JOURNAL OF EUROPEAN ACADEMY OPEN UNIVERSITY
Vol. 2, No. 7, 2026 23
Research Article

Global Evolution of Ecosystem Services Research Reveals a Shift toward Restoration, Data-Intensive Methods, and Policy Integration

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Abstract

Ecosystem services (ES) research has expanded from a valuation-oriented ecological economics concept into a broad interdisciplinary field connecting biodiversity conservation, spatial planning, climate adaptation, human well-being and ecosystem accounting. However, the knowledge structure and post-2021 frontier shift of ES research require updated bibliometric evidence. This study analyzes 5,319 core publications exported from the Web of Science Core Collection. The original export contained 6,200 records from 13 plain-text files; after de-duplication based on Web of Science unique identifiers, 5,319 valid records published from 1998 to 2026 were retained. Annual publication output, source journals, Web of Science categories, countries, institutions, authors, keyword co-occurrence, co-cited references, thematic evolution and model/method terms were analyzed using reproducible bibliometric statistics and network-visualization procedures. The results show four stages of ES research: an initial emergence stage before 2005, a post-Millennium Ecosystem Assessment expansion stage during 2006-2010, a rapid consolidation stage during 2011-2015, and a mature diversification stage after 2016. Publication output peaked in 2021-2022 and remained high through 2025. China, the United States and the United Kingdom were the leading contributors, while the Chinese Academy of Sciences, Wageningen University & Research, the University of Chinese Academy of Sciences and Beijing Normal University were among the most productive institutions. The journal Ecosystem Services was the dominant publication outlet, followed by Ecological Indicators, Sustainability and Ecological Economics. Keyword and method-term analyses reveal that the field has moved from valuation, classification and land-use assessment toward trade-offs and synergies, supply-demand matching, InVEST-based mapping, remote sensing, restoration, nature-based solutions, ecosystem accounting and machine learning. The 2021-2026 period shows a clear frontier shift toward restoration-oriented, data-intensive and policy-integrated ES research. This study provides a systematic article-level bibliometric assessment of ES research and identifies future directions for integrating ecological processes, social demand, human well-being and decision-support tools.

Keywords

ecosystem services; bibliometric analysis; Web of Science; knowledge structure; keyword evolution; nature-based solutions; ecosystem restoration

Highlights

• A cleaned Web of Science dataset of 5,319 ecosystem services publications from 1998 to 2026 was analyzed.
• China, the United States and the United Kingdom formed the largest national knowledge-production groups.
• Keyword evolution shows a transition from valuation and biodiversity to trade-offs, supply-demand, restoration and nature-based solutions.
• Recent frontiers after 2021 include ecosystem restoration, machine learning, ecosystem accounting and spatially explicit decision support.
• The article positions ecosystem services research as moving from biophysical assessment to social-ecological governance.

1. Introduction

Ecosystem services refer to the direct and indirect contributions of ecosystems to human survival, production, health and well-being [1–4]. Since the concept became widely used in ecological economics, conservation science and sustainability research, it has provided a common language for describing the benefits generated by biodiversity, landscapes, forests, wetlands, oceans, agricultural systems and urban green-blue infrastructure [5–9]. The ecosystem services framework is particularly influential because it connects ecological functions with human needs and policy decision-making, thereby translating ecological processes into planning, management and governance questions [10–12].

The intellectual development of ES research has been shaped by several milestones. Early work focused on identifying, classifying and valuing the services provided by natural capital [1,2,13,14]. The Millennium Ecosystem Assessment stimulated a major expansion by classifying services into provisioning, regulating, cultural and supporting categories, and by linking ecosystem change with human well-being [15,16]. Later studies increasingly emphasized spatially explicit assessment, service bundles, trade-offs, synergies, land-use change, biodiversity conservation, green infrastructure, climate adaptation and natural capital accounting [17–25]. In recent years, the field has entered a new phase driven by ecological restoration, the United Nations Decade on Ecosystem Restoration, nature-based solutions, remote sensing, machine learning and decision-support systems [26–32].

Bibliometric analysis provides an effective method for examining such a large and evolving research field. Unlike narrative reviews, bibliometric analysis can quantify annual publication growth, identify leading countries and institutions, reveal author collaboration patterns, map keyword co-occurrence networks and detect changes in research frontiers [33–35]. Co-citation analysis, burst detection and network modularity further help identify intellectual bases, emergent themes and structural communities in a research domain [36,37]. For a rapidly expanding field such as ES research, bibliometric evidence helps clarify not only what has been studied but also how the structure of knowledge has shifted across time.

Previous bibliometric and review studies have provided important insights into ES research, including highly cited articles, human well-being links, urban ecosystem services and regional or ecosystem-specific applications [8,12,14,38,39]. However, many existing studies either ended before the recent post-2021 period or focused on a narrower subset of the field, such as cultural services, urban systems, land-use decision-making, restoration, biodiversity-mediated services or climate-change impacts [27,30,40–42]. The period after 2021 is particularly important because global environmental governance increasingly emphasizes ecosystem restoration, climate adaptation, biodiversity recovery and the operationalization of ecosystem accounting. Therefore, an updated bibliometric analysis that focuses on publication growth, knowledge structure and recent frontiers is necessary.

This study analyzes 5,319 core publications on ecosystem services exported from the Web of Science Core Collection. The analysis addresses four research questions: (1) How has publication output in ES research evolved from 1998 to 2026? (2) Which countries, institutions, journals and authors constitute the main knowledge-production structure? (3) What are the dominant keywords, co-cited foundations and thematic clusters? (4) What frontier topics have emerged during 2021-2026? By answering these questions, this article provides a data-driven overview of ES research and identifies future directions for more integrated social-ecological assessment.

2. Materials and methods

2.1 Data source and search strategy

The bibliographic data were exported from the Web of Science Core Collection in plain-text format. The search topic was centered on ecosystem services, using the Web of Science topic-field logic TS=("ecosystem service*" OR "ecosystem benefit*"). The export included full records and cited references, which is a standard data structure for bibliometric analysis, co-citation analysis and science mapping [33–35]. The original compressed dataset contained 13 Web of Science plain-text files and 6,200 raw records. Records were de-duplicated by the Web of Science unique identifier (UT); records without valid bibliographic identifiers were checked using title and year information. After cleaning, 5,319 valid records remained for analysis. The dataset covered the period 1998-2026. Because the initial broad search returned approximately 70,000 records, this study is explicitly positioned as an analysis of exported core publications rather than the complete global ES literature.

Table 1. Data source and processing protocol.

