

Article

Recent Trends in Landscape Sustainability Research—A Bibliometric Assessment

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Abstract: Landscape sustainability (LS) has received widespread attention from both scientists and practitioners in recent decades. However, a systematic review of the recent trends in this field remains scarce. Here, we present a bibliometric analysis of 715 English papers published in SCI journals (i.e., indexed by Web of Science) during 2006–2023, whose titles, abstracts, or keywords contain both landscape-related terms and sustainability-related terms. Specifically, we quantitatively analyzed the LS literature using a variety of bibliometric methods and qualitatively analyzed the full text of highly cited seminal literature to cross-validate the bibliometric findings. We found that: (1) LS has entered the exponential growth phase (2013–present) after experiencing the incubation phase (pre–2006) and emerging phase (2006–2013). (2) Early LS themes focused on landscape change and the relationship between landscape ecology and sustainability science, while recent LS themes have shifted towards more sectoral topics, such as the relationship between ecosystem services and human well-being, climate change, and urbanization. (3) The closely connected network of cross-citations in seminal literature indicates strong communication among scientists in the field of LS. However, the participatory and solution-oriented research streams of LS have not been well integrated into the core research network of LS. Our results suggest that LS has evolved into a rapidly growing discipline with a stable scientific community and core research themes. To become a well-established discipline, LS needs to further enhance its unique scientific core rather than only drawing knowledge from other related fields. Constructing social–ecological-centered, solution-oriented landscape pattern analysis theory and methods for LS should be a top priority.

Keywords: landscape sustainability; ecosystem services; nature-based solutions; green space



Citation: Fang, X.; Kong, L. Recent Trends in Landscape Sustainability Research—A Bibliometric Assessment. *Land* **2024**, *13*, 811. <https://doi.org/10.3390/land13060811>

Academic Editor: Augusto Pérez-Alberti

Received: 3 May 2024

Revised: 24 May 2024

Accepted: 4 June 2024

Published: 6 June 2024



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1. Introduction

The achievement of global sustainable development goals requires a concerted effort across disciplines and practices [1]. Landscapes, as land mosaics composed of different types of ecosystems [2], are important platforms for the study and practice of sustainability. Human interaction with the environment is at its closest in the landscape, where our lives, work, and leisure take place in specific landscape settings and where human activities continually reshape the surrounding landscape [3]. Landscapes also serve as pivotal scales that connect the global to the local, facilitating cross-scales in the study and practice of sustainability [4]. As landscape scientists advocate, it is challenging to attain global sustainability until most landscapes worldwide become sustainable.

Landscape sustainability (LS) or sustainable landscapes (SL) as a buzzword has existed for a long time [5,6], but its scientific conceptualization and theoretical foundations have only begun to take shape in the last 20 years [4,7]. Landscape scientists began actively exploring the relationship between landscape science and sustainable science at the beginning of the 21st century in response to global aspirations to achieve sustainable

development [8–14]. Since then, a series of conceptual and theoretical contributions to operationalize the LS concepts have emerged, including the Design in Science paradigm [15], landscape services concepts [16], spatial resilience concepts [17], and landscape sustainability science [4]. In the last decade, LS research has shown rapid growth, driven by a variety of professional conferences and special issues of journals [18]. Researchers have begun to explore the critical role of LS in achieving government policy goals, such as China's ecological civilization [19]. LS principles have also begun to be widely applied in various landscape types, including grassland landscapes [20,21], agricultural landscapes [22], and urban landscapes [23,24].

In a rapidly evolving field, a timely review of existing research progress is needed to identify current challenges and future priorities. Existing reviews in LS are mainly focused on a specific landscape type (e.g., grassland landscapes [25] and urban landscapes [23]) or on a specific aspect of the LS field, such as distinguishing similar concepts [18], summarizing theoretical foundations [26], and exploring the relationships between landscape pattern and ecosystem service [27]. However, systematic reviews of the whole picture in this field remain scarce. Recently, Wu [7] reviewed the current state of LS research using qualitative and subjective approaches and proposed eight core questions and ten key approaches to guide future LS research directions. In line with this effort, this study aimed to conduct a quantitative bibliometric review of the full landscape of LS to help researchers better understand the status and trends in this field.

A bibliometric review is a commonly used method to understand the state of research on a specific topic or field. It usually uses quantitative methods to systematically analyze and evaluate patterns in the literature, such as the number of publications, citations, co-authorship networks, and keywords, among others [25]. Several studies have shown that supplementing bibliometric reviews with qualitative analyses of key literature can help overcome the drawbacks of bibliometric analysis [18,28,29]. Thus, this study will combine quantitative bibliometric analysis with qualitative analysis of highly cited literature to review the field of LS. We will answer the following three questions: (1) At what stage of development is the field of LS currently at? (2) What are the main themes emerging from LS research? How have these themes evolved? (3) What are the major challenges and future research directions for LS research?

2. Materials and Methods

2.1. Literature Search

We conducted a literature search in the Web of Science Core Collection database on 17 August 2023. While this dataset may not be as comprehensive as Google Scholar and Scopus, most of its publications have undergone a rigorous peer-review process, and it is one of the most widely recognized databases in academia used for bibliometric analysis. While there are many fields closely related to landscape sustainability, such as landscape multifunctionality and landscape resilience, this study only focuses on research that employs both landscape-related and sustainability-related terms. Based on Zhou, Wu and Anderies [18], we selected “landscape sustainability” OR “sustainable landscape” OR “sustainable landscapes” as search terms. Literature in the English language from all timeframes in which search terms appear in the title, abstract, or keywords are included. Our literature search retrieved a total of 715 records, and all the bibliometric information for these 715 documents was derived for further analysis.

