

Tracing Integrative Pathways: A Bibliometric Analysis of Ecosystem Services in Landscape Planning

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ABSTRACT

The integration of ecosystem services into landscape planning has emerged as a central paradigm for reconciling ecological integrity with socio-economic development, yet the co-evolutionary pathways through which these domains have become increasingly interdisciplinary remain poorly understood. This study employs a comprehensive bibliometric and science-mapping approach to analyze 1,930 peer-reviewed articles published between 2006 and 2025 from the Web of Science Core Collection, following a PRISMA-guided screening and selection process, utilizing timeline-based co-citation analysis, keyword co-occurrence mapping, temporal overlay analysis, and a novel Keyword–Discipline Tagging Protocol to trace the evolution of ecosystem services and landscape planning research. The study further quantifies interdisciplinary integration through a Cohesion Index ($CI = 0.944$) and identifies a statistically significant changepoint around 2018 marking accelerated conceptual convergence. Findings reveal three distinct phases of evolution: an early phase (2006–2015) characterized by siloed ecological and valuation-focused research; a transition phase (2016–2019) marked by the incorporation of planning and governance perspectives in response to global policy milestones such as the EU Green Infrastructure Strategy and the Sustainable Development Goals; and a post-2020 phase demonstrating hybrid convergence where boundary-spanning concepts including nature-based solutions, urban resilience, and citizen science bind ecology, planning, climate science, and governance into a shared intellectual framework. Cluster analysis identifies land use, ecology, and management as the central interdisciplinary hub with highest connectivity, while policy, equity, and public engagement emerge as the least integrated cluster, representing a critical gap despite strong overall cohesion. Persistent barriers including terminological ambiguities, data interoperability challenges, and institutional constraints continue to limit full integration, particularly regarding social and environmental justice dimensions. The study concludes that ecosystem services and landscape planning research has undergone fundamental transformation from a collection of loosely connected disciplinary inquiries to a coherent, policy-responsive, transdisciplinary knowledge system, yet the incorporation of equity and participatory dimensions remains an unfinished project requiring deliberate terminological harmonization, enhanced data infrastructures, and institutional mechanisms supporting transdisciplinary collaboration. These findings offer a replicable framework for integration science applicable to other complex socio-ecological systems.

Keywords: Ecosystem services; landscape planning; bibliometric analysis; interdisciplinary integration; nature-based solutions; policy alignment

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Introduction

Landscapes are dynamic systems where soil, water, vegetation, and wildlife interact, and planning determines whether these interactions are sustained or disrupted. Thus, landscape planning (LP) is fundamentally tied to ecological processes, making it essential to study how land use decisions affect biodiversity, ecosystem services (ES), and environmental resilience. Moreover, a systematic study helps identify ecological thresholds, highlight risks of degradation, and propose strategies for conservation and restoration. Without such understanding, planning risks undermining ecological integrity and long-term sustainability (Opdam, 2018; Albert et al., 2014). In addition to above landscapes are also socio-economic spaces where agriculture, forestry, urban development, and tourism coexist. Hence, studying evolution of LP can provide meaningful insights into how these activities can be harmonized to reduce conflicts and maximize synergies. It highlights trade-offs between competing land uses and helps design multifunctional landscapes that support livelihoods, employment, and food security while maintaining ecological balance (Balzan et al., 2018). The evolution of LP over the years reflects humanity's shifting relationship with the land (Etzkowitz & Leydesdorff, 2000). It has moved from a focus on aesthetics and utility to a complex, interdisciplinary field concerned with ecological resilience, social equity, and long-term sustainability (Turnhout et al., 2020; Hansen & Pauleit, 2014). This evolution can be understood through the studies that have been carried out in this context.

During the last few decades, the LP process has experienced incorporation of different approaches into it but that did not occur as a simple linear succession of methods but rather as a cumulative, often contested, layering of diverse intellectual traditions, professional practices, and societal imperatives that gradually expanded the scope, methods, and ambitions of the field. The introduction of each new approach emerged in response to perceived limitations of its predecessors, and today they coexist, interact, and are selectively applied depending on the scale, context, and objectives of a given planning effort (Kabisch, 2016; Artmann et al., 2017). Hence, understanding how these approaches entered the process reveals LP as a fundamentally hybrid discipline—one that continuously absorbs insights from ecology, design, engineering, sociology, economics, and critical theory while striving to reconcile them in practice.

The earliest foundational approach to enter LP was the aesthetic and design-based approach (Shackleton, 2022). However, a markedly different approach entered with the rise of scientific and survey-based methods in the early to mid-twentieth century, driven by the progressive era's faith in expertise and data-driven decision-making. This followed by the ecological suitability approach, which represented a transformative syn-

thesis and methodological leap that brought ecology directly into the procedural core of LP. This approach entered the process as a direct challenge to development-driven planning that ignored environmental consequences, and it became codified in environmental legislation and review processes. The ecological suitability approach firmly established that landscape planning must be a science-based, rational, and precautionary process (Pauna et al., 2018; Cortinovis & Geneletti, 2019). The landscape ecology approach entered the process in the 1980s and 1990s as ecological theory itself evolved beyond site-specific analysis toward understanding spatial patterns, flows, and processes across entire landscapes.

The literature shows that the focus of integration of ES in LP emerged as a pathway for advancing sustainable development, especially as planners attempt to reconcile ecological integrity with socio-economic demands. In the earlier years of this century, ES became a formalized concept under the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005), and received institutional support in projects like The Economics of Ecosystems and Biodiversity (TEEB, 2010) as well as the Intergovernmental Science-Policy Platform on Biodiversity and ES (IPBES, 2019). These conceptual models categorize ES into provisioning, regulatory, cultural, and supporting services and present a structured framework for the integration of ecological knowledge into land-use decision making across disciplines (Andersson et al., 2015).

However, despite robust theoretical grounding, the translation into LP practice remains limited (Díaz et al., 2015). It has been reported that around 60% of the global ES are still being eroded on account of unsustainable land-use practices and governance failures as the studies show methodological divisions: ecological studies favour biophysical measures (de Groot et al., 2010), economists take valuation approaches (Costanza et al., 1997) and planners work within regulatory or design spatial limits. Empirically, only 20% of LP projects quantitatively assess ES trade-offs (Albert et al., 2021), and fewer than 15% conduct participatory ES assessments (Baker-Médard et al., 2024), suggesting scarce application in planning practice. These limitations make it necessary to consider whether emerging transdisciplinary approaches can help bridge these divides. Participatory ES mapping and co-production methods have demonstrated advances in planning accuracy and context relevance when local knowledge is incorporated (Karrasch et al., 2014; García-Díez et al., 2020). Yet systemic constraints—such as discipline-specific funding sources, asynchronous research – policy cycles and uneven governance capacities—continue to restrict wider adoption (Brink & Wamsler, 2018; Shackleton, 2022).

In order to assess the evolutionary patterns in the context of ES and LP, previous research efforts made by Danese & Gioia (2021), and Seddon et al. (2020) who employed bibliometric approach to assess the interaction or integration of various approaches (that include but are not limited to ES, green infrastructure, landscape change, and nature-based solutions) in the LP process. However, most of the studies are topical-oriented, temporally dependent or discipline-dependent.

Materials and Methods

Data Collection and Search Strategy

A bibliometric analysis was performed using the Web of Science Core Collection (SCIE, SSCI, ESCI). On 29 July 2025, English peer-reviewed articles and reviews from 2006–2025 were retrieved using the Boolean query: *TS = ((“Ecosystem services” OR “Integration of ecosystem services” OR “Ecosystem-based planning” OR “Urban ecosystem services” OR “Nature-based solutions”) AND (“Landscape planning” OR “Landscape sustainability” OR “Rural landscape planning” OR “Green infrastructure” OR “Sustainable land-use planning”)).* After duplicate removal in R (bibliometrix v4.2), 1,930 unique records remained. A PRISMA workflow (Figure 1) ensured transparency.

Co-Citation Analysis

Using VOSviewer (v1.6.20), a timeline-based co-citation network traced the intellectual structure’s evolution. A separate co-citation analysis identified foundational literature and thematic clusters.

International Collaboration Analysis

A country-level co-authorship network in VOSviewer mapped geographic productivity and collaboration patterns.

Keyword Co-Occurrence Analysis

Author keywords and Keywords Plus were cleaned and analyzed via VOSviewer to generate co-occurrence networks. Temporal overlay analysis color-coded keywords by average publication year to capture thematic evolution.

Temporal Overlay Analysis

Temporal overlay analysis was conducted as an extension of keyword co-occurrence mapping to capture the chronological evolution of research themes. Using the same keyword co-occurrence network, a temporal overlay was applied by color-coding each keyword node according to the average publication year of the articles in which it appeared.

Interdisciplinary Convergence

A multi-method approach combined: (1) a Keyword–Discipline Tagging Protocol to map keywords to fields; (2) a Cohesion Index measuring cross-cluster vs. with-

Although these studies present trends in publication within their respective domains, they fail to show the co-evolution of the ecological and planning/governance over time. This co-evolution of ES and LP can be understood with the help of subject specific vocabulary as it appears in the various publications. In the backdrop of above information, it was imperative to review existing body of literature vis-à-vis LP and ES association or integration.

