REVIEW

Emerging trends in GIS application on cultural heritage conservation: a review

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Abstract

Geographic Information Systems (GIS)-based technologies are increasingly crucial in the domain of cultural heritage conservation, facilitating the construction of dynamic information management systems and serving as robust platforms for research and display. This review utilizes CiteSpace and Bibliometrix R language to perform a bibliometric analysis of academic literature sourced from the Web of Science (WoS) Core Collection, focusing on the application of GIS in cultural heritage conservation. The analysis covers a broad spectrum of academic articles, identifying research hotspots, patterns of national cooperation, interdisciplinary mobility, knowledge structure, and developmental trends. The findings reveal that this research area is experiencing a phase of steady growth. While three emerging trends have been identified, demonstrating significant theoretical and technical advancements, there remains considerable potential for enhancing in their practical implication within conservation efforts. The study advocates for the integration of digital technologies into the humanities, emphasizing the need for a heritage database equipped with standardized data exchange protocols to support display and analytical functions. This systematic research approach not only illuminates new strategies for the inheritance and innovation in the conservation of cultural heritage, but also paves the way for future explorations in this increasingly vital field.

Keywords CiteSpace, Bibliometrix R, Co-citation analysis, GIS, Cultural heritage conservation, Bibliometric

Introduction

Cultural heritage preserves spontaneous history and collective memories, shaping societal understanding and appreciation of historical narratives. Its preservation allows successive generations to comprehend and value historical significance, which holds profound implications for national cultural dissemination [1]. Despite serving as a medium for the interpretation, dissemination, iterative accumulation, and active inheritance of historical memory, cultural heritage is also susceptible to degradation and destruction [2, 3]. Recognizing cultural heritage as a non-renewable resource with intrinsic potential for future exploration [4] has recently elevated the role of geographic information systems (GIS) in cultural heritage management [5]. The pioneering GIS, developed by Canadian surveyor R. Tomlinson in 1963, marked the beginning of GIS as an important tool in cultural heritage fields. Its application has transformed traditional operating mechanisms by equipping stakeholders with an information management platform for storage, analysis, management and dissemination of data, alongside facilitating spatial analysis, risk prediction, evaluation monitoring, and data information integration calculation [6–9]. This has broadened participation in conservation efforts beyond professional circles [10]. Coupled with advancements in modern technologies like remote sensing, Artificial Intelligence (AI), Virtual Reality (VR), 3D modeling, Building Information Modelling (BIM), laser scanning, and web map services, GIS has

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Liu *et al. Heritage Science*   (2024) 12:139

Page 2 of 14

become integral to advanced and digital conservation practices [11, 12].

Existing academic literature and research increasingly recognize the role of information technologies in cultural heritage. While some scholars have elucidated the combined application of 3D LiDAR and other technologies such as GIS, Historic Building Information Modeling (HBIM), 3Ds Max in heritage conservation, these studies have clearly delineated research hotspots and specific challenges [13]. For instance, discussions on the use of advanced technologies like GIS, VR and Web-GIS platform in geological heritage conservation suggest these methods might soon lead the research in geological visualization and valorization [14]. Yao et al. illustrated both the benefits and limitations of using GIS and RS in archaeological and cultural heritage contexts, anticipating the creation of an integrated cloud management platform for heritage conservation [15]. Similarly, Yang et al. reviewed the use of the Historic/Heritage Building Information Model (HBIM) alongside other information technologies for parametric modeling and spatial information analysis within GIS frameworks, providing the basis for further conservation efforts [16]. However, these reviews lacked dedicated bibliometric analysis focused on the specific application of GIS technology in heritage conservation research. In 2024, Huang conducted a bibliometric and visualization analyses on the application of GIS in heritage research, although this work did not delve deep into or interpret the relevant literature and the emerging trends in GIS for heritage conservation [5]. Therefore, systematically organizing these research outputs is crucial for comprehensively understanding the developmental trajectory and cutting-edge dynamics of this field. In this review, we employ CiteSpace and Bibliometrix R to objectively describe the research structure and dynamics of GIS in cultural heritage conservation. Our study distinguishes itself in three ways: First, it encompasses all relevant articles published between 1999 and 2022, aiming to completely reveal the latest trends and transformations in this domain. Second, our dataset is exhaustive, examining GIS applications across all types of "tangible" cultural heritage, thus providing a more holistic view. Third, this paper identifies hotspots and emerging trends through objective data analysis using CiteSpace and thorough literature evaluation, minimizing subjective interpretations by domain experts based on existing results or personal experience. This approach permits replication across various disciplines, enhancing the reliability and accuracy of the findings.

This paper undertakes a dynamic analysis of research literature on the application of GIS in cultural heritage and its conservation over the past 20 years using CiteSpace and Bibliometrix R. This analysis furnishes a valuable overview of the historical context and delineates the structure of the field, its dynamic evolution, and emerging trends, thereby informing and inspiring future research and practical applications in this area.

Method and data analysis
Research methods
This study sources its literature from the WoS Core Collection, utilizing a comprehensive search strategy. The search query employed was as follows: TS = ("cultural heritage" OR "heritage") AND TS = ("protection" OR "conservation" OR "preservation") AND TS = ("GIS" OR "geographic information system"). The analysis spans the period from 1999 to 2022 and includes only "Article" and "Review Article" document types, with all documents in "English". As of December 31, 2022, this approach yielded a total of 411 documents. Data analysis was conducted using the Bibliometrix R package and CiteSpace, enhancing the accuracy of the research by incorporating three terms associated with "conservation".