2.2. Trend Analysis

We indicate the development of the research field based on temporal changes in publications and citations. Fang, Li, and Ma [28] and Fang et al. [30] found that the Mann–Kendall (MK) and Pettitt's tests are highly effective for detecting trends and change points. Therefore, this study employs these two methods to identify the development trends and change points in the field. In addition, we identified the top 10 countries, institutions, journals, and authors contributing to the field based on the number of publications and

local citations. Local citations refer to the number of times a piece of literature is cited by all the sampled pieces, and higher local citations usually indicate greater influence in the field. The Mann–Kendall [31] and Pettitt’s tests [32] were conducted using the trend package in R [33]. All the bar graphs were created using the ggplot2 package in R.

2.3. Theme Mining

Theme mining, as a data analysis method, aims to automatically identify and extract themes or topics from textual data collections, including documents, articles, or any text-based content. The objective of theme mining is to uncover significant patterns and topics within the text, eliminating the requirement for human preconceptions or manual coding [25,34]. In this study, we combined several methods for theme mining. First, we used word clouds to visualize the keywords in LS research, and then we used keyword co-occurrence clustering analysis to identify the theme structure of the LS domain. Finally, trend topic analysis was used to identify the temporal evolution of keywords under different themes. Wordcloud and trend topic analysis were conducted using the Bibliometrix package in R [35], and the keyword co-occurrence analysis was generated in VOSviewer software (version 1.6.20) [36].

2.4. Citation and Collaboration Network Analysis

Citation networks can reveal the relationships among influential works in LS based on their citations [28]. In order to identify the development paths of LS research, we performed citation network analysis using the HistCiteTM software (Pro 2.1) [37]. HistCiteTM is a commonly used citation network analysis tool that has the advantage of not only identifying seminal work in the searched literature but also identifying seminal literature that does not exist in the searched literature based on the cited literature [38]. In this study, we included seminal literature that was not in the sampled literature but was highly cited by the sampled literature. In addition, we qualitatively read the full text of the top 20 most locally cited pieces of literature to dig deeper into the development of the LS research field.

Collaborative network analysis is a methodology used to study and visualize relationships, interactions, and collaborations between individuals, institutions, or countries in a given context [28,39]. In this study, we use co-author collaborative network analysis to understand the structure of the LS academic community and how researchers, faculties, and countries in the LS field relate to each other. The co-author’s collaborative network analysis was conducted using VOSviewer software (<https://vosviewer.affinitycn.cn/> (accessed on 25 August 2023)).

3. Results

3.1. The Trends and Probable Change Points of Landscape Sustainability

The number of publications and citations in the field of LS showed a significant growth trend (Figure 1). The number of publications increased from 13 per year in 2006 to 91 per year in 2022, and the number of citations increased from 13 per year in 2006 to 3081 per year in 2022. The growth trend in the number of publications and citations has significantly strengthened during the last decade. The results of the change point detection indicate that the possible change point for the number of publications is in about 2012, and the potential change point for citations is in about 2013.

Figures 2 and 3 show the Journals, Countries, Institutions, and Authors that have contributed significantly to the field of LS in terms of the number of publications and local citations. The Journals that have contributed most to the development of LS are Landscape Ecology and Landscape and Urban Planning, both of which rank in the top three in terms of number of publications and local citations. Notably, Sustainability and Land ranked second and fourth in terms of the number of publications, but neither ranked in the top ten in terms of local citations. The United States and China are major contributors to the development of LS, with both countries well ahead of others in terms of the number of publications and local citations. The top three institutions with the highest number of publications are

Beijing Normal University, Arizona State University, and the Chinese Academy of Sciences, while the top three institutions with the highest number of local citations are Arizona State University, Beijing Normal University, and Inner Mongolia University. The top three Authors with the highest number of publications are Wu JG, Liu ZF, and He CY, while the top three authors with the highest number of local citations are Wu JG, Opdam P, and Musacchio LR.

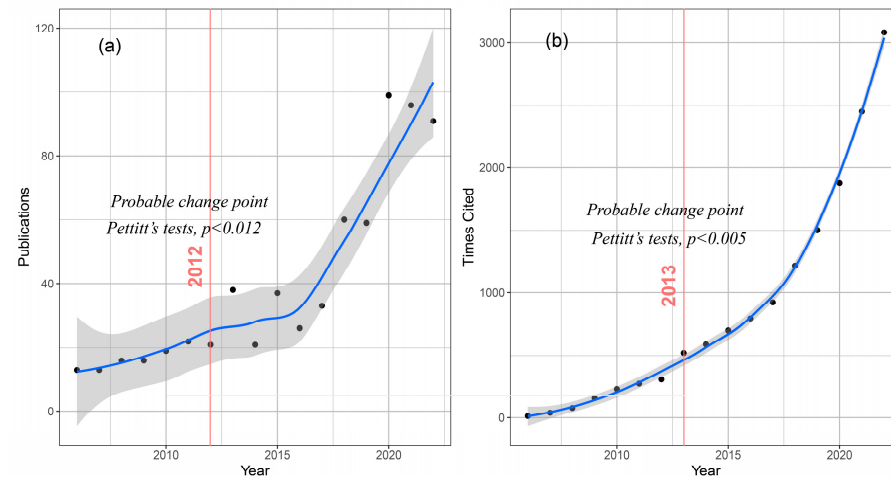


Figure 1. The development trends of landscape sustainability are indicated by (a) the number of publications and (b) the citations. Probable change points were identified by Pettitt's test.