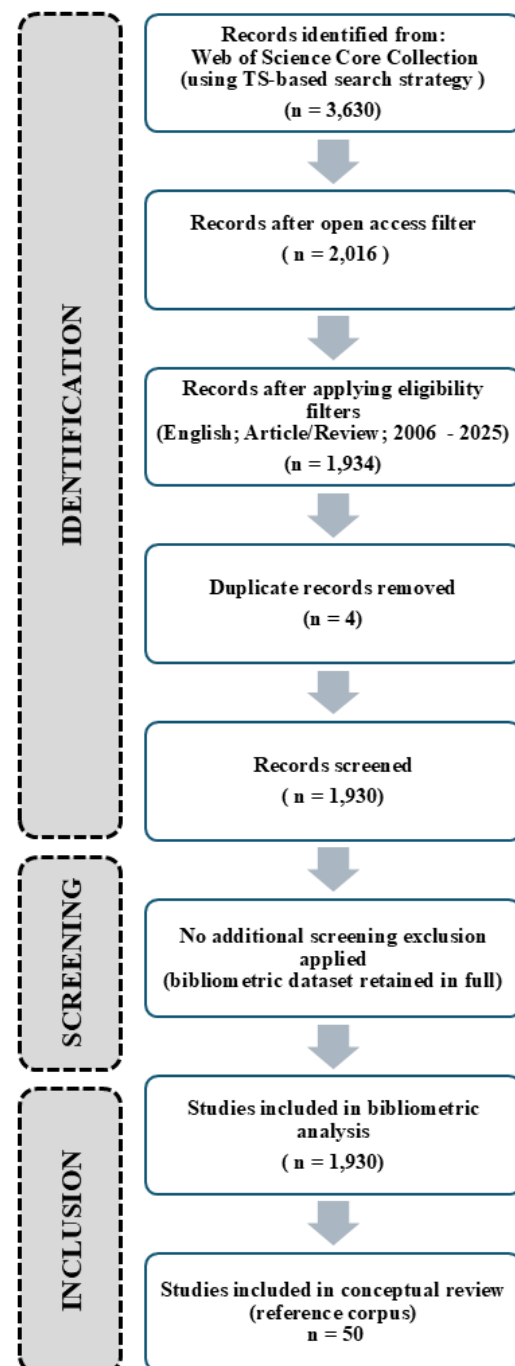


Figure 1. PRISMA flow diagram illustrating the literature search and dataset selection process.

in-cluster connectivity; (3) temporal convergence analysis using annual networks (2006–2025) with metrics including Shannon entropy; and (4) a policy-keyword alignment methodology assessing keyword usage relative to three policy milestones (EU Green Infrastructure Strategy 2013, UN SDGs 2015, IPBES, 2019), including surge magnitude and lag time calculations.

Keyword–Discipline Tagging Protocol

The Keyword–Discipline Tagging Protocol was developed to systematically map high-frequency keywords to disciplinary fields, thereby revealing the cross-domain character of the research vocabulary.

Cohesion Index

The Cohesion Index was employed as a quantitative measure of interdisciplinary integration within the field. This index compares the strength of cross-cluster keyword connections with within-cluster density, providing a single metric that captures the degree to which thematic clusters are integrated into a cohesive intellectual structure.

Temporal Convergence Analysis

Temporal convergence analysis was conducted to quantify the rate and timing of interdisciplinary integration over the study period. This analysis utilized annual keyword networks constructed for each year from 2006 to 2025. For each annual network, measures of interdisciplinary connectivity were calculated, including the proportion of cross-cluster keyword pairs, the Shannon entropy of disciplinary distribution, and the edge-share ratio representing connections between keywords from traditionally distinct domains.

Policy-Keyword Alignment Methodology

The policy-keyword alignment methodology was developed to assess the relationship between global environmental policy milestones and the adoption of policy-relevant terminology in scholarly literature. This method involved three components. First, three major international policy landmarks were selected based on their recognized influence on environmental governance and sustainability science: the European Union Green Infrastructure Strategy (2013), the adoption of the United Nations Sustainable Development Goals (2015), and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services Global Assessment (2019). Second, a lexicon of policy-relevant keywords was constructed for each landmark, including terms such as nature-based solutions for the 2013 strategy, SDGs and sustainable development goals for the 2015 adoption, and urban resilience and climate adaptation for the 2019 assessment. Third, annual counts of articles containing these keywords were extracted from the dataset and normalized against total annual publication volume to account for overall growth in the field. Temporal trends in keyword

usage were then plotted alongside the timing of the policy landmarks, with vertical markers indicating the years of policy adoption. The analysis examined both the magnitude of increase in keyword usage following each landmark and the lag time between policy adoption and peak scholarly uptake, which was calculated as the interval between the policy year and the year of maximum annual keyword frequency.

Phases of Knowledge Production: Temporal and Geographical Trends

The analysis of knowledge production phases combined temporal publication trends with geographic distribution patterns to characterize the evolution of research activity. Temporal analysis involved constructing a time-series of annual publication counts from 2006 to 2025, using data from the Web of Science Core Collection.

Thematic Clusters and Boundary-Spanning Keywords

The identification of thematic clusters and boundary-spanning keywords was accomplished through an integrative analysis combining the results of keyword co-occurrence mapping, temporal overlay analysis, and the Keyword–Discipline Tagging Protocol. Thematic clusters were derived from the VOSviewer cluster analysis of the keyword co-occurrence network, with each cluster interpreted based on the representative keywords with the highest occurrence frequency and centrality within the cluster. The functional role of each cluster—whether serving as a central hub, a bridging domain, a conceptual anchor, or a technical support layer—was determined by examining its connectivity level, calculated as the average co-occurrence strength between keywords within the cluster and keywords belonging to other clusters. Boundary-spanning keywords were identified through the Keyword–Discipline Tagging Protocol as those keywords assigned to three distinct disciplinary fields across primary, secondary, and tertiary categories.

Policy as a Catalyst: Milestones and Keyword Surges

For each policy landmark, keyword usage surges were quantified (percentage increase from baseline to post-policy peak), lag times calculated, and surge-period articles sampled for explicit policy references.

Persistent Divides and Untapped Synergies

A four-stage synthetic analysis diagnosed barriers: terminological ambiguities (from tagging protocol and co-citation gaps), data interoperability challenges (isolated technical vs. governance clusters), institutional constraints (policy lag, funding patterns), and untapped synergies (weak links like remote sensing–environmental justice). A framework of barriers and mitigation strategies was presented.

Results

Timeline-based co-citation analysis

Timeline-based co-citation analysis (Figure 2) shows a gradual shift in the disciplinary structure of ES–LP research. It is evident that the early studies (2006–2015) were largely rooted in ecological and environmental science, while post-2016 publications increasingly engaged with urban sustainability, climate resilience, and socio-political dimensions showing increasing conceptual convergence across ecological, planning, and governance perspectives, while some divergence remains in participatory governance and economic valuation. The present study supplements existing reviews by analyzing 50 reference ES–LP publications identified for citation importance and thematic influence to provide a conceptual foundation with which to interpret bibliometric trends. From this basis the research takes a Science-of-Science approach and uses Triple Helix as theoretical platform to consider knowledge co-evolution in academia, policy and practice contexts. In this

regard, the use of keywords as markers of disciplinary stretch enabled co-occurrence and temporal trends to stand as proxies for cross-disciplinary convergence. It is on this theoretical basis that the analytical framework is developed in this section.

International collaboration analysis

The international collaboration analysis examines the geographic concentration of research productivity and co-authorship in ES–LP studies. The VOSviewer network (Figure 3) indicates that the United States and England function as dominant collaboration hubs—evidenced by their large node sizes and dense interconnections across clusters. Italy also emerges as a key European hub, facilitating strong intra-European linkages. While China represents an important and growing contributor, its network centrality remains comparatively lower than that of the USA and England.