Basic information
Statistical analysis of the number of articles
Figure 1 presents an overview of the development trends in GIS research applied to cultural heritage conservation since 1999. The volume of research exhibits a growth pattern across three stages: an initial slow development phase (1999–2015), followed by a rapid increase (2015–2018), a brief decline (2018–2019), and a subsequent period of vigorous growth (2019–2022). Publications significantly increased after 2015, peaking at 78 publications in 2022. The average annual growth rate of publications from 1999 to 2022 was 20.86%, indicating a robust upward trajectory.

Country cooperation and disciplinary mobility
The collaboration networks among countries and researchers in the field of cultural heritage conservation were generated by Bibliometrix (Fig. 2) [17]. Notably, countries with a substantial output of publications, such as the United States, China, Italy, and Australia, exhibit the highest internet connectivity rates, facilitating information exchange, mutual learning, and continuous innovation. Additionally, the dual-map overlay of cultural heritage conservation research, depicted in Fig. 3, extends the analysis to the disciplinary level. This illustrates citation patterns across multiple domains, highlighting the interdisciplinary nature of research in cultural heritage conservation (see Additional file 1: Fig. S1) [18].
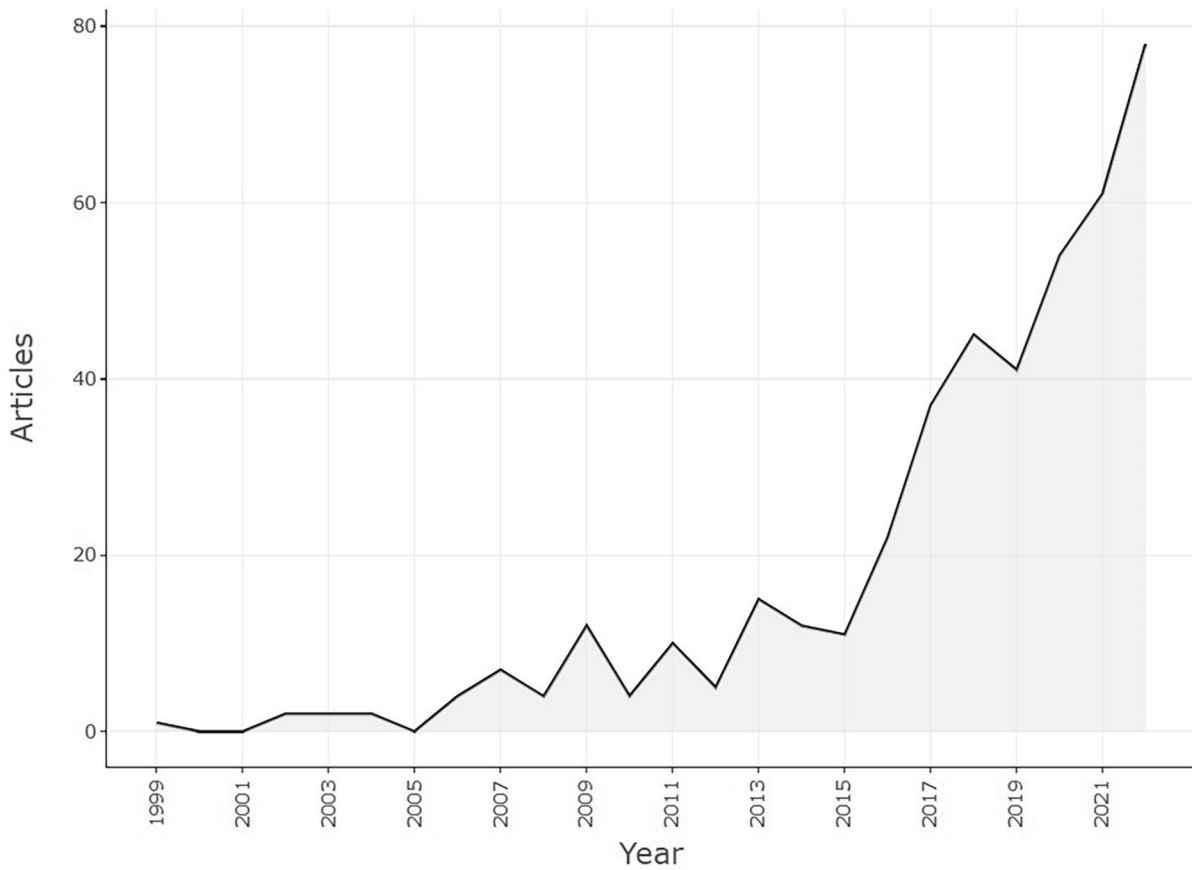
Liu *et al. Heritage Science*   (2024) 12:139

Page 3 of 14

Fig. 1 Overall trend chart of publication
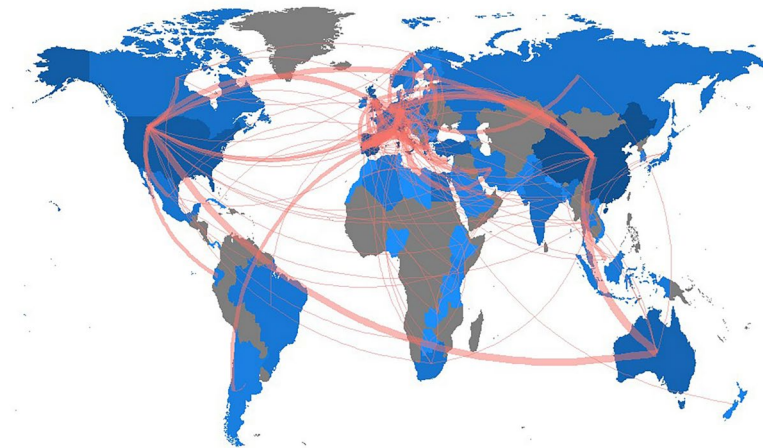
Fig. 2 Country scientific production in the field of GIS in cultural heritage conservation

Intellectual structure
Cluster analysis
This study primarily employs bibliometric techniques and utilizes CiteSpace software to analyze relevant data in annual time slices, exploring the development status and trends of GIS in cultural heritage conservation [19].