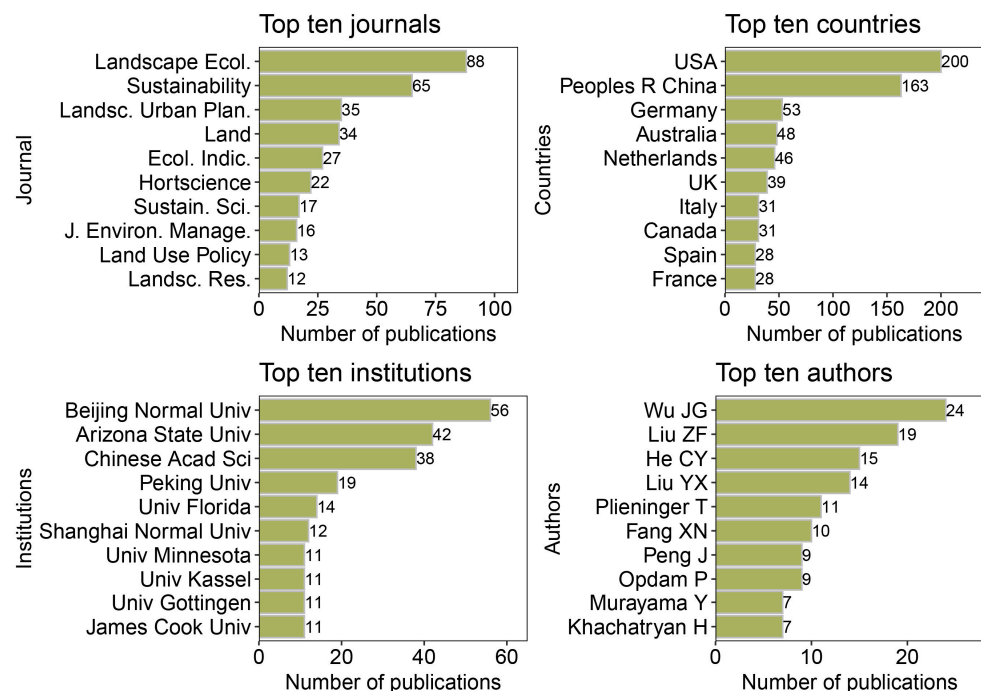


Figure 2. Top ten Journals, Countries, Institutions, and Authors with the largest number of publications in landscape sustainability.

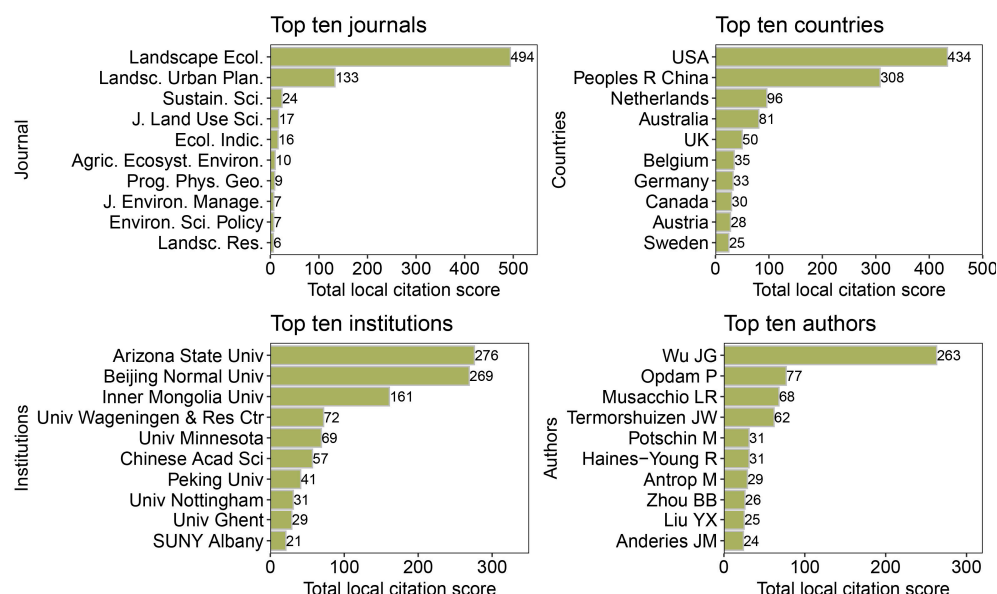


Figure 3. Top ten Journals, Countries, Institutions, and Authors with the largest local citations in landscape sustainability.

3.2. The Multi-Fact Themes of Landscape Sustainability

Word clouds visualized keywords in LS research (Figure 4). The top ten keywords with the highest frequency include landscape sustainability (89), ecosystem services (88), sustainability (58), sustainable landscapes (42), landscape management (38), landscape planning (29), biodiversity (25), sustainable development (23), urbanization (21), and climate change (20). The keywords landscape sustainability, sustainability, sustainable landscapes, and sustainable development, which are closely related to sustainability, are the ultimate goals of LS research. Biodiversity and the ecosystem service it provides are the core research objects of LS. Urbanization, climate change, and land use change are the main drivers of landscape change. Landscape management and landscape planning are important policy tools for achieving LS.



Figure 4. Word clouds are generated based on author keywords.

Eight theme clusters can be identified in LS research (Figure 5). Nodes with the same color belong to the same theme, although they may not always be close in position. In addition, the naming of each theme is somewhat subjective. However, we primarily base the theme names on the most frequently occurring keywords in each theme. Cluster 1:

Landscape change and driving forces. The keywords include landscape change, driving forces, scenarios, GIS, landscape conservation, protected area, etc. Cluster 2: The relationship between landscape ecology and sustainability science. The keywords include sustainability, sustainable development, sustainability science, social–ecological systems, etc. Cluster 3: Biodiversity conservation. The keywords include biodiversity, landscape pattern, landscape approach, sustainable development goals, remote sensing, etc. Cluster 4: Urban and dryland landscape sustainability case study. The keywords include landscape sustainability, urbanization, ecosystem service, dryland, urban expansion, urban planning, etc. Cluster 5: Land use and cover change (LUCC). The keywords include LUCC, Land metrics, etc. Cluster 6: Landscape management. The keywords include sustainable landscape management, landscape cultural landscapes, indicators, tradeoffs, etc. Cluster 7: Climate change. The keywords include sustainable landscapes, climate change, landscape design, resilience, etc. Cluster 8: Ecosystem services and human well-being. The keywords include ecosystem services, landscape sustainability science, landscape management, landscape services, and human well-being.