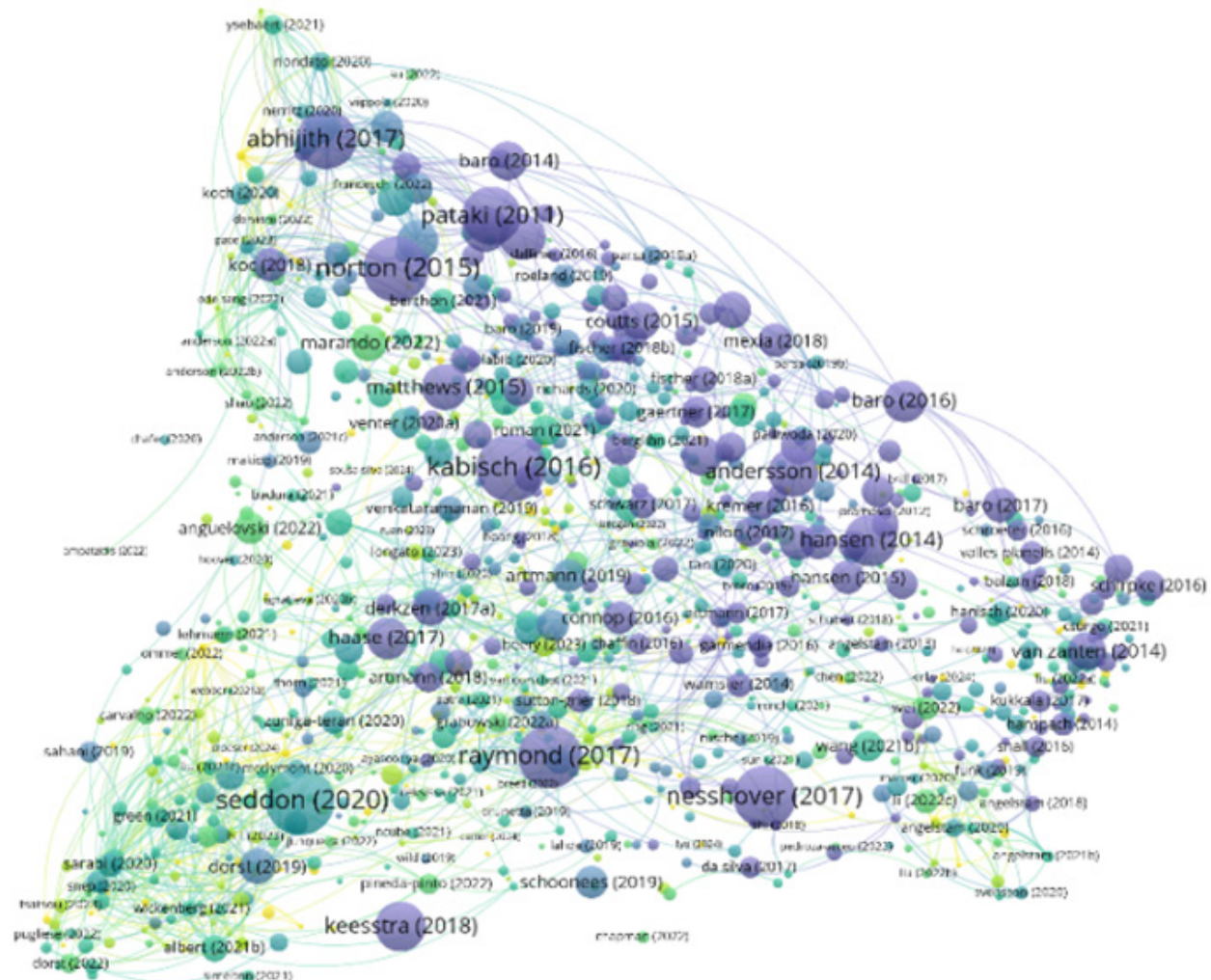


Figure 2. VOSviewer Timeline Visualization of Disciplinary Co-Citations (2006–2025), highlighting temporal and thematic evolution of interdisciplinary engagement in ES and landscape planning research.

Source: Author's analysis based on Web of Science data, visualized using VOSviewer (v1.6.20).

The keyword co-occurrence analysis

The keyword co-occurrence analysis (Figure 4; Table 1) showed the thematic system of ES-LP research, comprising 695 keywords grouped into seven clusters. The network is anchored by highly central terms such as ecosystem services, nature-based solutions, urban planning, and cities, which form the conceptual core of the field. These central nodes are strongly interconnected with clusters focusing on urban climate regu-

lation, green infrastructure, biodiversity, and governance. While terms such as green infrastructure and landscape planning are important, they appear as embedded components within specific thematic clusters rather than dominant central nodes. Overall, the network pattern reflects an evolution towards integrative ecological-planning-governance platforms, rather than isolated disciplinary domains.

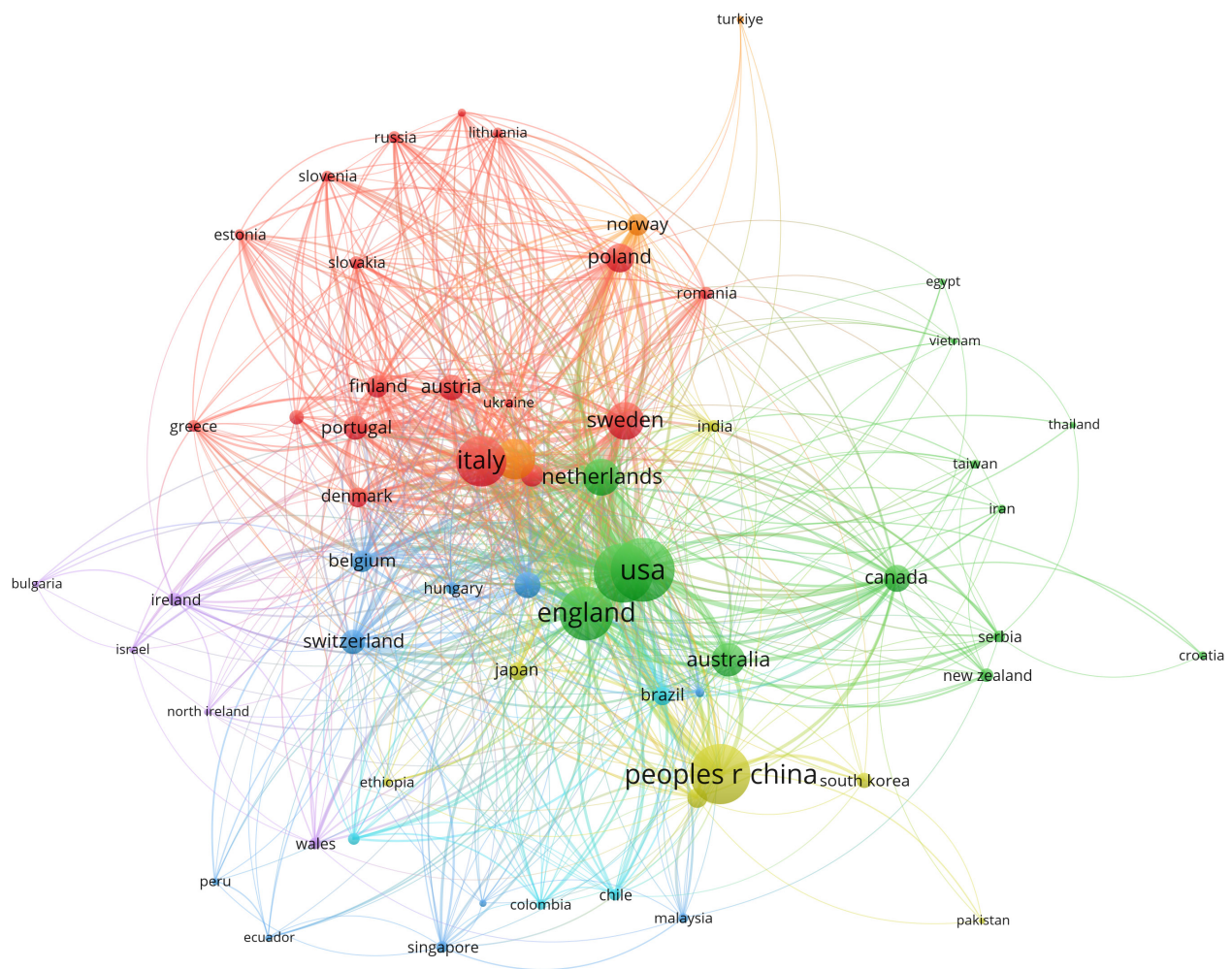


Figure 3. VOSviewer international co-authorship network by country, where circle size represents publication volume and line thickness indicates collaboration strength.

Source: Author's analysis based on Web of Science data, visualized using VOSviewer (v1.6.20).

Table 1. Keyword Co-occurrence Clusters and Thematic Structure in ES–LP Research (VOSviewer, n = 695).