Item	Description
Database	Web of Science Core Collection
Search query	TS=("ecosystem service*" OR "ecosystem benefit*")
Export format	Full Record and Cited References; Plain Text
Raw records	6,200
Duplicates removed	881
Final valid records	5,319
Time span in cleaned data	1998-2026
Main analytical units	publications, years, journals, countries, institutions, authors, keywords and cited references

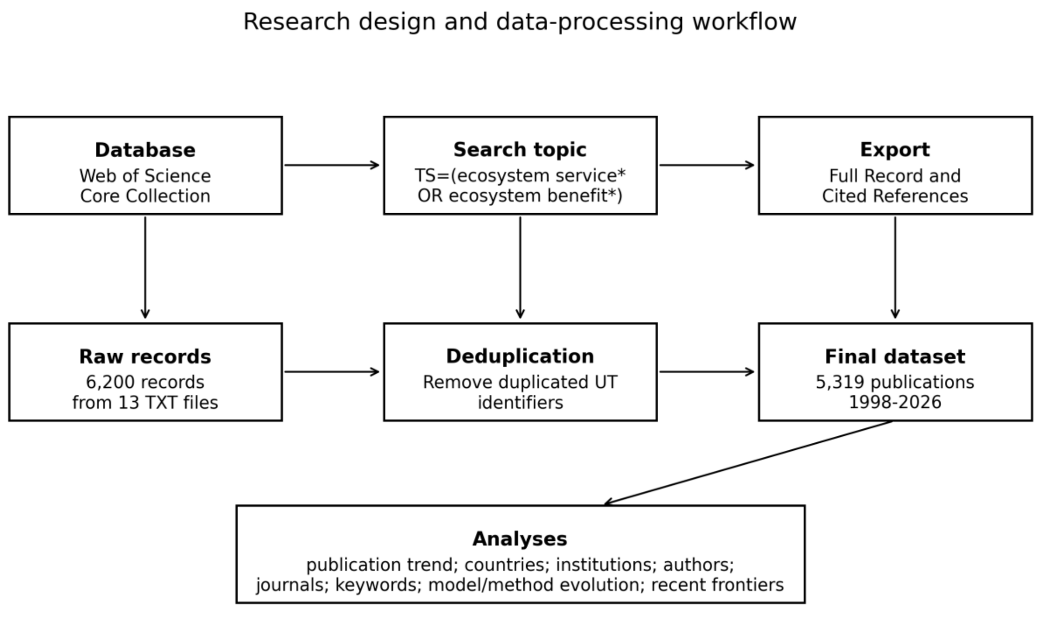

Figure 1. Research design and data-processing workflow.

2.2 Bibliometric indicators and analytical procedures

Annual publication output and cumulative output were calculated to characterize temporal growth. Source journals and Web of Science categories were counted to identify disciplinary distribution. Country productivity was extracted from author-address fields, and each country was counted once per publication. Institutional productivity was extracted from Web of Science organization fields. Author productivity was counted using author names recorded in the AU field. These descriptive indicators are commonly used to characterize publication growth, source concentration, institutional productivity and collaboration structure in bibliometric studies [33–35].

Keyword analysis integrated author keywords and Keywords Plus. Terms were lowercased and normalized to merge variants such as "land-use" and "land use", "tradeoffs" and "trade-offs", "human wellbeing" and "human well-being", and singular/plural forms of nature-based solutions. Keyword co-occurrence networks were constructed by linking terms that appeared in the same record, following the logic of co-word analysis and bibliometric mapping [34,35]. Node size represents document frequency and edge width represents co-occurrence strength.

To reveal temporal change, the publication period was divided into five stages: 1998-2005, 2006-2010, 2011-2015, 2016-2020 and 2021-2026. These stages correspond to conceptual emergence, post-Millennium Ecosystem Assessment expansion, consolidation, diversification and recent frontier development, following the conceptual and policy turning points discussed in the ES literature [15,16,26]. In addition to keyword frequency, a model/method term analysis was conducted by scanning titles, abstracts and keywords for terms such as valuation, GIS/spatial mapping, InVEST, ARIES, SolVES, remote sensing, machine learning, supply-demand, trade-offs/synergies, nature-based solutions, restoration, green infrastructure and ecosystem accounting.

Co-cited references were counted from the CR field. Highly cited publications within the exported dataset were ranked by Web of Science citation counts. These indicators were used to interpret the intellectual base and the evolution of research priorities, following common practice in bibliometric mapping, burst detection and network-community analysis [33,36,37].

3. Results

3.1 Publication growth and developmental stages

The annual publication trend shows a strong transition from slow emergence to sustained high output. Only 60 records were published during 1998-2005, indicating that ES research was still a relatively small field during its early stage. Output increased after 2005, with 255 records during 2006-2010 and 978 during 2011-2015. The field then entered a mature expansion stage, producing 1,773 records during 2016-2020 and 2253 records during 2021-2026. Annual output reached the highest value in 2022, with 433 records.

The growth curve is not simply linear. It reflects the influence of conceptual consolidation, policy demand, tool development and interdisciplinary expansion. The post-2005 increase is consistent with the impact of the Millennium Ecosystem Assessment, while the post-2016 growth reflects a broader incorporation of ES concepts into land-use planning, climate adaptation, biodiversity policy, urban sustainability and natural capital accounting. The recent high-output period shows that the field remains active, although the partial 2026 record should not be interpreted as a full-year value.

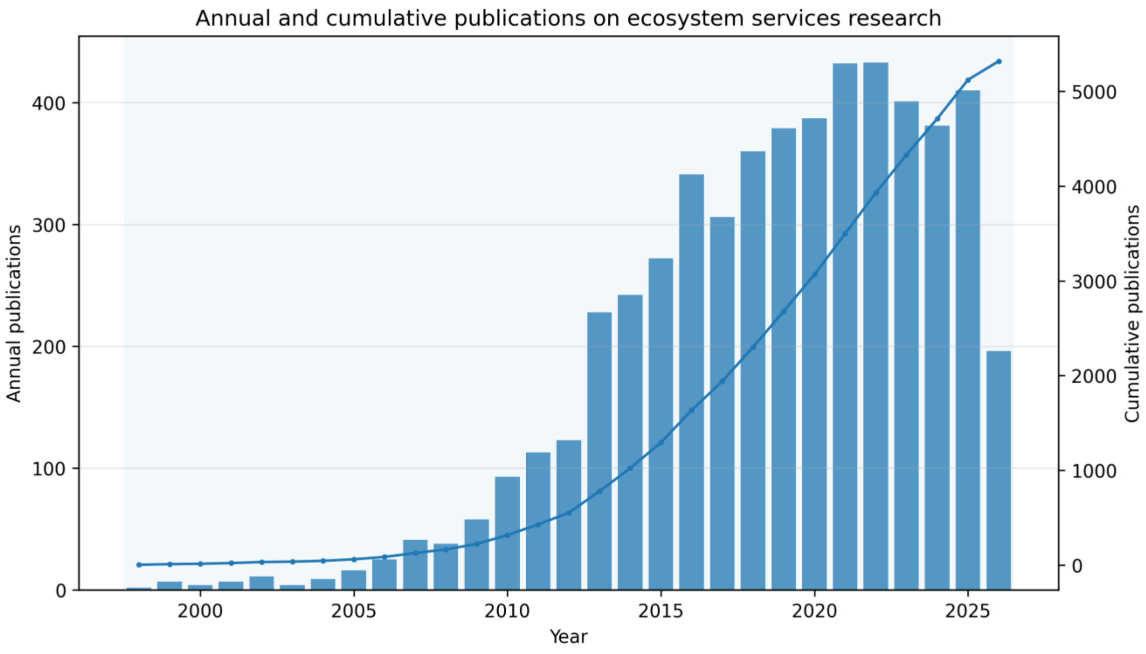

Figure 2. Annual and cumulative publication trends of ecosystem services research in the cleaned Web of Science dataset.