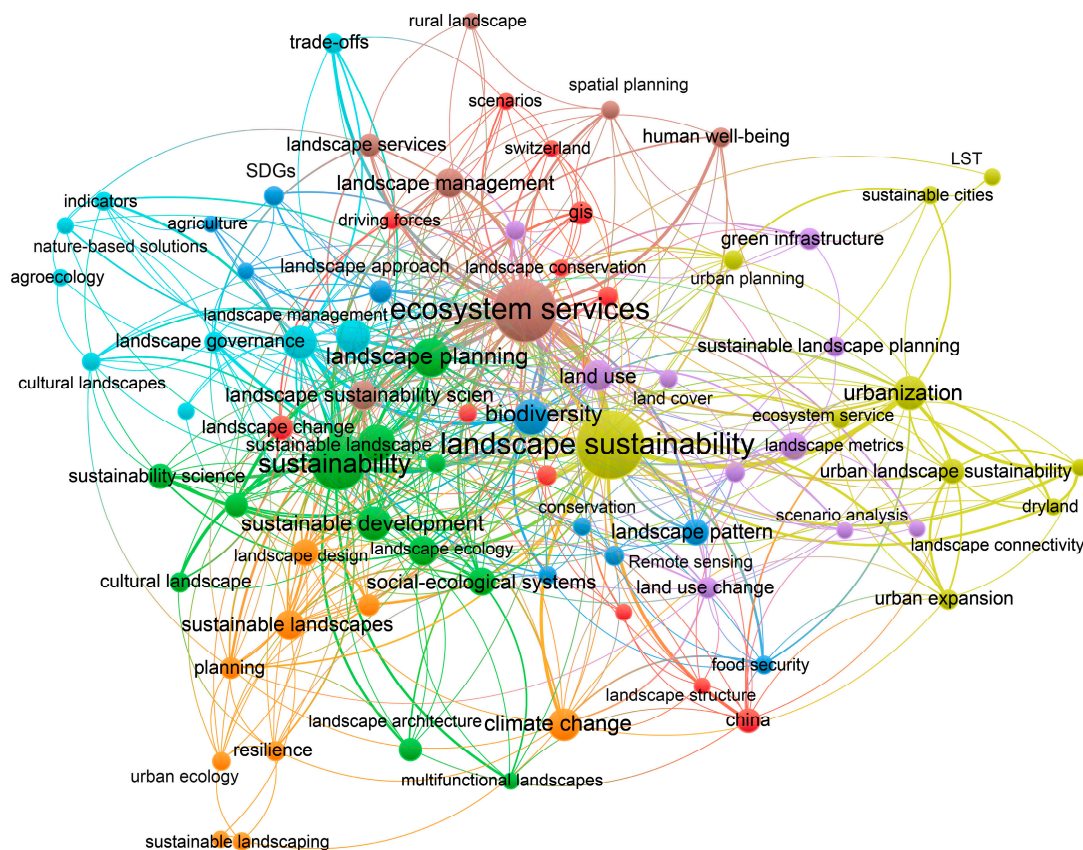


Figure 5. Clustering of landscape sustainability themes based on the co-occurrence of keywords.

Landscape sustainability's research focus has evolved over time (Figure 6). In the early stages of LS development, the dominant keyword for related research was landscape change, a traditional topic in landscape ecology. Later, many studies began to explore the relationship between landscape ecology and sustainable development, and many long-lasting keywords emerged, such as sustainable development, sustainability science, sustainable development, and landscape ecology. During the same stage, researchers were interested in applying landscape metrics and GIS to LS research. More recently, more sectoral and case-specific keywords are beginning to appear, such as climate change, landscape management, ecosystem services, landscape pattern, landscape design, urbanization, etc. The evolving keywords of LS suggest a gradual transition of research themes from the traditional focus

on landscape ecology to the relationship between landscape ecology and sustainability science and its application in addressing sustainability issues in different landscapes.