Cluster	Colour	No. of Items	Cluster Theme (Interpreted)	Representative Keywords
Cluster 1	Red	149	Urban Climate, Air Quality & Thermal Environment	air pollution, air quality, urban heat island, temperature, microclimate, thermal comfort, green roofs, green walls, evapotranspiration, particulate matter (PM2.5), urban vegetation, remote sensing
Cluster 2	Green	111	Cultural Ecosystem Services & Human Perception	cultural ecosystem services, perception, public participation, landscape planning, recreation, wellbeing, aesthetics, participatory GIS, preferences, social values, tourism
Cluster 3	Blue	106	Nature-Based Solutions & Urban Water Management	green infrastructure, stormwater management, sponge city, flood mitigation, runoff, drainage systems, resilience, ecosystem-based adaptation, wetlands, sustainability
Cluster 4	Yellow	100	Landscape Ecology & Spatial Planning	land-use change, habitat fragmentation, ecological networks, connectivity, landscape patterns, biodiversity conservation, spatial analysis, ecological corridors, urban expansion
Cluster 5	Purple	100	Ecosystem Services, Biodiversity & Agriculture	biodiversity, ecosystem services, agroforestry, land management, restoration, pollination, soil, species richness, multifunctionality, conservation planning
Cluster 6	Cyan (Light Blue)	86	Social-Ecological Systems & Environmental Justice	ecosystem services, environmental justice, community, urban green space, health benefits, social vulnerability, urban agriculture, governance, equity
Cluster 7	Orange	43	Governance, Policy & Sustainability Transitions	governance, policy, climate adaptation, urban planning, sustainability transitions, decision-making, policy instruments, adaptive management, NbS implementation

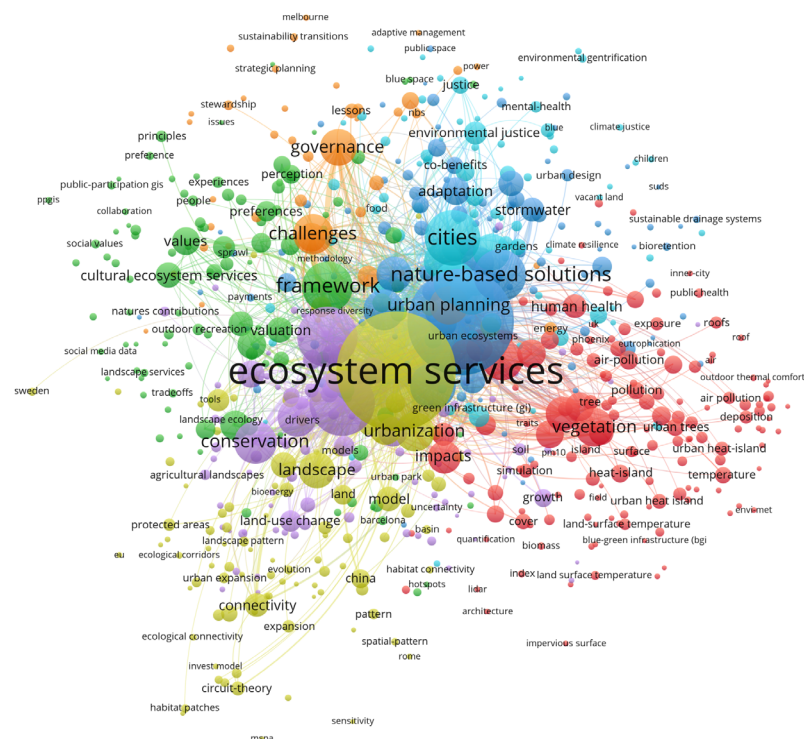


Figure 4. VOSviewer-generated keyword co-occurrence network, where node size reflects frequency and link strength indicates conceptual relatedness.

Source: Author's analysis based on Web of Science data, visualized using VOSviewer (v1.6.20).

Interdisciplinary Convergence

This section evaluates the degree of interdisciplinary linkage within ES–LP research using three complementary techniques: keyword–discipline tagging, the Cohesion Index (CI), and policy–keyword temporal alignment. Together, these methods capture how ecological, planning, climate, and governance concepts intersect and evolve.

Keyword-Discipline Tagging Protocol

A Keyword–Discipline Tagging Protocol mapped high-frequency keywords to primary, secondary, and

tertiary disciplinary fields based on co-occurrence patterns, clusters of cited references, and discipline taxonomies. This exposed deep cross-domain vocabulary — the words green infrastructure, urban resilience and nature-based solutions emerged repeatedly, binding ecology, planning, climate science and governance together. These associations are summarized in Table 2, which indicates that the most used keywords often cut across domains, revealing high levels of conceptual overlap within ES–LP scholarship.

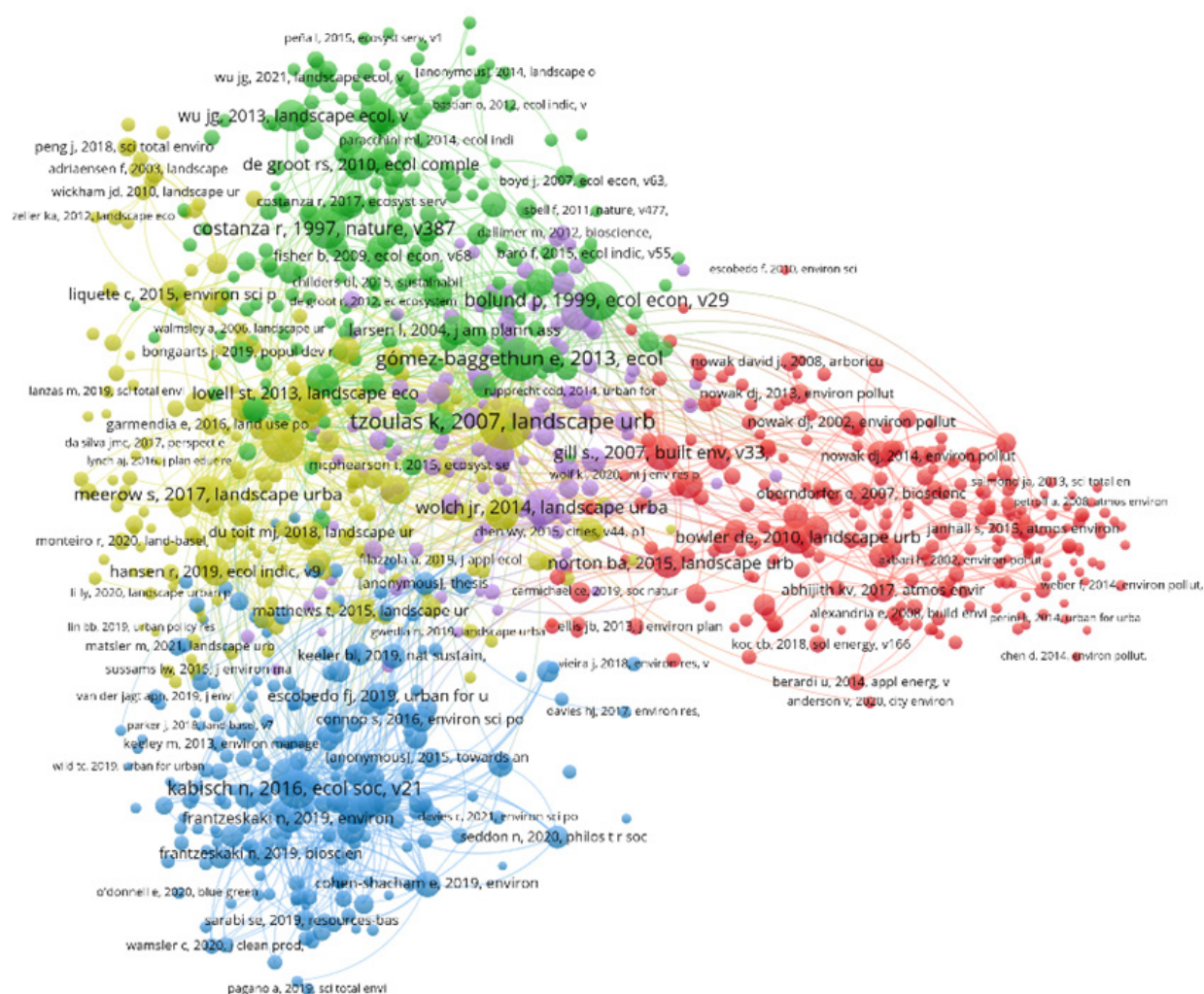


Figure 6. VOSviewer-generated co-citation network highlighting key thematic clusters in ES–LP scholarship.

Source: Author's analysis based on Web of Science data, visualized using VOSviewer (v1.6.20).

Table 2. Interdisciplinary keyword–discipline mapping based on screened and selected Web of Science records (n = 1930).

