical Mapping

The use of mapping and modeling techniques is essential in ecological assessment from the perspective of compensation, as it focuses on the spatial distribution of various ecosystem services at the local, regional, and global levels. Multiple approaches have been developed for this technique, demonstrating the versatility of ecosystem service applications, such as comparing the supply and demand of ecosystem services, monetary valuation, and identifying areas that require immediate attention for their management and planning [83].

The ecological footprint method, frequently referenced in the scientific literature, is often used for geographic mapping and is considered a valuable tool for assessing the sustainability of human activities. However, criticisms have been raised regarding the method's core model, including the assumption that biologically productive land uses are mutually exclusive, oversight of their complexity, and reliance on equivalence/yield factors based on differing rationales. Furthermore, the method has limitations in analyzing excessive land use, depletion of renewable resources, and inaccurate measurement of its most significant component, the carbon footprint [102].

Despite its longstanding importance in sustainability assessment, the traditional ecological footprint model is constrained by the absence of value accounting, incomplete account content, disregard for multiple functions of land, and geographic spatial heterogeneity. These limitations compromise the universality [98].

In this context, the ecological footprint plays a significant role in ecological and geographical analysis; however, it can only be determined from the statistical data of a region, such as a country or city. It is imperative to have high-resolution mapping of the ecological footprint to carry out a detailed analysis of carbon emissions and resource consumption [103].

The authors' contribution from this bibliographic study is the affirmation of the existence of a common element in the clusters generated, consisting of a lack of comparability between the results of the various models applied, making it difficult to generalize their use in other contexts. Therefore, it is necessary to establish unified criteria for their application in different ecosystems that must be compensated and conserved. It is necessary to deepen the theory of ecological valuation to determine the ecological units of value that facilitate their measurement and the homogenization of magnitudes that facilitate their comparability. Finally, a joint epistemological commitment is required to provide theories that can be unified in the face of the social demand for ecological protection.

4. Conclusions

4.1. Research Contributions

The consultation and analyzed bibliography highlighted important aspects of classification concerning the subject of ecological compensation models referenced in the articles listed in the Scopus and WoS scientific databases. Based on the multiple classifications according to the selected criteria, citation by author co-occurrence was considered, resulting in three clusters that guided the analysis of research trends regarding ecological compensation models. These clusters are:

1. Multivariate statistical models for ecological compensation
2. Models based on compensation accounting and the value of ecosystem services, and
3. Valuation models for ecological compensation through geographical mapping.

The initial method provides a mathematical approach for systematically expressing the variability and fluctuations in data by examining the relationship between the average and dispersion using statistical techniques commonly applied in ecological compensation case studies. However, its constraints include the inability to effectively manage specific data types, resulting in challenges in attaining accurate solutions. These limitations stem from the homogeneity and dissimilarity metrics, along with potentially misleading interpretations that can lead to incorrect conclusions owing to inadequate analysis of data properties, lack of alignment with theories, and an inability to infer relationships between the data.

The second cluster categorizes the models based on compensation accounting and the value of ecosystem services. These models use methodologies of environmental economic valuation and can be classified into two major groups: 1) those based on revealed preferences, which identify values through information from markets indirectly related to ecosystem services; and 2) those based on stated preferences, which involve direct interactions with individuals to obtain the economic value of ecosystem services. In this sense, the need for objective appraisals intensifies as global society demands more consistent parameters than purely economic ones because, in this way, ecological compensation can be understood as the socially accepted balance between excessive consumption of ecological components and the economic remuneration of their consumers.

The third sector focuses on assessing the value of ecological compensation using geographic mapping, monitoring land quantity and quality, and addressing the undervaluation of land to minimize land resource waste. To achieve this, a scientific natural capital accounting system for land resources must be established to understand the quantity and value of these resources over time. While the ecological footprint is subject to criticism for its generalized approach in combining different input flows, the method of calculating and translating various types of land has provoked the most debate. Specifically, the current method includes only land types associated with one function, even though many lands serve multiple purposes and do not fit neatly into one measurement category.

There is no single universal application model; therefore, it is necessary to build evaluation bases that allow for the standardization of measurements from different ecological compensation models. Measurements to achieve the proposed objectives are a common element in the three generated clusters. However, although the measurement is objective, when compared with different models, it results in a heterogeneous set of information that lacks comparability, making it difficult to widely accept some models that could respond to other types of scenarios given the lack of unified criteria for their application to various ecosystems that need to be compensated, protected, and preserved.

4.2. Trends for Future Research

Ecosystems are composed of biotic and abiotic components that require a balance to maintain equilibrium and prevent depletion. The third sector focuses on assessing the ecological compensation value through mapping, monitoring land quantity and quality, and addressing undervaluation to reduce the waste of land resources. Establishing a scientific natural capital accounting system for land resources is essential for understanding the quantity and value of these resources over time. Although the ecological footprint has been criticized for its general approach in combining different inputs, the method of calculating and translating various types of land has sparked significant debate. Currently, this method only includes land types associated with one function, even though many lands serve multiple purposes and do not neatly fit into one measurement category. Future research should concentrate on constructing models with a conversion coefficient to estimate the ecological components consumed in different production processes for economic, social, and environmental projects.

The possibility of integrating various models and methodologies aimed at compensation could guide the harmonization of validated procedures for case studies. These synergies could complement the weaknesses of each of the models classified in this study, serving as a starting point for the universal expansion of effective solutions for ecosystem conservation.

Declarations

Author Contributions

Conceptualization, H.M.H. and D.P.F.C.; methodology, H.M.H. and M.J.R.V.; software, H.M.H. and J.D.C.G.; validation, H.M.H., J.D.C.G. and L.S.G.P.; formal analysis, H.M.H.; investigation, H.M.H., D.P.F.C. and M.J.R.V.; resources, H.M.H.; data curation, H.M.H. and M.J.R.V.; writing—original draft preparation, all authors contributed equally; writing—review and editing, H.M.H.; visualization, J.D.C.G. and L.S.G.P.; supervision, H.M.H.; project administration, H.M.H. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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