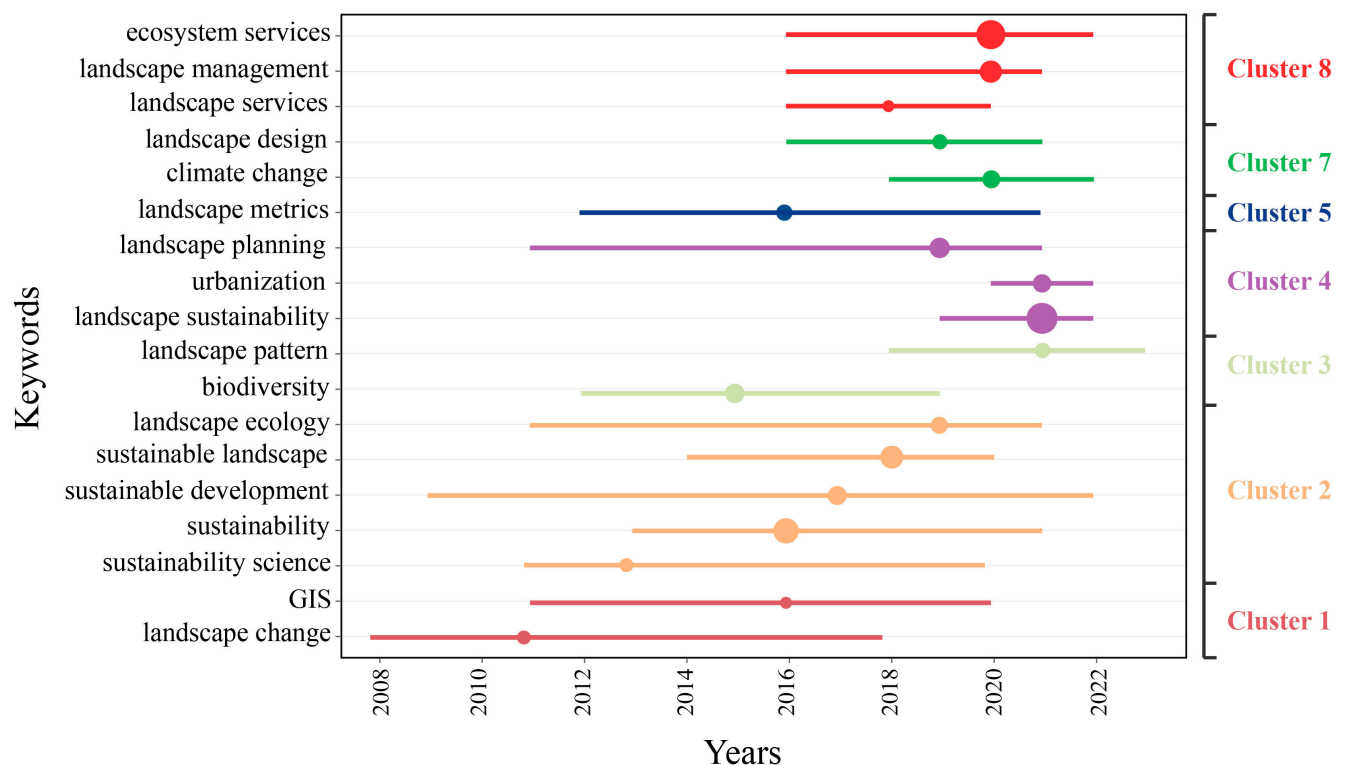


Figure 6. Temporal evolution of LS research keywords, with different colors representing the different theme clusters to which the keywords belong.

3.3. The Development Path and Collaborative Networks

The very tight mutual citation relationships among the researchers in the development path network indicate that there is a substantial amount of communication and dialogue among the core researchers in this field. It also suggests that a research community in LS has already formed (Figure 7). Delving into these highly cited studies in the development path network can help us understand how the field has evolved. Initially, there were two seed articles that were not mutually cited: Wu and Hobbs [14] first listed LS as one of the ten major topics in landscape ecology, and Leitao and Ahern [40] explored the necessity of combining knowledge from landscape ecology with sustainable development from a landscape planning perspective. This suggests that the emergence of the field of LS was driven by both landscape ecology and landscape planning. Around 2006, a series of studies began to explore the possibility of combining landscape ecology and sustainable science to promote sustainable landscape planning [8–12]. Subsequently, a range of theories and methods related to LS emerged. For instance, Nassauer and Opdam [15] extended the traditional landscape ecology pattern–process framework to pattern–process design to enhance LS. Termorshuizen and Opdam [16] introduced the concept of landscape services to integrate landscape ecology and sustainable development. Musacchio [41] further elaborated on the scientific foundations of sustainable landscape design and the primary challenges to operationalizing LS [42].

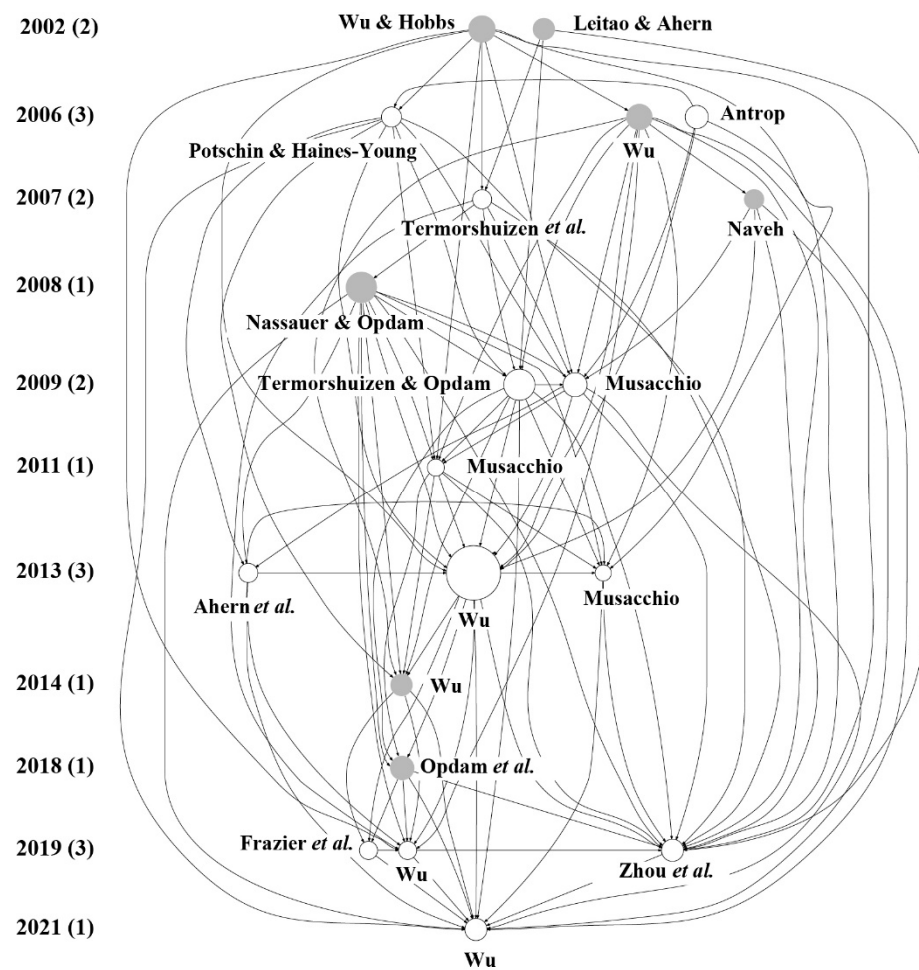


Figure 7. The development paths for landscape sustainability. Arrows indicate cross-citation relationships. Node size is proportional to the local citation score. White nodes indicate that the node literature was from the sampled dataset, and gray nodes indicate that the node literature was manually added based on its local citation score.