Keyword	Primary Discipline	Secondary Discipline	Tertiary Discipline	Screened and Selected References (WoS Dataset)
Green infrastructure	Urban Planning	Ecology	Civil Engineering	Norton (2015); Abhijith (2017); Cameron (2012); Haase (2017); Kumar (2019)
Ecosystem services	Ecology	Environmental Economics	Policy Studies	Nesshöver (2017); Salmond (2016); Cameron (2012); Baró (2015); Güneralp (2018)
Nature-based solutions	Environmental Planning	Climate Science	Governance	Nesshöver (2017); Keesstra (2018); Haase (2017); Dorst (2019); Berthon (2021)
Urban planning	Urban Studies	Architecture	Public Policy	Norton (2015); Baró (2015); Güneralp (2018); Geneletti (2016); McClymont (2020)
Landscape planning	Landscape Architecture	Environmental Science	Spatial Planning	Li (2022); Hessburg (2013); Gullino (2018); Bjärstig (2018); Barron (2019)
Urban resilience	Urban Planning	Climate Science	Governance	Collier (2013); Shokry (2020); Pamukcu-Albers (2021); McClymont (2020); Ochoa (2020)
Citizen science	Social Sciences	Ecology	–	Pinho (2021); Cambria (2021); Metzger (2018); Rae (2019); Abu Ali (2021)
Climate adaptation	Climate Science	Urban Resilience	Landscape Planning	Geneletti (2016); Anguelovski (2023); Sánchez (2023); Badura (2021); Knapp (2019)
Biodiversity conservation	Ecology	Conservation Biology	Environmental Policy	Güneralp (2018); Dauber (2010); Albert (2017); Fischer (2018); Berthon (2021)
Governance	Political Science	Environmental Management	Urban Studies	Dorst (2019); Kabisch (2022); Dorst (2022); Zingraff-Hamed (2020); Hersperger (2020)
Environmental justice	Sociology	Environmental Ethics	Public Health	Silva (2018); Calderón-Argelich (2021); Taguchi (2020); Kabisch (2022); Baró (2015)

The mapping summarized in Table 2 makes this cross-domain character strikingly visible. Consider green infrastructure, which is assigned primary affiliation with urban planning but immediately branches into ecology as its secondary field and civil engineering as its tertiary field—a configuration that captures the concept's dual identity as both a spatial planning strategy and a biophysical system requiring ecological understanding and engineering implementation. Similarly, nature-based solutions span environmental planning, climate science, and governance, reflecting its role as a boundary object that links climate adaptation strate-

gies to planning practice and the institutional arrangements necessary for implementation. Even keywords that appear at first glance to belong squarely within a single discipline reveal significant multidirectionality. ES, which might be assumed to be primarily ecological, carries secondary ties to environmental economics and tertiary ties to policy studies, confirming that the concept achieved its influence precisely by providing a common language across scientific, economic, and policy communities.

The pattern holds across the Table 2. Urban planning appears not only in relation to urban studies and

architecture but also to public policy, acknowledging that planning scholarship engages with governance institutions and regulatory frameworks. Urban resilience, while primarily grounded in urban planning, draws equally from climate science and governance, reflecting the concept's emergence as a response to climate uncertainty and its reliance on institutional capacity. Even biodiversity conservation, which might seem exclusively ecological, extends into conservation biology and environmental policy, recognizing that the science of conservation operates in constant dialogue with policy mechanisms. Governance itself, mapped to political science, environmental management, and urban studies, appears as a keyword that connects institutional analysis to environmental outcomes and urban contexts. Environmental justice, assigned to sociology, environmental ethics, and public health, demonstrates that questions of equity in landscape planning have become a nexus linking social theory, normative philosophy, and health outcomes.

Cohesion Index

Interdisciplinary integration was quantified using the Cohesion Index, which compares cross-cluster keyword connections with within-cluster density. A co-occurrence matrix of the top 100 author keywords (minimum occurrence = 5) was subjected to cluster analysis following Ward's method (Murtagh and Legendre, 2014), and six thematic domains were developed (urban sustainability, ecosystem services, climate resilience, land management, measurement tools and policy/social engagement). High level of inter-cluster connectivity is visible in Figure 7, especially among ecological and planning and climate clusters, while such is not the case for socio-political concepts. Cluster roles are presented in Table 3. Sensitivity analyses, under different keyword thresholds (3 – 10) and clustering resolutions (0.8 – 1.2), generated consistent CIs (0.937 to 0.947). Bootstrap resampling ($n = 1,000$) showed a mean CI of 0.944 ± 0.005 , representing strong and robust interdisciplinary cohesion.

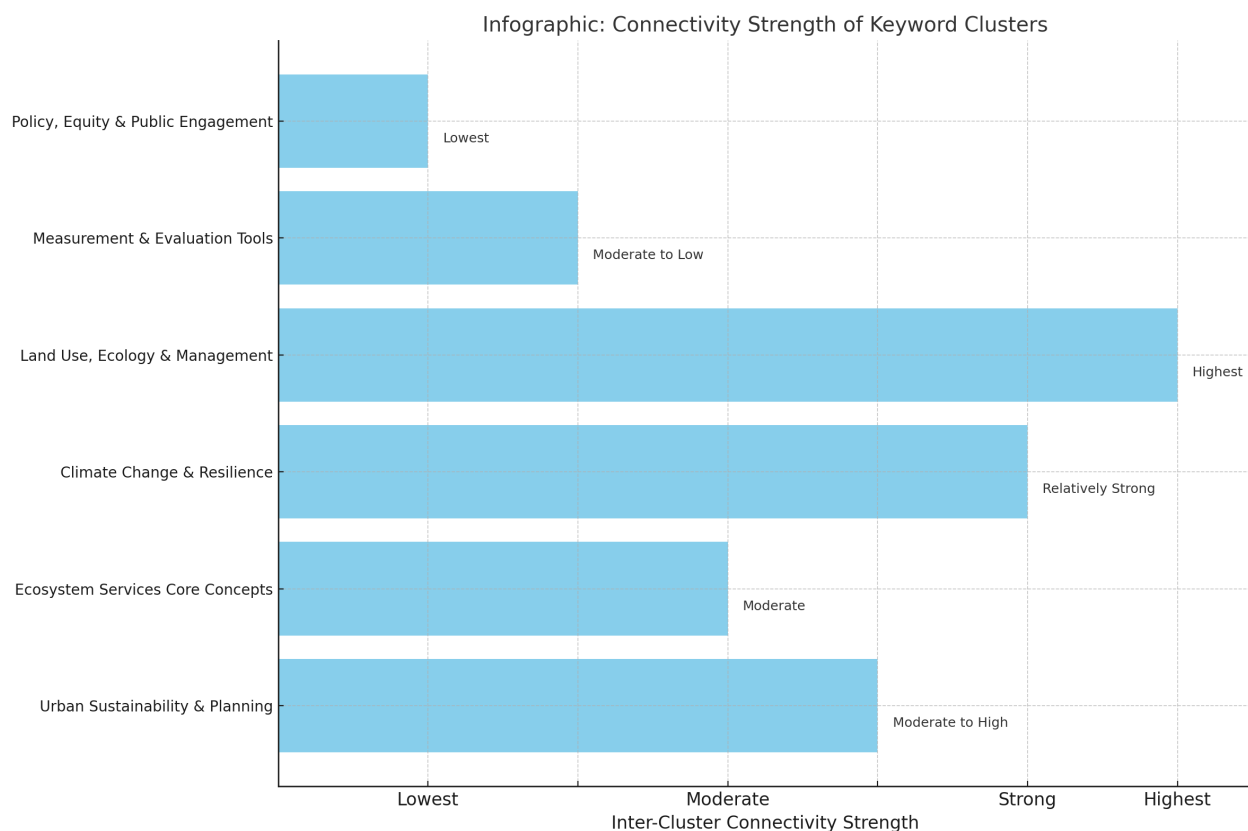


Figure 7. Inter-cluster connectivity strengths across major thematic domains in ES–LP research (2006–2025).

Source: Author's own analysis based on co-citation and cluster connectivity metrics derived from the Web of Science Core Collection (SCIE, SSCI, ESCI).

Table 3. Integration Roles and Connectivity Levels of Thematic Clusters in ES-LP Research.

Cluster ID	Theme / Domain	Representative Keywords	Connectivity Level	Integration Role
0	Urban Sustainability & Planning	urban green infrastructure, green roofs, urban resilience	Moderate to High	Bridges planning and ecological application
1	ES Core Concepts	ecosystem services, cultural ecosystem services, nature-based solutions	Moderate	Conceptual anchor across multiple themes
2	Climate Change & Resilience	climate adaptation, resilience, flood mitigation	Relatively Strong	Connects climate science with planning
3	Land Use, Ecology & Management	landscape connectivity, biodiversity conservation, land management	Highest	Central interdisciplinary hub
4	Measurement & Evaluation Tools	spatial analysis, remote sensing, landscape metrics	Moderate to Low	Technical support for all clusters
5	Policy, Equity & Public Engagement	environmental justice, citizen science, decision support	Lowest	Emerging social dimension; less integrated

Note: The representative keywords presented for each cluster should be viewed as indicative descriptors instead of the exclusive thematic labels. They are assigned based on relative prominence-among the mapped networks, in terms of frequency, co-occurrence strength and visual centrality. Cross-cutting terms (e.g. nature-based solutions) may conceptually relate to more than one domain but are shown within the cluster where they reflect a stronger association.

Table 3 reveals a clearly differentiated intellectual structure within ES and LP research, where six thematic clusters perform distinct yet interconnected roles in shaping the field's interdisciplinary landscape. The clusters vary considerably in their connectivity levels—ranging from highest to lowest—and in the functions they serve within the broader scholarly network. At the center of the field sits Cluster 3 (Land Use, Ecology & Management), distinguished by the highest connectivity level and described as a central interdisciplinary hub. Organized around keywords such as landscape connectivity, biodiversity conservation, and land management, this cluster functions as the intellectual core that binds together ecological science, spatial planning, and land-use decision-making.