Table 2. Publication stages and document counts.

Period	Documents
1998-2005	60
2006-2010	255
2011-2015	978
2016-2020	1773
2021-2026	2253

3.2 Source journals and disciplinary distribution

The journal distribution indicates that ES research is concentrated in a set of interdisciplinary environmental and sustainability journals. Ecosystem Services was the dominant outlet, publishing 633 records, followed by Ecological Indicators (346), Sustainability (336), Ecological Economics (196) and Science of the Total Environment (138). This distribution confirms that ES research is located at the interface of ecological economics, environmental indicators, sustainability science and environmental management.

The Web of Science category distribution further shows the interdisciplinary nature of the field. Environmental Sciences and Ecology, Green and Sustainable Science and Technology, Biodiversity Conservation, Environmental Studies, Geography and Planning-related categories were all strongly represented. This disciplinary pattern explains why ES research has become a bridge between ecological assessment, economic valuation, spatial planning and governance.

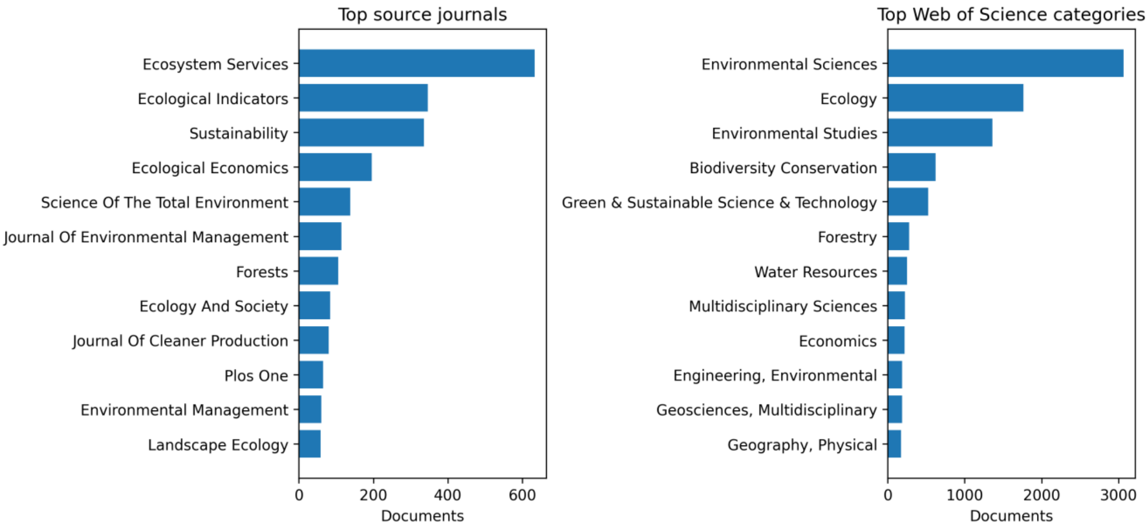

Figure 3. Leading source journals and Web of Science categories.

Table 3. Top 15 source journals.

Journal	Documents
Ecosystem Services	633
Ecological Indicators	346
Sustainability	336
Ecological Economics	196
Science Of The Total Environment	138
Journal Of Environmental Management	114
Forests	106
Ecology And Society	84
Journal Of Cleaner Production	80
Plos One	65

Environmental Management	60
Landscape Ecology	58
Ocean & Coastal Management	54
Landscape And Urban Planning	53
Frontiers In Environmental Science	51

3.3 Country collaboration and geographic knowledge production

Country analysis identified China, the United States and the United Kingdom as the three largest contributors. China ranked first with 1470 records, followed by the United States with 1130 and the United Kingdom with 642. Germany, Australia, Spain, the Netherlands, Italy, France and Canada formed the second tier of contributors. The country collaboration network shows that ES research has a globalized but still uneven structure, with strong connections among China, the United States, the United Kingdom, Germany, Australia and major European countries.

The dominance of China reflects the rapid expansion of land-use change, ecological civilization, ecological restoration, natural capital accounting and ecosystem service supply-demand assessment in Chinese research. The United States remains a central knowledge hub because many foundational ES concepts, valuation studies, natural capital frameworks and spatial decision-support models were developed or popularized in North American research systems. European countries show strong participation in ecosystem accounting, landscape planning, biodiversity policy and cultural ecosystem service research.