Around 2013, the potential change point in the development of LS, Musacchio [43] introduced the main concepts and research priorities in LS. In the same line of efforts, Wu [4] formally defined LS and proposed the Landscape Sustainability Science (LSS) research framework with landscape patterns at its core. Since then, there has been an increased focus on applying LS to urban landscapes [23,44] and its integration with government policies [19]. Researchers suggest that LS has evolved into a vibrant research field [18] that can make significant contributions to sustainability science in terms of spatially explicit approaches, multiple-scale approaches, stakeholder engagement, transdisciplinary collaboration, etc. [45]. Wu [7] further outlined eight key scientific questions and ten core research approaches for LSS, which has promoted the confluence of LS research.

The collaboration network analysis of co-authors in LS research reveals two main sub-networks of the research community (Figure 8a): (1) A research network predominantly led by institutions such as Beijing Normal University, the Chinese Academy of Sciences, and Arizona State University. Key node researchers in this sub-network include Jianguo Wu, Zhifeng Liu, Chunyang He, Yanxu Liu, and Jian Peng, among others. (2) A collaboration network primarily composed of researchers from European countries. Notable node researchers in this network include Tobias Plieninger, Joern Fisher, Cristina Quintas-Soriano, and others. Within each of these research sub-networks, there is a strong level of collaboration among the researchers. However, there is relatively weaker communication and collaboration between these two distinct sub-networks.

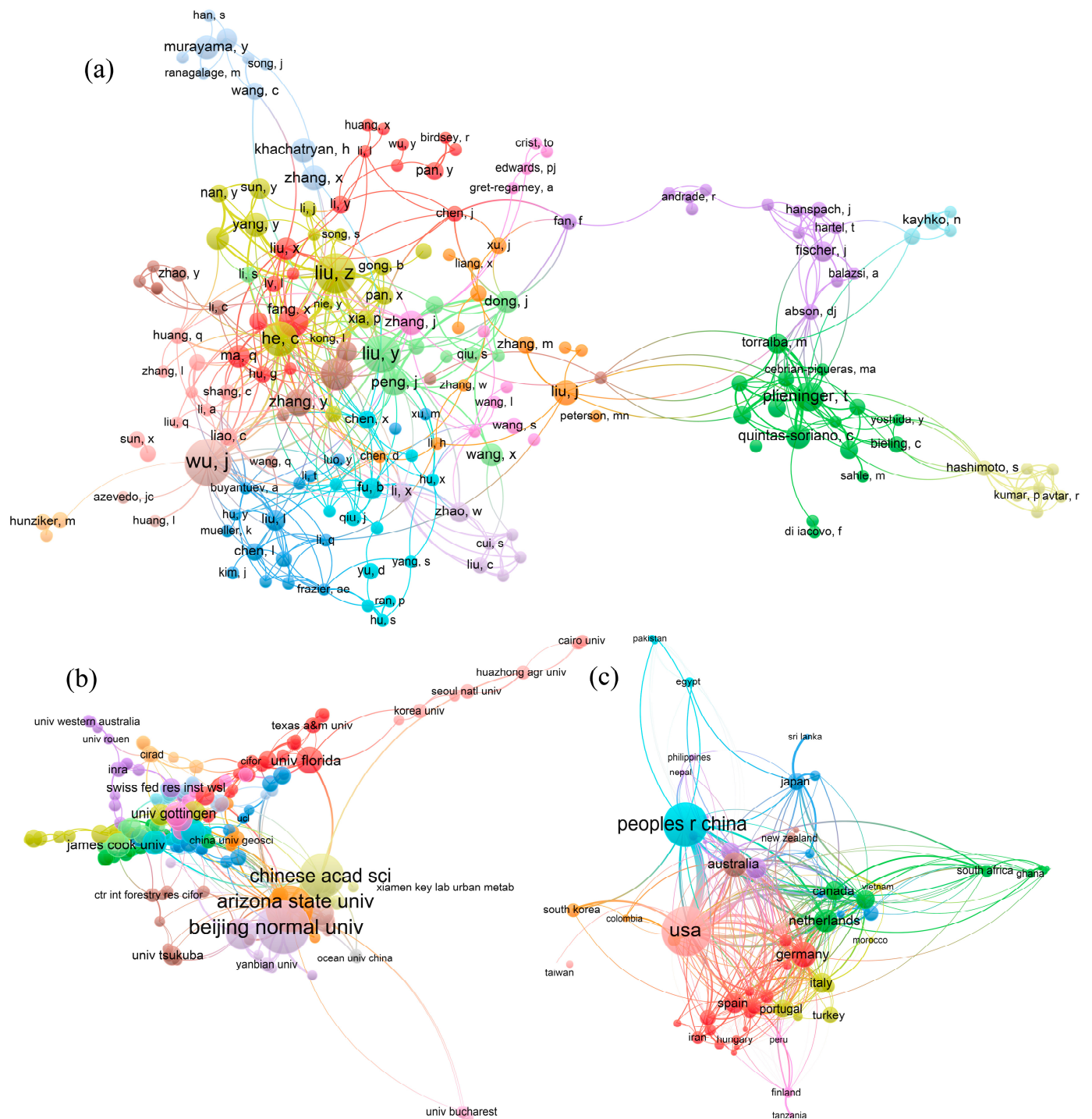


Figure 8. The co-author collaboration network between researchers (a), institutions (b), and countries (c).