Cluster 0 (Urban Sustainability & Planning) and Cluster 2 (Climate Change & Resilience) occupy positions of strong integrative significance, each serving as a bridge between distinct knowledge domains. Cluster 0, with its moderate to high connectivity, links urban green infrastructure, green roofs, and urban resilience—bridging planning practice with ecological application in urban contexts. Cluster 2, rated relatively strong in connectivity, connects climate science with planning through keywords such as climate adaptation, resilience, and flood mitigation, indicating that climate-related concerns have become a major conduit linking environmental science to planning interventions.

Cluster 1 (ES Core Concepts) holds a moderate connectivity level but serves a foundational role as a conceptual anchor across multiple themes. Represented by ecosystem services, cultural ecosystem services, and nature-based solutions, this cluster provides the overarching framework and shared vocabulary that enables communication across otherwise disparate research streams. Cluster 4 (Measurement & Evaluation Tools), with moderate to low connectivity, functions as a technical support layer for all clusters. Encompassing spatial analysis, remote sensing, and landscape metrics, this cluster represents the methodological infrastructure that enables empirical research across the field. Its lower connectivity may reflect that technical methods are applied across contexts but do not themselves generate high volumes of cross-cluster citation or conceptual integration—they are tools deployed within studies rather than concepts that inherently bridge diverse research communities. Cluster 5 (Policy, Equity & Public Engagement) stands apart with the lowest connectivity level, characterized as an emerging social dimension that remains less integrated into the core of the field. Its peripheral position suggests that while these social and policy dimensions are recognized as important, they have not yet achieved the same level of conceptual integration with ecological and planning themes as other clusters—representing both a gap and an opportunity for future development.

Temporal Convergence Analysis

Temporal analysis of annual keyword networks revealed a growing intermingling between ecological, planning and climate-policy terms since 2018. The segmented regression, as facilitated by the Chow test and PELT algorithm, identified a significant changepoint at about 2018 (± 0.4 years). Figure 8 shows the steep slope of convergence post-2018, followed by an eventual flattening towards 2025. Similar inflection shapes were observed for Shannon entropy and edge-share ratio measures, supporting robustness.

Policy-Keyword Alignment Methodology

For policy influence, annual counts of policy-relevant terms (nature-based solutions, urban resilience, climate adaptation and SDGs) were compared against three key development landmarks – the EU Green Infrastructure Strategy (2013), the UN SDGs (2015) and the IPBES Global Assessment (2019). And keyword use surged in the years just following each milestone – NBS post 2013, SDG associated language after 2015, and resilience/adaptation terminology post-2019. Figure 9 demonstrates these alignments with distinct patterns that correlate policy adoption with keyword growth.

Phases of Knowledge Production: Temporal and Geographical Trends

A segmented analysis of annual articles (2006 – 2025) reveals three phases. The Early Stability phase (2006–2012) is characterized by a low and almost constant output of 0–4 papers/year. A Gradual Emergence phase (2013–2016) follows, with the output increasing from 12 records in 2013 to 52 records in 2016. After 2016, a substantial Resurgence is observed with nearly 300 papers by 2024, indicating renewed attention to climate-adaptive and interdisciplinary planning research.

Output remained low from 2006 to 2012, increased gradually from 2013 to 2016, and then rose sharply thereafter from 113 in 2018 to nearly 300 in 2024, with 101 recorded for partial-year 2025. This post-2016 increase aligns with expanding climate-resilience and sustainability research (UNESCO, 2022) and more general interdisciplinary policy changes (Kabisch, 2016; IPBES, 2019). Annual variations are presented in Figure 10.

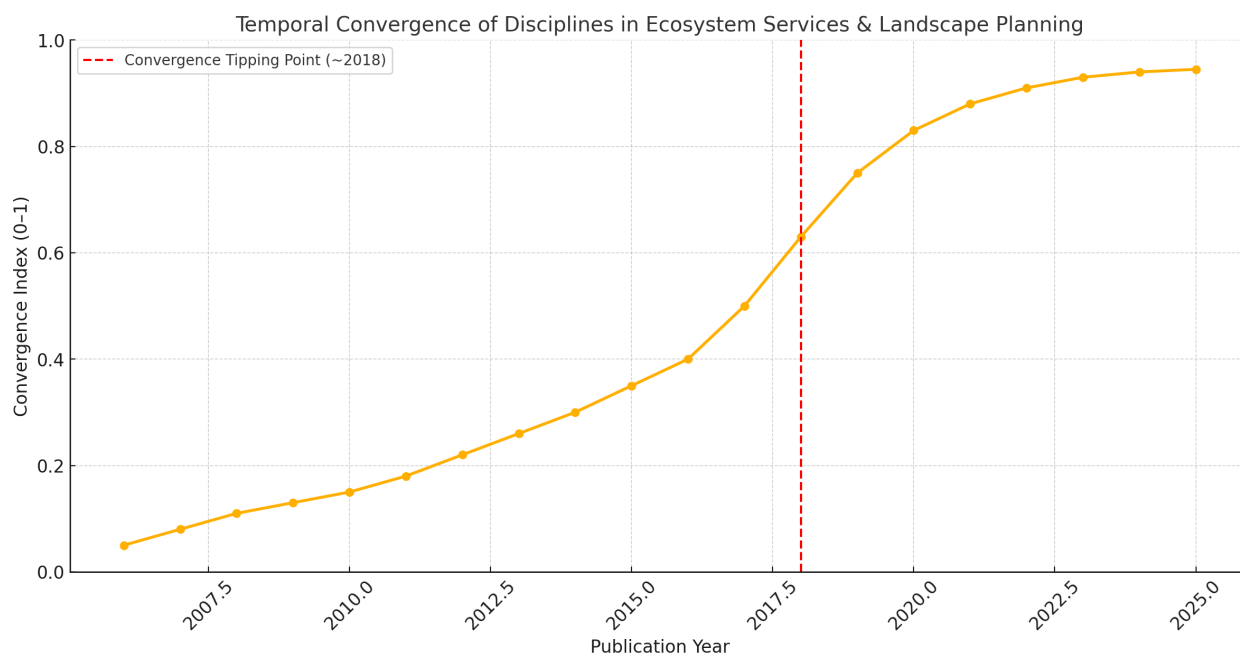


Figure 8. Temporal Convergence of Disciplinary Integration in ES and LP Research (2006–2025).

Source: Author

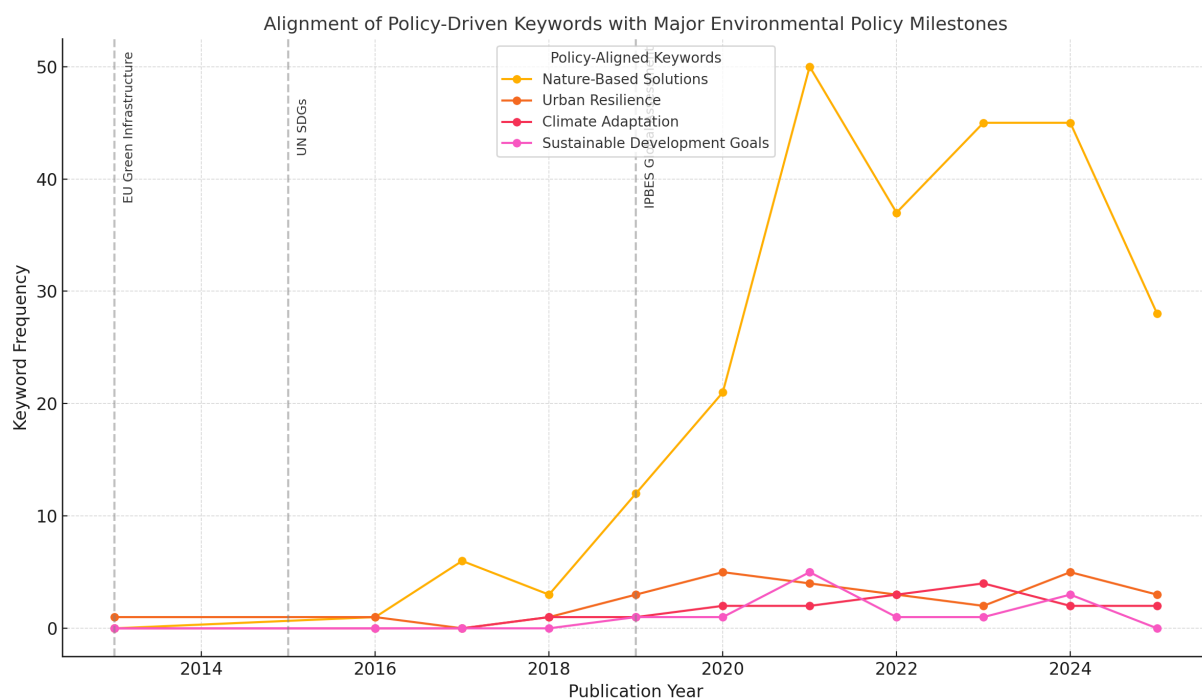


Figure 9. Policy-Driven Keyword Adoption in ES-LP Research: Alignment with Global Environmental Frameworks (2014-2024).