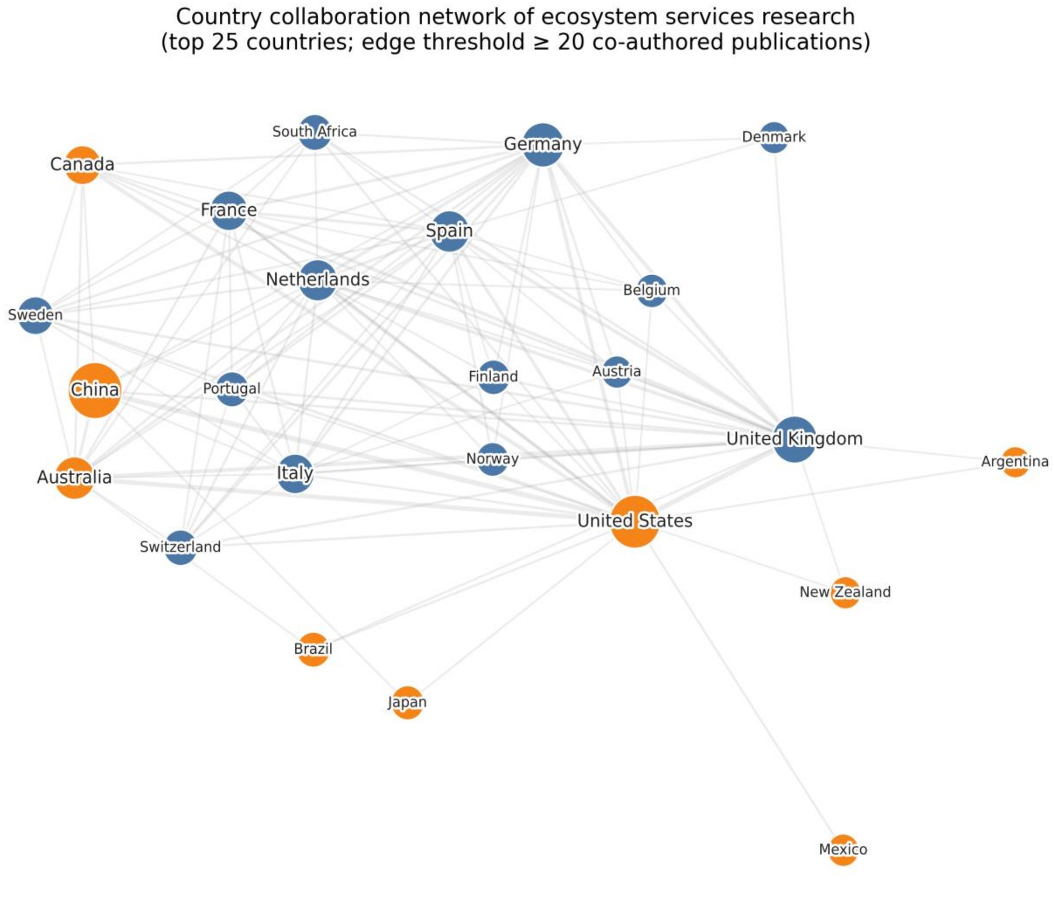

Figure 4. Country collaboration network. Node size represents publication count, and edge width represents co-authorship frequency between countries.

Table 4. Top 20 contributing countries.

Country	Documents
China	1470
United States	1130
United Kingdom	642

Germany	480
Australia	392
Spain	349
Netherlands	335
Italy	271
France	268
Canada	246
Sweden	212
South Africa	162
Switzerland	151
Portugal	140
Brazil	139
Finland	129
Japan	121
Norway	112
Belgium	108
India	107

3.4 Institutions and authors

Institutional productivity was led by the Chinese Academy of Sciences, which contributed 435 records. Other leading institutions included Wageningen University & Research, the University of Chinese Academy of Sciences, Beijing Normal University, the University of California System, CNRS, the Institute of Geographic Sciences and Natural Resources Research of CAS, and the Research Center for Eco-Environmental Sciences of CAS. These institutions represent the strong roles of China, the Netherlands, the United States and France in ES research.

Author productivity was relatively dispersed but several scholars were repeatedly visible in the dataset. The most productive authors included B. Martin-López (44 records), Z. Y. Ouyang (43), H. Zheng, L. Hein, J. Li, E. M. Bennett, J. Maes, Y. Xiao, E. Gómez-Baggethun and S. Lavorel. These scholars are associated with major research themes including social-ecological systems, ecosystem service valuation, biodiversity, European ecosystem accounting, landscape planning and Chinese ecosystem assessment.

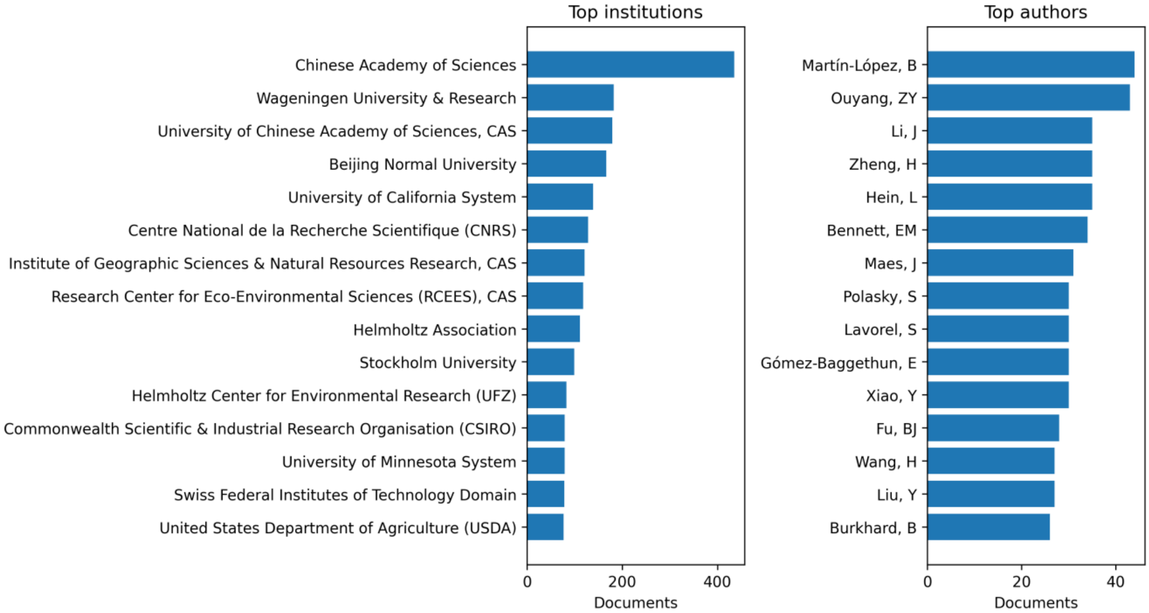

Figure 5. Productive institutions and authors in the cleaned dataset.

Table 5. Top 10 institutions and authors.

Top institutions	Institution documents	Top authors	Author documents
Chinese Academy of Sciences	435	Martín-López, B	44
Wageningen University & Research	182	Ouyang, ZY	43
University of Chinese Academy of Sciences, CAS	179	Zheng, H	35
Beijing Normal University	166	Hein, L	35
University of California System	139	Li, J	35
Centre National de la Recherche Scientifique (CNRS)	128	Bennett, EM	34
Institute of Geographic Sciences & Natural Resources Research, CAS	121	Maes, J	31
Research Center for Eco-Environmental Sciences (RCEES), CAS	118	Xiao, Y	30
Helmholtz Association	111	Gómez-Baggethun, E	30
Stockholm University	99	Lavorel, S	30

3.5 Keyword co-occurrence and knowledge structure

Keyword analysis shows that “ecosystem services” was the most frequent term, appearing in 2344 records. Other high-frequency terms included biodiversity, management, conservation, valuation, trade-offs, land use, climate change, land use change, sustainability, China and indicators. These terms indicate that the core of ES research is organized around four knowledge domains: ecological foundations, valuation and decision support, land-use and spatial assessment, and social-ecological governance.