CiteSpace divides the co-citation network into multiple co-cited literature clusters, identifying 8 main clusters

Liu *et al. Heritage Science*   (2024) 12:139

Page 4 of 14

Fig. 3 Domain-level citation patterns in cultural heritage conservation research

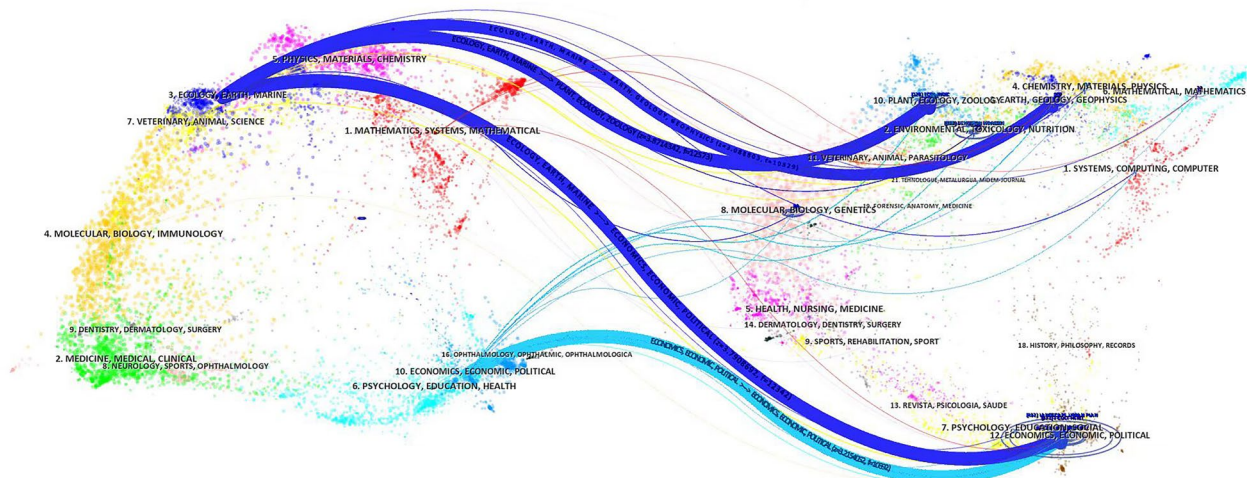(Table 1), each marked with labels derived using the log-likelihood ratio (LLR) method [20].

An overview of the co-cited literature and emerging terms related to GIS in cultural heritage conservation was generated by CiteSpace (Fig. 4). Each cluster includes citing articles and reference literature. The table below outlines the main members in four significant clusters, namely #0, #1, #2, and #6, highlighting their key research focus (Additional file 1: Fig. S2).

Cluster #0 represents important milestones in the field of remote sensing technology and GIS. Members of this cluster have pioneered interdisciplinary research, proposing new applications of GIS technology for comprehensive risk assessments of cultural heritage, refined automatic detection at archaeological sites, and land cover analysis of heritage sites using remote sensing technologies (Additional file 1: Table S1) [18, 21, 22].

Cluster #1 features critical advancements in prevention and protection strategies. Notably, Ortiz et al. used GIS software to assess flood and moisture-induced damage to cultural heritage, establishing preventive conservation methods [23]. The most cited articles within this cluster, predominantly published in 2021, focus on the application of 3D GIS in the restoration of cultural heritage (Additional file 1: Table S2).

Cluster #2 includes groundbreaking applications in GIS research, such as assessing conservation statuses and monitoring environmental risks at cultural heritage sites

Table 1 Largest clusters of co-cited references among the 130 clusters

| Cluster-ID	Size	Silhouette	Mean (Year)	Label (LLR)
0	41	0.94	2014	Cultural heritage assessment (39.63, 1.0E−4); historical map (24.94, 1.0E−4); anthropic risk (24.94, 1.0E−4); land use change (21.32, 1.0E−4); luxor city (21.32, 1.0E−4)
1	36	0.888	2018	Conservation management plan (22.3, 1.0E−4); Twentieth-century architectural heritage (22.3, 1.0E−4); photogrammetric technique (19.78, 1.0E−4); affordable degradation mapping (19.78, 1.0E−4); foss gis (19.78, 1.0E−4)
2	34	0.927	2018	Preventive conservation (21.72, 1.0E−4); restoration monitoring (21.72, 1.0E−4); fuzzy logic (21.72, 1.0E−4); extreme precipitation trend (18.96, 1.0E−4); andalusia spain (18.96, 1.0E−4)
3	29	0.992	2015	Using gis tool (24.94, 1.0E−4); vernacular heritage landscape (24.94, 1.0E−4); heritage value (24.94, 1.0E−4); abandoned vernacular landscape (19.86, 1.0E−4); sustainable tourism strategies (19.86, 1.0E−4)
5	17	0.97	2017	Other information technique (22.83, 1.0E−4); heritage modeling (22.83, 1.0E−4); damaged cultural heritage (15.05, 0.001); multiscale 3d gis (15.05, 0.001); southern Italy (7.44, 0.01)
6	17	0.972	2019	Degrees photography (21.51, 1.0E−4); cultural heritage building (21.51, 1.0E−4); digital documentation (21.51, 1.0E−4); scanning technologies (21.51, 1.0E−4); dissemination assessment (16.05, 1.0E−4)
7	14	0.982	2016	Non-invasive methodology (23.59, 1.0E−4); historical document (23.59, 1.0E−4); documentation management (17.59, 1.0E−4); cultural heritage data (11.65, 0.001)
19	8	1	2017	Mapping (14.73, 0.001); assessment (14.73, 0.001); aesthetic quality (14.73, 0.001); landscape (14.73, 0.01)
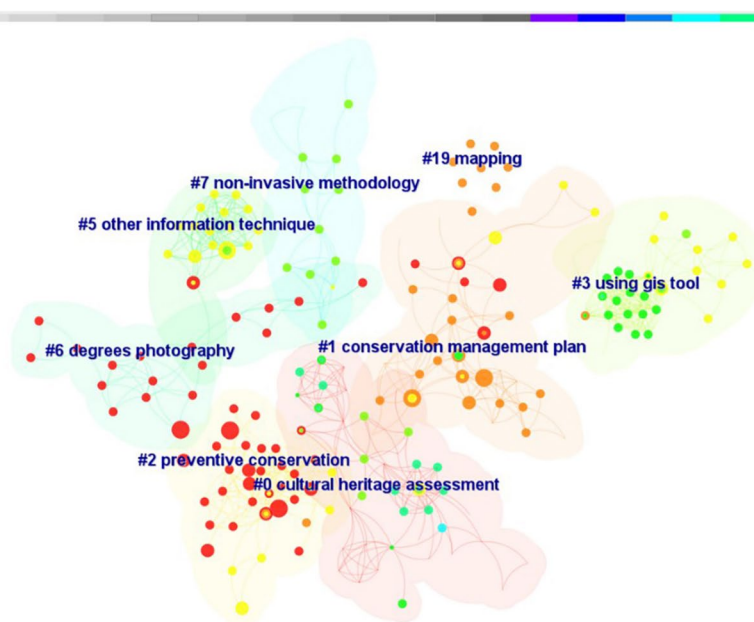
Fig. 4 A landscape view of the co-citation network, and clusters are labeled in blue text