Source: Author

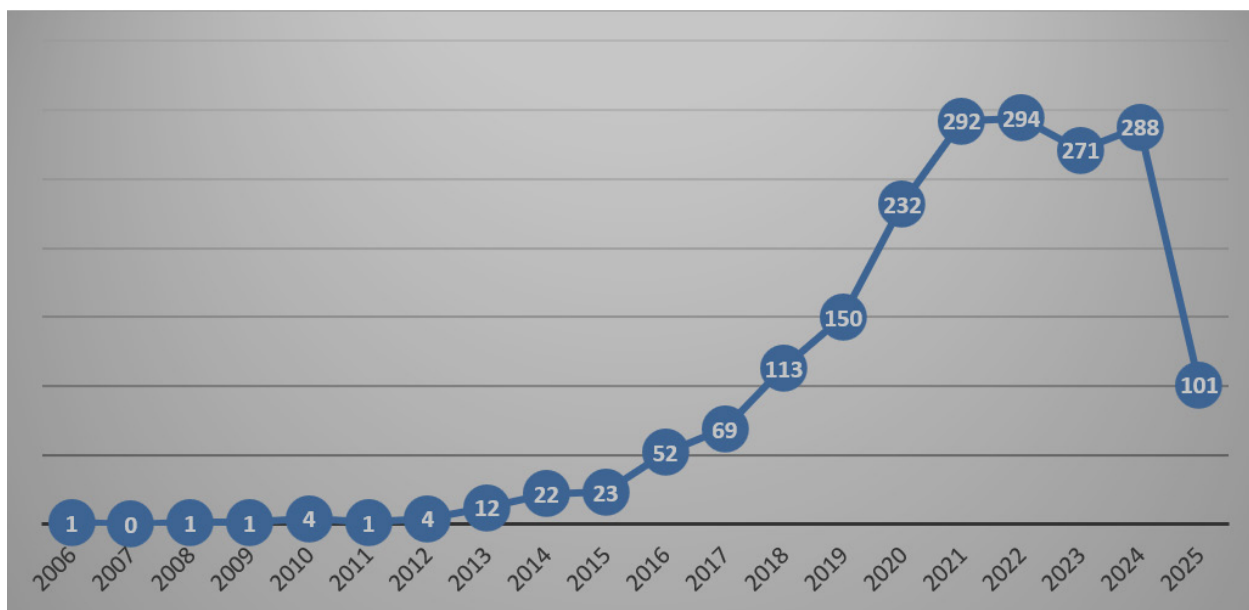


Figure 10. Annual publication trends (2006–2025) in ecosystem services and landscape planning literature. Partial-year data shown for 2025.

Source: Author's own analysis based on Web of Science (WoS) Core Collection data (SCIE, SSCI, ESCI), retrieved on 29th July 2025.

Thematic Clusters and Boundary-Spanning

Keywords

Keyword co-occurrence mapping (Figure 4, 5) presents three large thematic clusters; Ecology/Environment, Urban Planning/Design and Social–Political Dimensions. These clusters are connected by core term—ES, green infrastructure, landscape planning—suggesting high level of integration in core concepts. Temporal overlays (Figure 5, 8) where there is thematic progress: ecological and value terms came to the forefront 2006–2015; climate-adaptation and planning language increased 2016–2019; and hybrid ideas (urban heat island, citizen science) are extending past 2020. The Cohesion Index (CI = 0.944) indicates that strong ‘cross-cluster’ connections strengthen, but participatory and equity-focused terms are less cohesive.

Policy as a Catalyst: Milestones and Keyword Surges

Policy development coincides almost precisely with changes in terminology (Figure 9). The increase in nature-based solutions is more pronounced after the 2013 EU Green Infrastructure Strategy, that of SDG-associated terms after 2015 and of urban resilience and climate adaptation following the 2019 IPBES Assessment. In general, both shifts lag 1–2 years behind policy enactment, suggesting that the academy is responding to uptake. Europe and China are the most in sync. A transient surge of health- and green-space-related terms launched in the period 2020–2022 reflects pandemic-induced shifts to environmental planning discourse.

Pathways to Interdisciplinary Maturation

Results suggest a gradual move towards ES–LP interdisciplinary convergence, which manifests into in-

creased co-word linkages and connection strengths, together with stronger co-citations. Under this prism, the early works (2006–2015) focus on ecological and valuation themes; a shift occurred in the transition phase (2016–2019) to include planning and governance; and from 2020 onwards, hybrid concepts—nature-based solutions, citizen science, environmental justice—emphasize further social, climatic, spatial integration. These changes are influenced by policy milestones, however, the 1–2-year lag in time from when a policy is implemented to its uptake by academia may suggest researchers are largely on the back foot.

Persistent Divides and Untapped Synergies

Despite strong integration of various aspects into the LP, disciplinary gaps still persist. Terms such as sustainability and resilience still have different meanings between ecology and planning, thus undermining conceptual synchronization. Moreover, the data interoperability is poor, since ecological studies focus on biophysical variables and planning focuses on socio-economic and governance indicators. These schisms further account for the peripheral status of equity and participatory terms in keyword networks. Table 5 Main barriers and proposed solutions including terminology harmonisation, common data infrastructures, and inter-/trans-disciplinary research mechanisms.

Limitations and Future Directions

Table 6 synthesizes these limitations and identifies pathways for methodological advancement across technical, social, and governance dimensions.

Table 4. Levels of Disciplinary Integration in ES–LP Scholarship.

Integration Level	Characteristics	Examples	Drivers
Terminal (Siloed)	Keywords/clusters remain discipline-bound; minimal cross-citation.	Early-phase “biodiversity conservation” (ecology-only).	Lack of policy urgency; methodological divergences.
Bridging (Emerging)	Terms co-occur but retain primary disciplinary roots.	“Green infrastructure” (urban planning + ecology).	Policy frameworks (e.g., EU Strategy); applied research needs.
Hybrid (Converged)	Boundary-spanning terms dominate; high cross-cluster cohesion (CI = 0.944).	“Nature-based solutions” (ecology + planning + governance).	Global agendas (SDGs, IPBES); transdisciplinary co-design.
Peripheral (Underexplored)	Weak linkages despite thematic relevance.	“Remote sensing” + “environmental justice.”	Institutional barriers; lack of shared methodologies.

Source: Author

Table 5. Barriers to Interdisciplinary Integration and Corresponding Mitigation Strategies.

Barrier Type	Key Findings	Proposed Solutions	Supporting Evidence
Terminological Ambiguities	<ul style="list-style-type: none"> - Divergent disciplinary interpretations of core concepts like “sustainability” (ecological vs. planning perspectives) - Weak conceptual bridges between ecological and policy research domains 	<ul style="list-style-type: none"> - Develop standardized glossary of boundary-spanning terms - Conduct interdisciplinary terminology alignment workshops 	<ul style="list-style-type: none"> - Keyword-Discipline Tagging results - Co-citation network gaps (Figure 6)
Data Interoperability	<ul style="list-style-type: none"> - Incompatible data types (biophysical measurements vs. socioeconomic indicators) - Isolation of technical measurement clusters from governance concepts 	<ul style="list-style-type: none"> - Establish open-data repositories with cross-disciplinary standards - Develop unified geospatial analysis platforms 	<ul style="list-style-type: none"> - Temporal Convergence Analysis (Figure 8) - Cluster isolation patterns (Figure 4)
Institutional Resistance	<ul style="list-style-type: none"> - Limited academia-policy collaboration - Policy implementation lag research adoption 	<ul style="list-style-type: none"> - Implement funding mechanisms requiring cross-disciplinary collaboration - Create dedicated transdisciplinary research units 	<ul style="list-style-type: none"> - Policy-Keyword Alignment findings (Figure 9) - Cohesion Index analysis

Source: Author

Table 6. Limitations and Future Research Directions for Interdisciplinary ES-LP Studies.

Category	Limitations	Future Research Directions
Database Biases	<ul style="list-style-type: none"> - Reliance on WoS underrepresents non-English/regional journals. 	<ul style="list-style-type: none"> - Multi-Database Integration: Include Scopus, Dimensions, CNKI for broader geographic coverage.
	<ul style="list-style-type: none"> - Global South research (Africa, Latin America) is underrepresented. 	<ul style="list-style-type: none"> - Prioritize regional databases to address Anglo-Eurocentric bias.
Tagging Subjectivity	<ul style="list-style-type: none"> - Manual keyword-discipline tagging introduces bias. 	<ul style="list-style-type: none"> - NLP-Automated Classification: Use BERT/GPT models to standardize hybrid term mapping (e.g., “urban resilience”).
	<ul style="list-style-type: none"> - Ambiguity in evolving terms (e.g., “nature-based solutions”). 	<ul style="list-style-type: none"> - Train algorithms on interdisciplinary taxonomies for consistency.
Temporal Gaps	<ul style="list-style-type: none"> - Dataset ends in early 2025, missing later trends. 	<ul style="list-style-type: none"> - Longitudinal Cohesion Tracking: Apply Cohesion Index to 2025–2030 data to test convergence stability.
Policy-Research Linkages	<ul style="list-style-type: none"> - Policy-keyword alignment relies on retrospective correlation. 	<ul style="list-style-type: none"> - Dynamic Policy Analysis: Use NLP to track real-time policy language (e.g., UN reports) and keyword emergence.
Technical-Social Divides	<ul style="list-style-type: none"> - Weak co-occurrence between technical (e.g., “remote sensing”) and social terms. 	<ul style="list-style-type: none"> - Participatory-Technical Studies: Combine geospatial tools with community-driven data to bridge gaps.