4. Discussion

4.1. The Development Stages and Evolving Topics of Landscape Sustainability

Based on the Isserman Curve, the development of a discipline follows a sigmoidal curve described by a logistic function [30,46]. This curve is similar to the innovation-adoption curve; in comparison to late adopters, innovators and early adopters make more significant contributions to knowledge accumulation and the dissemination of innovation in a research field (Figure 9). Once a discipline reaches the later stages of the curve (phases D and E), the development will slow down, and the rate of knowledge accumulation will significantly decrease. However, later stages do not signify the end of innovation

in a discipline. On the contrary, new perspectives from outside the discipline might stimulate innovations during the later stages [47]. With the implementation of new tools, technologies, and ideas, the curve will once again continue its upward trajectory, and phase E will transform into a new beginning, phase A1, for innovation.

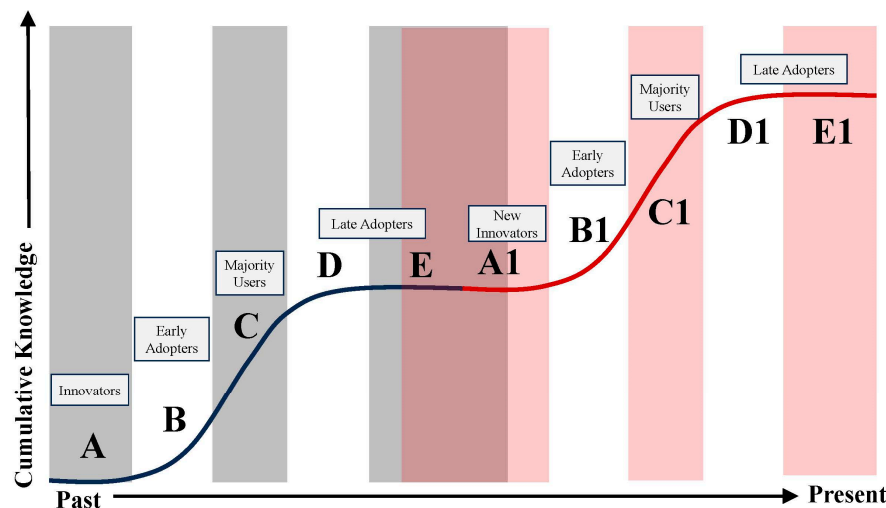


Figure 9. The Isserman curve shows that landscape sustainability is a new innovation rooted in landscape ecology.

Milovanović et al. [48] found that after 2006, landscape ecology started to move towards a stable development stage focused on the study of the symbiosis of ecological and social mechanisms for sustainable landscape planning and development, similar to phase E in Figure 9. We argue that LS research emerged during a period when the diffusion of innovations in landscape ecology was slowing down. It incorporated new ideas of sustainable science into landscape ecology and contributed to the transition from Phase E to Phase A1. Zhou, Wu, and Anderies [18] suggested that 2006 was a potential change point in LS research based on their bibliometric analysis results. Our qualitative literature analysis also found that around 2006, landscape scientists began to widely discuss the relationship between landscape ecology and sustainability science. Therefore, we speculate that 2006 might be the initial phase of the innovations in Landscape Ecology inspired by sustainability science. In addition, our change point detection results suggest that 2013 is another potential change point, after which the growth trend accelerated (Figure 1). This indicates that LS appears to have entered phase B1, the rapid development stage, in 2013.

In summary, we argued that the development of LS can be divided into three stages: (1) Incubation Phase (prior to 2006): Landscape ecologists and planners began to recognize the importance of integrating landscape ecology with sustainable development [8–10,14,40]. (2) Emerging phase (2007–2013): Researchers began to contribute to LS based on their respective backgrounds and gradually reached a consensus on the fundamental concepts and research priorities of LS [4,12,15–17,41]. (3) Rapid Development Phase (2014–Present): LS-related concepts began to move towards addressing real-world sustainability challenges, such as urbanization and climate change. Researchers also began to build the scientific core of LS [7,26,45].

4.2. Research Gaps and Challenges

Our results indicate that, to further advance LS research, at least three challenges need to be addressed. Firstly, there are missing themes from the current LS studies. Wu [7] proposed eight key core questions for LS, and our findings suggest that two of these questions are not covered in the identified themes. (1) Teleconnections and Spatial Externalities in Landscapes: Landscapes are not isolated entities, and they may have intricate connections with nearby or distant landscapes. For instance, urban landscapes might be closely linked

with distant wetland landscapes through water flows, and the disruption of distant wetland landscapes might influence the water security of urban landscapes. (2) The Impact of Socioeconomic Processes and Institutions on Landscape Sustainability: Current LS studies mainly focus on direct drivers of landscape change, such as LUCC or climate change, and often overlook indirect drivers like socioeconomic processes and institutions. This may be due to the dominance of researchers from ecological and geographical backgrounds in LS research, with less involvement from social scientists. However, socioeconomic processes and institutions can have a significant impact on landscape sustainability. For example, access to parks directly determines residents' use of parks, which in turn affects the realization of ecosystem service values. Differences in residents' socioeconomic levels can affect their perception and use of ecosystem services, thereby influencing the ES–HWB relationship.

Secondly, LS research exhibits an uneven geographic distribution. Our results demonstrate that the majority of LS studies are concentrated in a few developed countries, primarily in the United States, China, and some European countries, while there is a limited presence of LS research in global south regions such as Africa and South Asia (Figures 2 and 3). However, landscape sustainability challenges are often more acute in these less economically developed regions due to high land use intensity and the prioritization of economic development over environmental protection [49]. In addition, the lack of LS research cases from developing countries may lead to a lack of generalizability of the theories constructed. Thus, future LS research should include more cases from developing countries.