using satellite remote sensing (ASRS) and GIS technology [24]. Additionally, the use of laser and GIS technology for spatial simulation of hazards and vulnerability assessments has provided essential data for prioritizing cultural heritage conservation efforts and opened new areas of application for GIS in heritage conservation [25–27]. This cluster includes 34 co-referenced documents, with 8 of these published in 2022. Citation coverage for these articles ranges from 3 to 12%, with the highest citation coverage observed in three articles [28–30]. Unlike many existing projects that focus on managing heritage structures, vulnerabilities, and hazards using GIS, this cluster evaluates the applicability of the ART-RISK 3.0 tool, which integrates GIS and AI to comprehensively analyze the vulnerability, emergency response capability, and lifespan of buildings under environmental threats. This assessment facilitates in determining the need for preventive or restorative protection. Other cited articles question the effectiveness of current protective measures and call for enhanced heritage risk analysis research to ensure sustainable heritage conservation (Additional file 1: Table S3).

Cluster #6, a recently formed cluster, includes the four most-cited references and four citing articles. The leading article in this cluster discusses the integration and detection of multi-source data on cultural heritage using Web-GIS technology, effectively implementing a strategy of "preventive conservation". This innovative approach has propelled research forward by employing the latest technological methods [31]. Similarly, a related article

highlights the important role of digital integrated services in heritage conservation as demonstrated by the Heritage Care project, demonstrating how digital strategies can enhance the protection process and engage a broad range of stakeholders [32]. Additionally, Ferdani D explores the application of VR games and digital representation in cultural heritage, enabling comprehensive 3D reconstruction and exploring new possibilities [33]. The articles with the highest citation coverage within this cluster focus on the use of VR applications and 3D modeling, alongside laser scanning and 360° imaging, to create digital replicas for appropriate preventive conservation measures. Furthermore, Masciotta MG's article, also part of this cluster [34, 35], employ interdisciplinary and digital approaches to advance research in heritage conservation (Additional file 1: Table S4).

The timeline chart created by CiteSpace intuitively reflects the development relationships between different clusters over time (Fig. 5). It is evident that Clusters #0 and #1 have experienced citation explosions, corresponding with the numerous keywords related to heritage assessment and heritage management plans in a short period. Consequently, these areas—heritage management plans, preventive conservation, and degree photography—represent relatively new clusters that have garnered significant attention in the academic community.