The keyword co-occurrence network displays several closely connected thematic groups. Biodiversity, conservation, management and climate change form the ecological-conservation core. Valuation, values, indicators and framework form the assessment and decision-support core. Land use, land use change, landscape and spatial analysis form the spatial-planning core. Trade-offs, synergies, supply-demand, cultural ecosystem services and human well-being indicate a more recent social-ecological integration agenda.

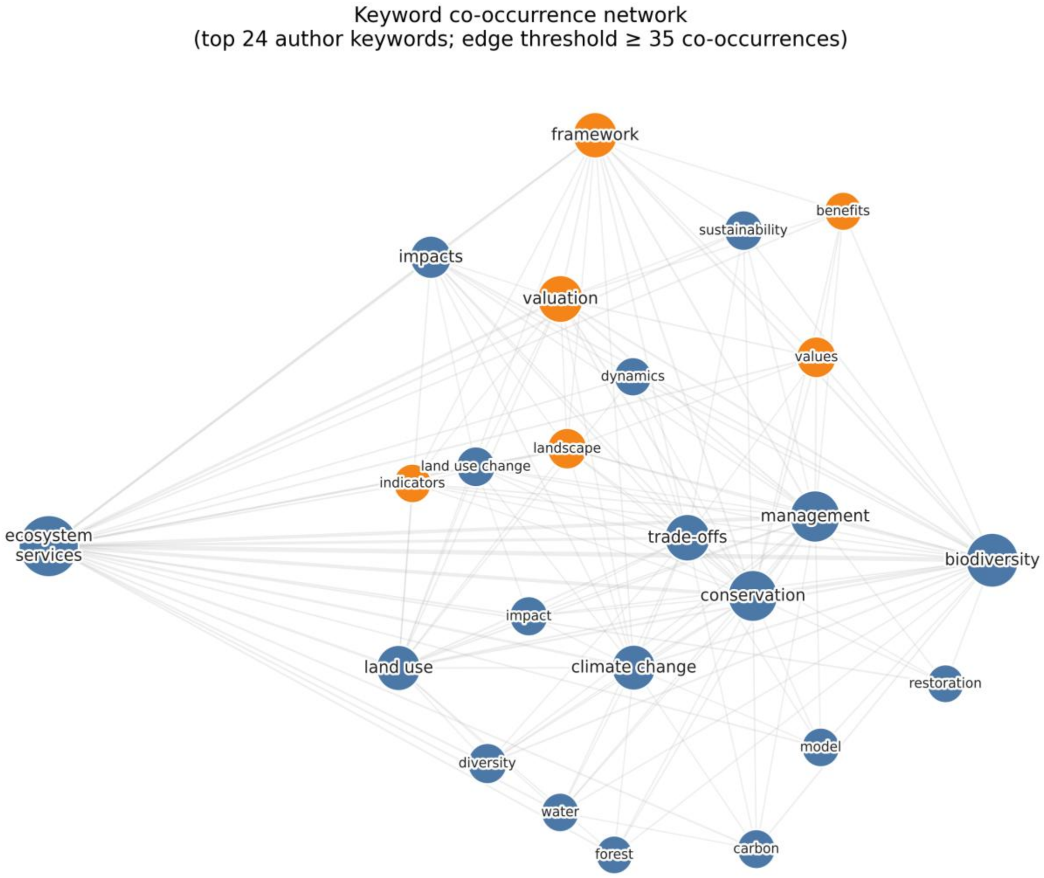

Figure 6. Keyword co-occurrence network based on author keywords and Keywords Plus.

Table 6. Top 25 keywords.

Keyword	Documents
ecosystem services	2344
biodiversity	1328
management	1050
conservation	1018
valuation	683
trade-offs	670
framework	585
land use	576
climate change	561
impacts	414
services	373
values	335
ecosystem service	333
landscape	329
diversity	318
land use change	300
sustainability	296
ecosystem	285
impact	280
china	272

carbon	269
model	258
indicators	256
water	254
dynamics	247

3.6 Co-cited foundations and highly cited publications

Co-cited references reveal the intellectual base of ES research. The most frequently co-cited reference was Costanza et al. [1], followed by Costanza et al. [43], de Groot et al. [2], Fisher et al. [3], de Groot et al. [17], Bennett et al. [18], Nelson et al. [19], Boyd and Banzhaf [4], Burkhard et al. [20], and Raudsepp-Hearne et al. [21]. These references define the conceptual and methodological backbone of the field: global valuation, classification, decision-oriented service definition, service bundles, spatial mapping, trade-offs and landscape-level assessment.

The highly cited publications in the exported dataset also show that the field has been driven by a relatively small set of influential conceptual and synthesis papers. Costanza et al. [43] and Barbier et al. [44] were the two most cited records in the dataset, followed by de Groot et al. [2], de Groot et al. [17], Fisher et al. [3], Haines-Young and Potschin, Bennett et al., and major studies on pollination, urban forests, climate change impacts and biodiversity-mediated ecosystem services. These works collectively shifted ES research from valuation to classification, spatial assessment and social-ecological management.

Table 7. Representative highly cited records in the dataset.

Year	Citations	Authors	Title	Journal	DOI
2014	4439	Costanza, R et al.	Changes in the global value of ecosystem services	Global Environmental Change-Human And Policy Dimensions	10.1016/j.gloenvcha.2014.04.002
2011	4371	Barbier, EB et al.	The value of estuarine and coastal ecosystem services	Ecological Monographs	10.1890/10-1510.1
2002	2982	de Groot, RS et al.	A typology for the classification, description and valuation of ecosystem f...	Ecological Economics	10.1016/S0921-8009(02)00089-7
2010	2429	de Groot, RS et al.	Challenges in integrating the concept of ecosystem services and values in l...	Ecological Complexity	10.1016/j.ecocom.2009.10.006
2009	2104	Fisher, B et al.	Defining and classifying ecosystem services for decision making	Ecological Economics	10.1016/j.ecolecon.2008.09.014
2016	2062	Delgado-Baquerizo, M et al.	Microbial diversity drives multifunctionality in terrestrial ecosystems	Nature Communications	10.1038/ncomms10541

Table 8. Top co-cited references.