Source: Author

The development of ES–LP research indicates a clear progression toward transdisciplinary harmonization. The quick uptake of hybrid concepts – urban resilience, nature-based solutions – shows that vocabulary is converging faster than practice, and this is driven by global policy agendas. To bridge long-standing divides—between, for example, geospatial

methods and environmental justice—the field will need further terminological harmonization, closer policy-research synchronization and expanded mixed method approaches. In general, ES–LP research offers a replicable approach to integration science across other complex socio-ecological systems.

Discussion

Theoretical Framework and Conceptual Approach

The analysis of collected data shows increasing conceptual convergence across ecological, planning, and governance perspectives, while some divergence remains in participatory governance and economic valuation. To fill these gaps, the present study supplements existing reviews by analyzing 50 reference ES–LP publications identified for citation importance and thematic influence to provide a conceptual foundation with which to interpret bibliometric trends. From this basis, the research takes a Science-of-Science approach and uses the Triple Helix as a theoretical platform (Etzkowitz & Leydesdorff, 2000) to consider knowledge co-evolution in academia, policy, and practice contexts. In this regard, the use of keywords as markers of disciplinary stretch enables co-occurrence and temporal trends to stand as proxies for cross-disciplinary convergence. It is on this theoretical basis that the analytical framework is developed in this section.

International Collaboration Patterns

The results of international collaboration analysis patterns align with global scientific trends where high-income countries and rapidly expanding research economies dominate environmental stewardship, probably due to stronger funding environments and extensive institutional networks (Nature Index, 2023; Wagner et al., 2017). Moreover, the strong intra-European collaboration reflects the influence of EU-funded research initiatives, particularly those supported through Horizon 2020 and related programmes (European Commission, 2020).

Keyword Co-occurrence and Intellectual Integration

The network pattern studied through keyword co-occurrence analysis reflects an evolution towards integrative ecological–planning–governance platforms, rather than isolated disciplinary domains. However, the co-citation analyses demonstrate that ES–LP research has transformed from an ecological and economic platform to a more holistic, policy-driven, and transdisciplinary knowledge system. The convergence of biophysical, geographical, and socio-political themes indicates the maturing discipline and its relevance for sustainable planning (Pataki et al., 2011; Andersson et al., 2015; Kabisch et al., 2015; Abhijith et al., 2017; Seddon et al., 2020).

Cross-Domain Conceptual Mapping

The mapping summarized in Table 2 makes the cross-domain character strikingly visible. The configuration of green infrastructure captures the concept's dual identity as both a spatial planning strategy and a biophysical system requiring ecological understanding and engineering implementation. Nature-based solutions reflect its role as a boundary object linking climate adaptation strategies to planning practice and institutional arrangements (Opdam, 2018). Ecosystem services confirms that the concept achieved its influence precisely by providing a common language across scientific, economic, and policy communities (Artmann et al., 2017). Urban planning acknowledges that planning scholarship engages with governance institutions and regulatory frameworks. Urban resilience reflects the concept's emergence as a response to climate uncertainty and its reliance on institutional capacity. Biodiversity conservation recognizes that conservation science operates in constant dialogue with policy mechanisms. Governance connects institutional analysis to environmental outcomes and urban contexts. Environmental justice demonstrates that questions of equity in landscape planning have become a nexus linking social theory, normative philosophy, and health outcomes.

Intellectual Structure: Cluster Analysis

Table 3 reveals a clearly differentiated intellectual structure. Various clusters showed that Land Use, Ecology & Management (Andersson et al., 2015) functions as the intellectual core binding together ecological science, spatial planning, and land-use decision-making. Cluster 0 (Urban Sustainability & Planning), while Climate Change & Resilience (Baker-Médard et al., 2024) serve as bridges between distinct knowledge domains. Moreover, the ES Core Concepts serves a foundational role as a conceptual anchor providing shared vocabulary and focus on Measurement & Evaluation Tools functions as a methodological infrastructure; its lower connectivity reflects that technical methods are tools deployed within studies rather than concepts that inherently bridge diverse research communities. Lastly, Policy, Equity & Public Engagement (Brink & Wamsler, 2018) stands apart as an emerging social dimension that remains less integrated—representing both a gap and an opportunity for future development.

Temporal Convergence and Policy Lag

In addition to above, the temporal convergence analysis results clearly showed that the steep post-2018 slope indicates accelerating interdisciplinary integration. However, the 1–2-year lag from policy enactment to academic uptake suggests that researchers are largely on the back foot, responding to rather than anticipating policy needs. The journey of interdisciplinary maturation suggests a gradual move towards ES–LP interdisciplinary convergence, manifested in increased co-word linkages, connection strengths, and stronger co-citations (Li et al., 2022). The evolution of concepts in ES–LP indicates that in the early stages the focus was on ecological and valuation themes, followed by planning and governance and subsequently introduction of hybrid concepts (nature-based solutions, citizen science, environmental justice) that emphasize further social, climatic, and spatial integration (Gullino, 2018). These changes are influenced by policy milestones; however, the 1–2-year lag suggests researchers are largely on the back foot.

Conclusion

Based on the bibliometric, keyword-discipline, cohesion, and temporal convergence analyses, this study reveals that ecosystem services (ES) and landscape planning (LP) research has evolved from loosely connected disciplinary inquiries into an increasingly coherent and transdisciplinary knowledge system over the past two decades. This transformation occurred through distinct phases: an early phase (2006–2015) rooted in ecological and environmental science, operating within a siloed integration level; a transition phase (2016–2019) marked by the growing prominence of planning and governance perspectives, catalyzed by policy milestones such as the EU Green Infrastructure Strategy and the Sustainable Development Goals; and a post-2020 phase characterized by a hybrid, converged knowledge system dominated by boundary-spanning concepts like nature-based solutions, urban resilience, and citizen science. The quantitative evidence strongly supports this maturation: a Cohesion Index of 0.944 indicates that cross-cluster connections substantially outweigh within-cluster density; a significant change-point around 2018 accelerated the intermingling of ecological, planning, and climate-policy terms; and policy-keyword alignment shows consistent responsiveness to global governance frameworks with a one-to-two-year lag. Furthermore, keyword-discipline mapping reveals that concepts such as green infrastructure, nature-based solutions, and ecosystem services function as boundary objects, encoding interdisciplinary relationships and enabling researchers from different backgrounds to communicate with increasing fluency. Cluster analysis identifies land use, ecology, and management as the central interdisciplinary hub, while ES core concepts serve as a conceptual anchor, and policy, equity, and public engagement exhibit the

Persistent Gaps and Obstacles to Integration

Despite strong integration, disciplinary gaps persist (Collier et al., 2013). Divergent interpretations of terms such as sustainability and resilience undermine conceptual synchronization. Poor data interoperability and institutional constraints—fragmented funding, weak academia-policy links (Hessburg et al., 2013), delays in policy uptake—exacerbate these obstacles. Table 5 presents proposed solutions including terminology harmonisation, common data infrastructures, and inter-/trans-disciplinary research mechanisms (Dorst et al., 2019).

Limitations of the Study

Although multiple disciplines are getting integrated, several limitations remain (Albert et al., 2014). For instance, the dependency on Web of Science is biased against non-English and Global South scholarship; manual keyword tagging introduces subjectivity, although at a high level of agreement between raters ($\kappa = 0.87$); the dataset extends only partially to 2025, limiting its ability to capture recent developments.

lowest connectivity—representing both a critical gap and a significant opportunity.

The persistence of disciplinary divides despite strong overall integration warrants careful attention. Terminological ambiguities persist, with concepts such as sustainability and resilience carrying divergent meanings across ecological and planning communities, undermining conceptual synchronization. Data interoperability remains poor, as ecological studies prioritize biophysical measurements while planning research focuses on socioeconomic and governance indicators, creating methodological fragmentation. Institutional constraints—including fragmented funding structures, weak academia-policy linkages, and delayed policy uptake—further exacerbate these barriers. The peripheral status of equity and participatory terms in keyword networks is particularly concerning given the normative commitments of sustainability science to inclusive and just outcomes. This finding suggests that while the field has achieved remarkable integration across biophysical, spatial, and climate domains, the full incorporation of social, participatory, and environmental justice dimensions remains an unfinished project—one that will require deliberate effort to address the institutional, methodological, and terminological barriers that have thus far limited their integration.

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