High-frequency articles analysis

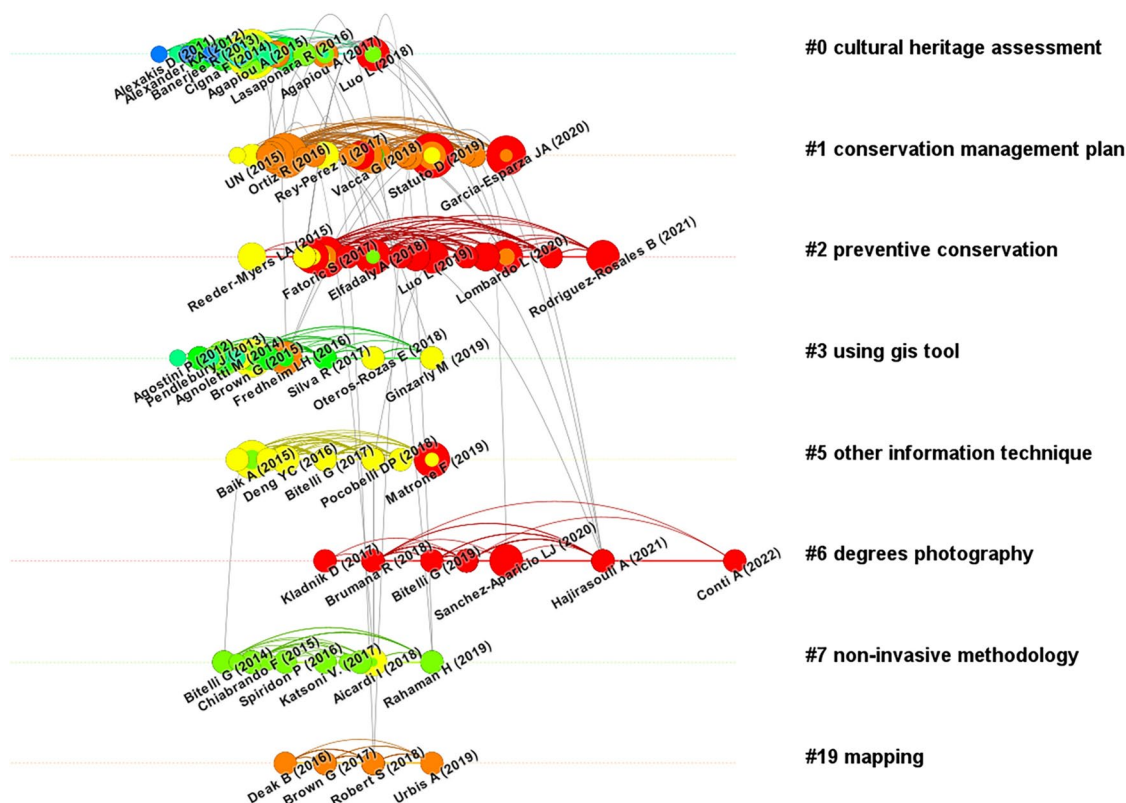In Cluster #1, the most cited articles have made pioneering contributions and possess significant reference values

Liu *et al. Heritage Science*   (2024) 12:139

Page 6 of 14

Fig. 5 A timeline visualization of the largest clusters of the total of 130 clusters, major clusters are labeled on the right

Table 2 Most cited references

Citation counts	References	Cluster#
11	Agapiou A, 2015, COMPUT ENVIRON URBAN, V54, P230	0
8	Ortiz R, 2016, SCI TOTAL ENVIRON, V551, P546	1
8	Statuto D, 2019, NAT RESOUR RES, V28, P61	1
7	Fatoric S, 2017, CLIMATIC CHANGE, V142, P227	2
6	Brown G, 2015, ECOSYST SERV, V13, P119	3
6	Baik A, 2015, INT ARCH PHOTOGRAMM, V40-5, P29	5
6	Garcia-Esparza JA, 2020, FRONT ARCHIT RES, V9, P900	1
5	Agnoletti M, 2014, LANDSCAPE URBAN PLAN, V126, P66	3
5	Campanaro DM, 2016, J CULT HERIT, V18, P321	1
5	Elfadaly A, 2018, J ARCHAEOL METHOD TH, V25, P587	2

(Table 2). In our dataset, the most frequently cited article by Agapiou A has garnered 11 citations. It is followed by Ortiz R and Statuto D, each with 8 citations, demonstrating substantial advancements in the use of GIS software for monitoring, management, assessing risks, and implementing preventive protection in cultural heritage

conservation [21, 23, 36]. In addition, notable progress has been reported in the domains of 3D GIS and Public Participation GIS (PPGIS) [37–39]. The fourth significant paper reviews the impact of climate change on cultural heritage, marking a new direction for conservation efforts, resource management, and policy development through interdisciplinary research [40]. Articles 2, 3, 7, and 9, all from Cluster #1, reflect a strong interest in applying GIS methodologies for the valuation of historic buildings or cities and conducting spatiotemporal analyses of cultural heritage across different periods using GIS tools [36, 41].

Furthermore, the impact alluvial diagram created by Bibliometrix vividly illustrates the sediment flow of highly cited articles in cultural heritage conservation literature over the past 20 years. This visual representation details the continuity and duration of citations for these articles across a span of 20 years [42]. In Fig. 6, the work of Rüther H is first noted in the sediment flow, persisting for 2 years and introducing the application of laser scanning in cultural heritage conservation [43]. Fagerholm N's contribution reveals the fundamental mapping function of GIS [44]. The sediment flows for Tehrany MS and Salazar LGF each extend for 3 years, highlighting recent trends in integrating evaluated research findings into GIS

Fig. 6 An alluvial flow diagram of highly co-cited articles during 23 years (1999–2022)

and simulating various scenarios and risks, such as those posed by earthquakes and floods, using GIS tools [45, 46]. While these articles have relatively short sediment flows, they reflect the dynamic shifts in research focus over time.

Emerging trends

Figure 7 illustrates the change in network modularity over time, as detailed in Additional file 1: Table S5. Notably, modularity decreased in 2013, rebounded, and then dropped dramatically in 2018. The pattern suggests important breakthroughs in 2013 and 2018, justifying a focused analysis on potential emerging trends identified particularly in these 2 years [47].

In 2013, if a paper experienced a citation explosion, it likely played a significant role in changing the overall knowledge structure within the field. For instance, 10 papers recorded a series of citation explosions, with the work by De Reu J leading this group (Additional file 1: Table S6). This paper, commencing a citation surge in 2016, represented high-precision techniques in the 3D recording and archiving of archaeological heritage [48]. Other papers from this year explored applications of GIS and satellite remote sensing technologies in various domains, such as visibility analysis, data storage, observation monitoring of cultural heritage, earthquake

vulnerability assessments, quantification of land parameters across different periods, and landslide hazard zoning maps [49–52]. Meanwhile, the Multi-Criteria Decision Support System (MCSDSS) emerged as a result of the integration of GIS with Multi-Objective Analysis (MCA), serving as an effective tool in addressing spatial planning challenges [53]. These findings suggest that the modular changes in 2013 heralded a significant trend toward three-dimensional research, which remains a dynamic and active research area as evidenced by the high number of citation explosions of publications in 2013.