Co-cited reference	Co-citations
Costanza R, 1997, NATURE, V387, P253, DOI 10.1038/387253a0	1568
Costanza R, 2014, GLOBAL ENVIRON CHANG, V26, P152, DOI 10.1016/j.gloenvcha.2014.04.00...	538
de Groot RS, 2002, ECOL ECON, V41, P393, DOI 10.1016/S0921-8009(02)00089-7	537
Fisher B, 2009, ECOL ECON, V68, P643, DOI 10.1016/j.ecolecon.2008.09.014	536
de Groot RS, 2010, ECOL COMPLEX, V7, P260, DOI 10.1016/j.ecocom.2009.10.006	530
Bennett EM, 2009, ECOL LETT, V12, P1394, DOI 10.1111/j.1461-0248.2009.01387.x	510
Nelson E, 2009, FRONT ECOL ENVIRON, V7, P4, DOI 10.1890/080023	394
Boyd J, 2007, ECOL ECON, V63, P616, DOI 10.1016/j.ecolecon.2007.01.002	391
Burkhard B, 2012, ECOL INDIC, V21, P17, DOI 10.1016/j.ecolind.2011.06.019	381

Raudsepp-Hearne C, 2010, P NATL ACAD SCI USA, V107, P5242, DOI 10.1073/pnas.090728410...	378
Costanza R, 2017, ECOSYST SERV, V28, P1, DOI 10.1016/j.ecoser.2017.09.008	355
Daily GC, 2009, FRONT ECOL ENVIRON, V7, P21, DOI 10.1890/080025	338

3.7 Thematic evolution across five periods

Temporal keyword analysis reveals that ES research has passed through a clear sequence of thematic transitions. During 1998-2005, the field was dominated by valuation, classification, biodiversity and ecological economics. During 2006-2010, spatial mapping, landscape planning and service classification expanded rapidly. During 2011-2015, land-use change, trade-offs, InVEST and ecosystem service bundles became more visible. During 2016-2020, supply-demand analysis, cultural ecosystem services, urban ecosystem services, green infrastructure and climate-related services gained importance. The 2021-2026 period shows stronger growth in restoration, nature-based solutions, ecosystem accounting, machine learning, high-resolution remote sensing and scenario simulation.

This progression indicates a methodological and conceptual transition. Early ES research asked how ecosystem services could be defined and valued. Mid-stage research asked how services could be mapped, modeled and compared across landscapes. Recent research increasingly asks how services can be restored, governed, predicted, integrated into accounting systems and linked to human well-being under climate and biodiversity crises.

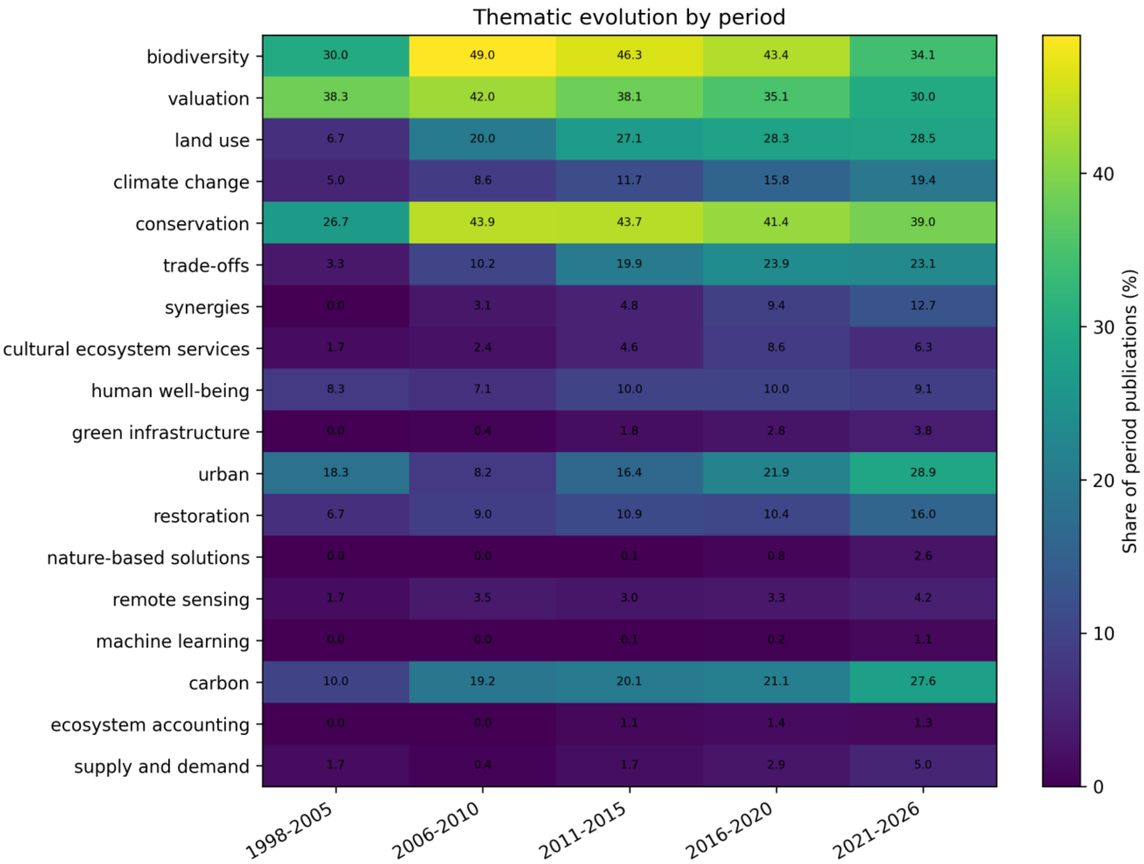

Figure 7. Thematic evolution by period. Cell values represent the percentage of period publications containing each term.