Thirdly, the “transformational” research streams within current LS research have not been sufficiently integrated into the core LS research community. Our collaborative network analysis reveals that LS researchers can be divided into two sub-collaborative networks. The first network primarily consists of researchers from China and the United States, focusing more on mechanistic analyses of landscape patterns and processes. The second network mainly comprises European scientists whose research leans toward participatory, solution-oriented, and transformative studies. Currently, the second research network has not been fully integrated into the mainstream citation network of LS research (Figure 7). As LS originated from landscape ecology, these differences between the two research branches might be influenced by distinct research traditions in North American and European landscape ecology [10]. Our research results also suggest that there is limited cooperation between these two branches of LS research. However, both analytical and transformative aspects are essential and complementary components of LS [7,30]. Therefore, future LS research needs to strengthen collaboration and communication between these two research streams.

4.3. Future Directions: Pursing Repeated Landscape Patterns for Sustainability

The current LS research is in a phase of rapid development, a crucial period for establishing core theories and methodologies in the field [46]. As an interdisciplinary research field, LS can draw theoretical and methodological knowledge from various related disciplines like sustainable science, landscape ecology, and land system science [26,50]. However, for any discipline to become a well-established field, relying solely on knowledge drawn from other related sciences is insufficient. It must develop its scientific core, which, in the case of LS, means building “the science of LS”. The landscape sustainability science framework, core research questions, and approaches proposed by Wu [4,7] are good starts for building the scientific core of LS. A key assumption of landscape sustainability science is that some landscape patterns are more sustainable than others [7]. Thus, finding these more sustainable landscape patterns and being able to reproduce them in real-world landscapes should be one of the central issues in building a science of landscape sustainability.

However, much of the current Landscape Sustainability (LS) research still relies heavily on traditional views of landscape ecology, particularly regarding landscape pattern analysis theories and methods. For instance, the fundamental theory often follows the patch–corridor–matrix model, the primary methods employed are often the Fragstats landscape pattern indices, and the main data type used is traditional land use classification data.

We believe that these landscape pattern analysis theories and methods rooted in landscape ecology provide an essential foundation for LS-oriented landscape pattern analysis. However, they fall short in some aspects. This is because the two core concepts of LS, Ecosystem Services (ES) and Human Well-Being (HWB), are both human-centered concepts. They not only involve ecological processes but also incorporate many socioeconomic processes, which are less addressed in traditional landscape pattern analysis methods that primarily focus on ecological aspects. For instance, in traditional landscape ecology pattern analysis, impervious surfaces within urban areas are often treated as a single land use category because they have a similar impact on species and other ecological processes. However, in LS research, the internal differences within impervious surfaces are often crucial for understanding the relationship between ES and HWB. For example, whether there are roads, squares, or infrastructure like plastic running tracks within the impervious surfaces around urban parks can significantly affect residents' usage of green spaces, thereby influencing the realization of ES values associated with urban green spaces. Therefore, we propose that LS-oriented landscape pattern analysis should go beyond the traditional ecological focus and develop a more people-centered approach.

Another issue faced in LS-oriented landscape pattern studies is that the concept of sustainable landscape patterns is too broad, making it difficult to concretize and operationalize in research and practice. This problem arises because sustainable landscape patterns involve two core concepts: ecosystem services (ES) and human well-being (HWB), both of which are rather broad in scope. For instance, ES encompasses four types of services—provisioning, regulating, cultural, and supporting—each of which comprises over 50 subcategories [51,52]. Similarly, HWB is an even broader umbrella concept, including dimensions such as basic material for a good life, safety and security, health, good social relations, and freedom of choice and action [52], with many dimensions of HWB having a limited connection to ES and primarily determined by other forms of capital such as social capital. We argue that a general and holistic landscape pattern involving most types of ES and HWB can serve as metaphors related to landscape sustainability, which represents the idealized goals to be achieved. However, while this holistic, sustainable landscape pattern is crucial, its complexity makes it challenging to study deeply and integrate into practice.

Enhancing specific ES types and associated specific HWB dimensions through the design of landscape patterns constitutes specific sustainable landscape patterns. The specific sustainable landscape patterns emphasize problem-driven and solution-oriented characteristics within LS, rendering their research content more operational and easily combinable with practice. Studies on specific sustainable landscape patterns often focus on addressing specific landscape sustainability challenges through coordinating ES–HWB relationships. In such cases, specific sustainable landscape patterns can be categorized into various types, such as those capable of mitigating the urban heat island effect, preventing flood risk, enhancing residents' physical health, and maintaining food security. These specific sustainable landscape patterns can serve as building blocks applied in landscape planning and design practices across various scales.

5. Conclusions

This study combined quantitative bibliometric analysis and qualitative, highly cited literature analysis to explore the development, research themes, challenges, and progress of Landscape Sustainability (LS). The results of change point detection and development path analysis indicate that LS, as a new innovation in the field of Landscape Ecology (LE), is now in an exponential growth phase after its incubation and formation periods. We identified eight major themes for LS research, showing a gradual shift from traditional LE research themes and exploration of the relationship between LE and sustainability science towards a problem-driven, solution-oriented direction. The tightly connected network of cross-citations between seminal literature suggests that the main scientific community for LS seems to have formed. However, the “transformational” research streams of LS are not yet well integrated into the core research network of LS. To become a well-established discipline,

LS needs to further enhance its distinctive scientific core and not just draw knowledge from other related fields. The construction of social–ecological-centered, solution-oriented theories and methods for analyzing LS-oriented landscape patterns should be a top priority.

Author Contributions: Conceptualization, X.F. and L.K.; methodology, X.F.; software, X.F.; validation, X.F. and L.K.; formal analysis, X.F.; investigation, X.F.; data curation, X.F.; writing—original draft preparation, X.F.; writing—review and editing, X.F. and L.K.; visualization, X.F.; supervision, X.F. and L.K.; funding acquisition, X.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Natural Science Foundation of China (No. 42201101).

Data Availability Statement: Data available on request from the authors.

Acknowledgments: We thank Jianguo Wu, Qun Ma, Zhifeng Liu, Lumeng Liu, Xin Wang, Xingyue Tu, and Chenwei Shang for their comments on an earlier version of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

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