In 2018, Oteros-Rozas E's research ranked first (Additional file 1: Table S7), highlighting the increasing use of geotagged photos as a source of data in online platforms, with a notable citation increase since 2020 [54]. Additional works discussed the applications of photogrammetry, various forms of laser scanning such as wearable mobile laser scanning (WMLS) and terrestrial laser scanning (TLS), remote sensing, and spatial information systems (SIS) in the preservation of cultural heritage, such as data storage, management, monitoring, and modeling [55–58]. Notably, in 2018, two overview articles published this year on the applications of BIM and large-scale geographic information computer programs in Google Earth (GE) also witnessed significant citation surges in 2020 and 2019 respectively [24, 59].
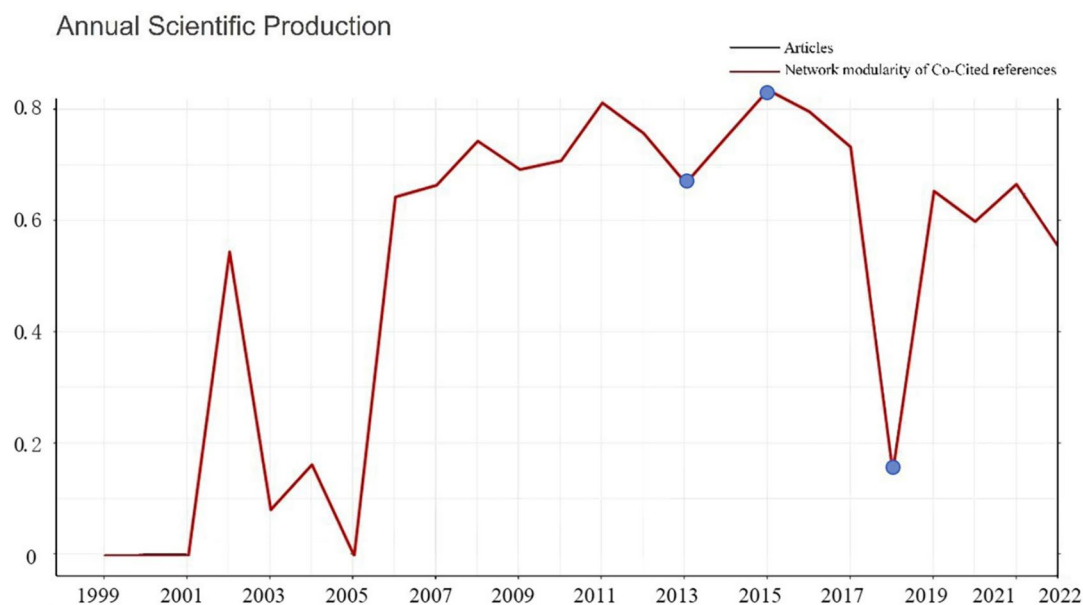
Fig. 7 Network modularity changes from 1999 to 2022

The profound modularity changes in 2013 indicated a new trend towards three-dimensional research. We investigated further to understand what prompted the more substantial modularity changes in 2018. Cluster #1, centered on conservation management plans, was crucial in the modular changes in 2018 and included numerous recent studies, especially from that year. Notably, this cluster contained articles that experienced a citation burst in 2016. The articles from 2018 shared a common objective of enhancing cultural heritage preservation by integrating GIS with other technologies, aiming for sustainable development. Although GIS applications are recognized for their contributions, they also have inherent limitations. Subsequent studies demonstrated that integrating GIS with various emerging technologies could enhance the certainty of results, thereby transforming conventional methodologies. These articles emerged within a short period, reflecting rapid developments in the field. For example, discussions on the potential and impact of GIS in strengthening cultural heritage preservation and promoting sustainable development were prevalent [60]. During one cultural heritage project, a substantial amount of data needs to be connected to the geographic database of GIS and Web GIS through Web Map Services (WMS) to formulate a Spatial Information System (SIS) that manages and archives data, making it accessible to the academic community [61]. Di Filippo A argued the accuracy of digital strategies by employing a wearable mobile laser scanning system (WMLS) for modeling complex cultural heritage buildings [56]. Tena Pa introduced methodologies for assessing heritage landscapes using GIS analysis among other techniques [41]. Additionally, in 2015, the peak in module value indicated that the utilization of PPGIS / PGIS to develop practice standards and evaluation indicators marked a significant shift and had profound impacts on the research landscape [38]. In Cluster 1, an article achieving a citation burst innovated by establishing a digital database based on GIS and incorporating multiple evaluation indicators to assess the value of cultural heritage. This innovation expanded the scope of participants in conservation practices and facilitated a deeper, multidimensional understanding of the original vitality and potential value of heritage after transformation [41].