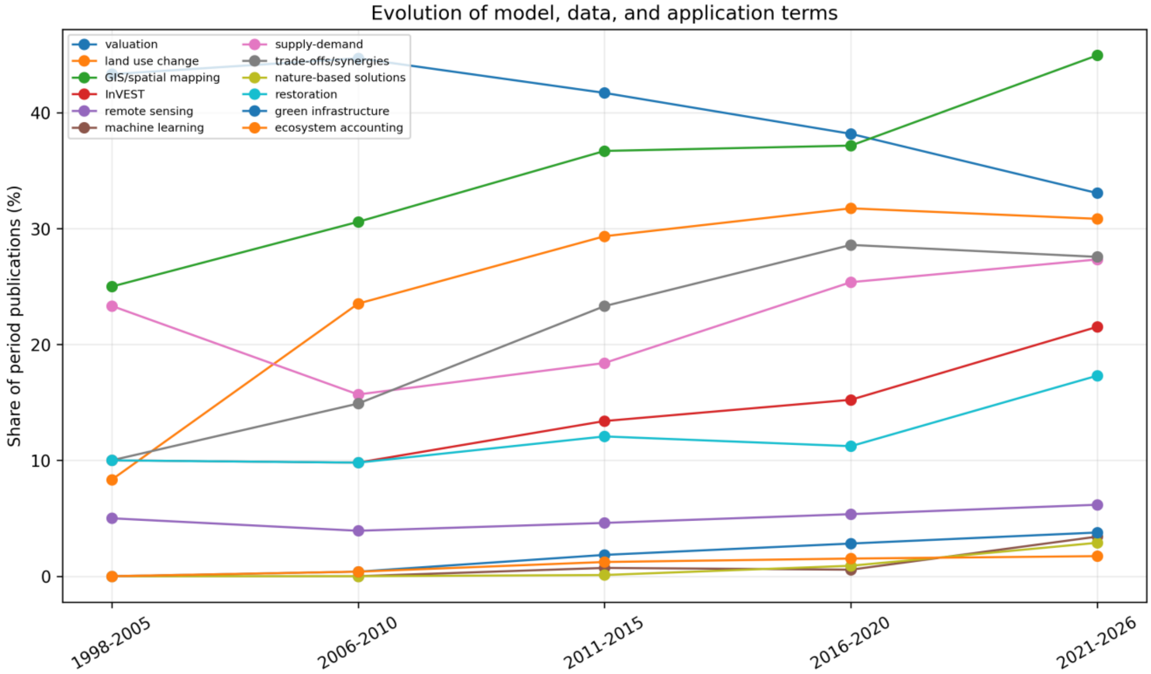

Figure 8. Evolution of model, data and application terms by period.

Table 9. Model, data and application terms by period.

Term	1998-2005	2006-2010	2011-2015	2016-2020	2021-2026	Total
GIS/spatial mapping	15	78	359	659	1013	2124
valuation	26	114	408	677	745	1970
carbon/climate	8	64	270	572	899	1813
land use change	5	60	287	563	695	1610
trade-offs/synergies	6	38	228	507	621	1400
supply-demand	14	40	180	450	616	1300
InVEST	6	25	131	270	485	917
restoration	6	25	118	199	390	738
ARIES	2	14	68	117	112	313
remote sensing	3	10	45	95	139	292
green infrastructure	0	1	18	50	85	154
machine learning	0	0	7	10	77	94

3.8 Emerging frontiers during 2021-2026

The 2021-2026 period is the most important window for identifying current research frontiers. Relative-frequency comparison between the recent period and the pre-2021 period shows the rapid growth of spatial autocorrelation, machine learning, habitat quality, nature-based solutions, karst ecosystems, Qinghai-Tibet Plateau studies, supply-demand matching, risk assessment, green infrastructure, carbon storage and ecosystem restoration. Some terms are region-specific, but collectively they indicate a broader shift toward spatial heterogeneity, fragile ecosystems, restoration diagnosis and process-based decision support.

The model/method analysis shows that GIS/spatial mapping, valuation, carbon/climate, land-use change, trade-offs/synergies, supply-demand analysis and InVEST remain dominant. However, the strongest recent changes are found in machine learning, nature-based solutions, restoration, green infrastructure and ecosystem accounting. This shift is consistent with the policy context of ecosystem restoration and with the increasing availability of high-resolution geospatial data. ES research is therefore moving toward a data-intensive and policy-integrated stage.

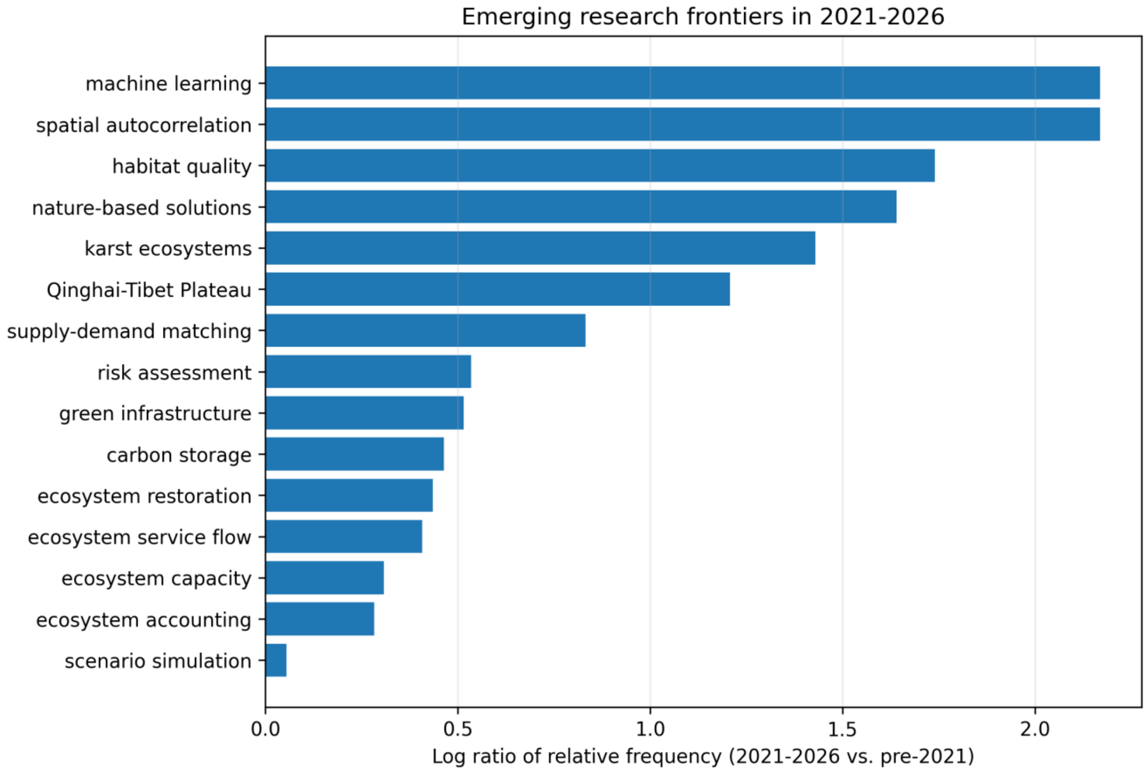

Figure 9. Emerging keyword frontiers during 2021-2026.

Table 10. Frontier terms with increased relative frequency during 2021-2026.

Frontier term	Recent docs	Earlier docs	Log ratio	Recent rate	Earlier rate
spatial autocorrelation	67	10	2.17	2.99	0.34
machine learning	67	10	2.17	2.99	0.34
habitat quality	169	40	1.74	7.52	1.32
nature-based solutions	62	16	1.64	2.77	0.54
karst ecosystems	44	14	1.43	1.97	0.47
Qinghai-Tibet Plateau	45	18	1.21	2.02	0.60
supply-demand matching	127	75	0.83	5.66	2.46
risk assessment	39	31	0.53	1.75	1.03
green infrastructure	85	69	0.52	3.79	2.27
carbon storage	450	385	0.46	20.0	12.6
ecosystem restoration	361	318	0.43	16.0	10.4
ecosystem service flow	63	57	0.41	2.82	1.87
ecosystem capacity	7	7	0.31	0.33	0.24
ecosystem accounting	39	40	0.28	1.75	1.32
scenario simulation	243	313	0.06	10.8	10.2

4. Discussion

4.1 From valuation-oriented research to decision-oriented governance

The bibliometric results indicate that ES research has moved beyond its early valuation-centered orientation. Valuation remains one of the largest method terms, but the increasing frequency of supply-demand, trade-offs/synergies, spatial mapping and ecosystem accounting shows that the field is now more closely linked to governance and decision support [4,17,20,24]. This transformation is important because valuation alone cannot resolve conflicts among biodiversity conservation, agricultural production, urban expansion and climate adaptation [22,45,46].