Figure 8 was generated by the CiteSpace software, presenting a notable article in the lower part of Cluster #1. Ortiz R et al.'s article, which has been cited 8 times in the dataset, experienced a citation burst beginning in 2020. They argued that GIS software could be utilized to assess damage caused by floods and moisture to cultural heritage, providing decision-makers with simulation tools to minimize harm [23]. A co-citation network analysis identified several articles that cited Ortiz's work. To determine whether Ortiz et al. represent the beginning of an emerging trend, we examined the cited articles listed in Additional file 1: Table S8. The most cited paper, authored by Lombardo, with 36 citations, proposed using GIS spatial statistics to identify hazardous areas, followed by spatial modeling of multiple hazards threatening cultural heritage sites. This approach produced a unified
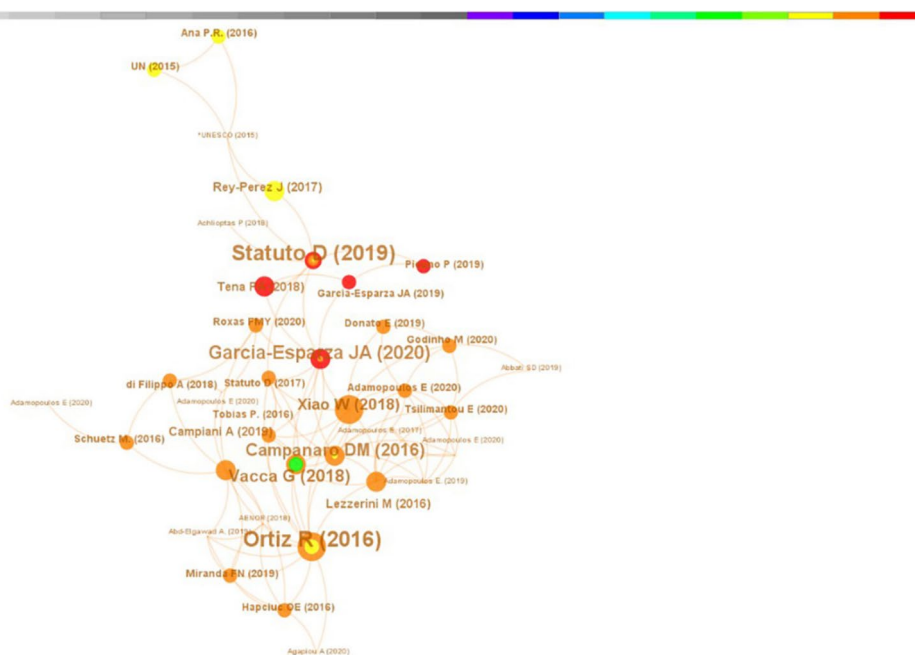
Liu *et al. Heritage Science*   (2024) 12:139

Page 9 of 14

Fig. 8 Co-cited reference networks in Cluster 1

multi-hazard vulnerability model that reliably supports the planning of protection practices for local cultural heritage sites at risk [25]. Their contributions have significantly advanced the practice of conserving cultural heritage at risk, marking a departure from the previous practices of using GIS for assessment that relied on subjective judgments about conservation modes.

In addition to the contributions of Ortiz et al. and Lombardo et al. a pioneering article by Javier explained an advanced Web-GIS technology that facilitates the transmission and visualization of information across different users. This technology integrates a vast array of data from diverse sources and types, enabling the accurate documentation, management and updating of cultural heritage [31]. Another study examined the collection and management of data concerning Twentieth-century architectural heritage through GIS, establishing Conservation Management Plans (CMP) [61]. Furthermore, a 2021 publication revealed the application of GIS in the surveying of historical building surveying sites to verify and update management databases, highlighting its benefits [7]. Additionally, Coli demonstrated the application of a detailed wireframe model developed via laser scanning surveys to 2D-GIS, creating a spatial geographic database that represents the "box" and stores all acquired information [62]. These studies represent the cutting-edge research directions, laying a foundation for profound inquiry into the application of GIS in cultural heritage conservation.

Subsequently, a thematic evolution analysis was conducted using Bibliometrix, with the results visualized in a Sankey diagram (Fig. 9). The Sankey diagram elucidates the volume and direction of topic flow as well as the transition relationships between topics, with the data span divided into five equidistant slices [63]. The diagram reveals a gradual shift in research themes from dispersion to unification, and from superficiality to depth. In the early stage (1999–2015), the application of GIS in cultural heritage conservation began to gain visibility, characterized by relatively broad keywords such as "GIS", "cultural heritage", and "example". In subsequent phases (2016–2018, 2019–2020, 2021–2021), GIS became firmly established and developed within the research field, fostering a plethora of interdisciplinary studies under the "conservation" theme. These studies addressed "data management" and practical applications of "climate change", "landscape analysis", "risk prediction", and "location selection". In the latest stage (2022–2022), the comprehensiveness of the research field was further enhanced, with various themes merging to new topics from earlier time slices. Emerging research trends include "3D modeling", "value assessment", "public participation" and "framework construction".

In summary, a series of recent articles have delved deeper into the establishment and application of GIS, along with making reasonable predictions based on GIS analyses. The data within the GIS database are accessible through mobile phones, tablets, and personal computers
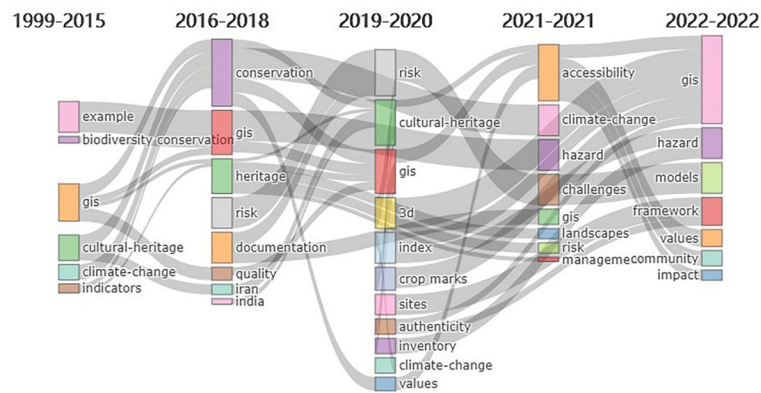
Fig. 9 Thematic evolution of the research field of GIS in cultural heritage conservation (1999–2022)

(PCs) via the network, allowing for queries or updates and serving as effective management tools for the conservation of significant historical and cultural buildings [62]. Additionally, the outcomes and analytical research derived from GIS-related software provide a significant instrument and scientific reference for stakeholders in cultural heritage to implement preventative actions and establish targeted risk mitigation strategies.