Contemporary ES research increasingly treats services as spatially variable, socially demanded and institutionally governed flows [18,21,23].

This transition also explains why journals such as Ecosystem Services, Ecological Indicators, Sustainability and Ecological Economics dominate the dataset. ES research has become a boundary field that connects ecological measurement, economic interpretation, planning applications and policy communication [12,25,47]. The strongest future contributions are therefore likely to come from studies that combine ecological process understanding with policy-relevant indicators and transparent uncertainty assessment [11,48,49].

4.2 Geographic leadership and the rise of Chinese ES research

The country and institution results show that China has become the largest producer of ES publications in this exported core dataset. This reflects the strong integration of ES assessment into Chinese land-use planning, ecological restoration, ecological civilization policy, national park construction and territorial spatial planning [29,32,50,51]. Leading Chinese institutions, including the Chinese Academy of Sciences, the University of Chinese Academy of Sciences and Beijing Normal University, occupy central positions in the institutional landscape.

At the same time, the United States, the United Kingdom, Germany, the Netherlands, Australia and other European countries remain highly influential. The United States maintains a strong conceptual and methodological legacy through natural capital valuation, InVEST-related decision support and long-term ecological research [19,47,52]. European institutions contribute strongly to ecosystem accounting, cultural services, landscape planning and social-ecological integration [12,25,38]. The field is therefore characterized by a dual pattern: rapid growth in China and persistent conceptual influence from North America and Europe.

4.3 Methodological transition: mapping, InVEST, remote sensing and machine learning

The method-term analysis reveals a clear methodological transition. Spatial mapping and GIS are the largest method-related category, which reflects the inherently spatial nature of ecosystem services [20,25,52]. Land-use change also remains one of the strongest themes because changes in land cover directly affect service supply, demand, trade-offs and ecological risk [53,54]. InVEST appears as a major model family because it provides accessible modules for estimating carbon storage, water yield, habitat quality, soil retention and other services [19,47]. ARIES and SolVES appear less frequently but represent distinct pathways toward decision-support modeling and social-value mapping [38,47].

The rise of remote sensing and machine learning is a recent methodological frontier. High-resolution remote-sensing data improve spatially explicit ES assessment and ecosystem accounting, while machine learning supports nonlinear prediction, driver identification and scenario simulation [30,55,56]. These methods can improve accuracy but also create new challenges related to interpretability, transferability, data bias and reproducibility. Future ES studies should therefore combine data-driven models with ecological mechanisms and transparent validation.

4.4 Post-2021 frontier: restoration, nature-based solutions and ecosystem accounting

The 2021-2026 period shows a noticeable frontier shift. Restoration, nature-based solutions, green infrastructure, ecosystem accounting and machine learning all increased during this period. This shift is consistent with global environmental governance priorities, especially ecosystem restoration, climate adaptation, biodiversity recovery and natural capital accounting [26–29]. The ES framework is increasingly used not only to measure ecosystem benefits but also to design restoration interventions, compare scenarios and evaluate policy outcomes [30,32,57].

This emerging orientation creates opportunities for stronger article-level innovation. Future ES research should not merely map current service supply. It should ask how restoration changes ecosystem capacity, how nature-based solutions generate multiple co-benefits, how ecosystem accounting can be linked to policy decisions, and how social demand and equity can be integrated into service assessments [27,46,55,58]. The strongest frontier is therefore the integration of ecological restoration, human well-being and spatial decision-support systems.

4.5 Limitations

This study has several limitations. First, the analysis is based on exported core publications rather than the full set of approximately 70,000 records returned by the broad Web of Science query. Therefore, the results should be interpreted as the knowledge structure of a large core sample, not as a complete census of all ES-related publications. Second, bibliometric results depend on search strategy. A broader topic search may include studies that mention ecosystem services only incidentally, whereas a title-only search may miss relevant applied studies. Third, country and institution extraction from Web of Science address fields may undercount or merge some organizations. Fourth, keyword normalization can reduce but cannot fully eliminate semantic ambiguity, especially for terms such as value, management, landscape and model.

Despite these limitations, the cleaned dataset is large enough to support article-level bibliometric analysis. It contains more than five thousand records, covers nearly three decades of publication history, includes cited references and provides sufficient information for identifying publication trends, leading contributors, co-cited foundations, keyword structure and emerging frontiers.

5. Conclusions

1. This study analyzed 5,319 core publications on ecosystem services from the Web of Science Core Collection. The results show that ES research experienced a slow emergence stage before 2005, rapid expansion after the Millennium Ecosystem Assessment, consolidation during 2011-2015, mature diversification during 2016-2020 and frontier transformation during 2021-2026.

2. China, the United States and the United Kingdom were the leading countries in publication output. The Chinese Academy of Sciences, Wageningen University & Research, the University of Chinese Academy of Sciences and Beijing Normal University were among the most productive institutions. Ecosystem Services, Ecological Indicators, Sustainability and Ecological Economics were the dominant publication outlets.

3. Keyword and co-citation analyses reveal a knowledge structure centered on biodiversity, conservation, valuation, land use, climate change, trade-offs, sustainability and spatial assessment. Foundational references include works on global valuation, classification, service bundles, trade-offs, spatial mapping and decision-oriented ES frameworks.

4. The field has shifted from valuation and classification toward spatially explicit, decision-oriented and social-ecological research. Recent frontiers after 2021 include restoration, nature-based solutions, green infrastructure, ecosystem accounting, machine learning, habitat quality, service flows and supply-demand matching.

5. Future ES research should strengthen the integration of ecological mechanisms, social demand, human well-being, ecosystem restoration, uncertainty analysis and policy implementation. The next stage of ES research will likely be characterized by high-resolution geospatial data, interpretable models, restoration-oriented evaluation and stronger links between ecosystem accounting and governance decisions.

Data Availability Statement

The bibliographic data used in this manuscript were exported from the Web of Science Core Collection as plain-text files containing full records and cited references. The cleaned metadata and intermediate statistical tables can be provided as supplementary material if required by the target journal.

Funding

This work was supported by the Science and Technology Program of Xizang Autonomous Region (No. XZ202403ZY0034).

Conflicts of Interest

The author declares no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

No external funding was used for the preparation of this study. The analysis was developed from Web of Science bibliographic records supplied by the author.

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