Figure 10 presents a strategic diagram of GIS in the field of cultural heritage conservation, as generated by Bibliometrix. This diagram is divided into four quadrants: Quadrant 1 (Q1) contains the main themes, while Quadrant 2 (Q2) contains highly developed and specialized themes. Quadrant 3 (Q3) includes disappearing or emerging themes, and Quadrant 4 (Q4) comprises foundational and transversal themes [65. 66]. A critical issue identified in Q1 is the impact of climate changes on heritage, which necessitates identifying risk areas and devising preventive measures through modeling. Also situated in Q1, the themes of "3D, BIM, and photography technologies in document recording, heritage restoration and reconstruction" are recognized
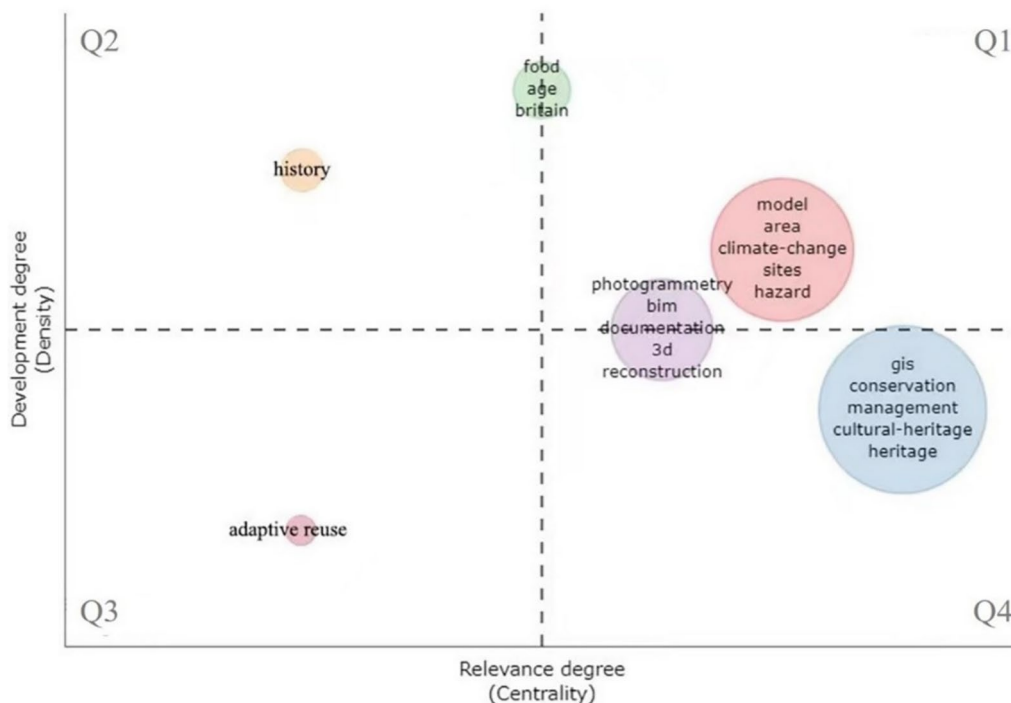

Fig. 10 Thematic map of the field of application of GIS in cultural heritage conservation

Liu *et al. Heritage Science*   (2024) 12:139

Page 11 of 14

as both significant and well-developed, straddling the boundary between Q1 and Q4. In Q4, the topics of "the conservation and management of cultural heritage and the use of GIS" are deemed fundamental and crucial for the advancement of the field. Although the theme of "history" in Q2 is currently less influential in field development, it holds potential. Scholars are encouraged to delve into the historical development context of heritage conservation, laying a foundational understanding for contemporary conservation efforts. Conversely, the theme of "adaptive renovation and reuse" in Q3 remains a relatively marginal topic.

The thematic analysis indicates a need to bolster efforts in areas such as "history" and its associated content, including historical maps, overviews and data, as well as enhancing integration with "modeling, risk prediction, 3D imaging and other technologies". Placing cultural heritage within the dialectical framework of historical time and space not only reveals its temporal and spatial behavioral processes, but also uncovers the spatial metaphors underlying these dynamics. Given the maturity of history as a discipline, it offers irreplaceable contributions to the sustainable development of cultural heritage conservation. The analysis and evaluation of historical values, supported by historical data and maps, are crucial for understanding the integrated development process and spatial characteristics of cultural heritage on a macro scale. This approach not only aids in comprehensively grasping the authenticity and value of cultural heritage, but also provides insights into interpreting urban spatial formation, renovation, and regeneration from a broader perspective.

Conclusion

This bibliometric analysis of "the application of GIS in cultural heritage conservation" has charted the development trajectory of related literature over the past two decades. Employing systematic methodologies provided by CiteSpace and Bibliometrix R, this study has identified research hotspots and emerging trends. The integration of GIS with cultural heritage conservation has been highlighted as a pragmatic focus that continues to evolve and expand, suggesting a future trajectory of practical applications over purely theoretical pursuits. The research landscape in this field has been thoroughly explored, by employing CiteSpace. Computational technologies play a crucial role in objectively identifying patterns and trends across various levels of abstraction. This includes monitoring the evolution of collective knowledge within the dynamic scientific community, evidenced by referenced and co-referenced clusters of literature, disciplinary flows, and thematic evolutions [50].

From the structural and temporal analysis of citations and co-citations, three major emerging trends have been identified:

(1) Sustainable Conservation Strategies: proposing sustainable conservation strategies for cultural heritage that has suffered external damage or functional degradation. This approach leverages digital technologies, such as GIS, to manage and assess both current and historical data, facilitating necessary restoration or modifications while ensuring the authenticity of the heritage. This strategy aims for long-term preservation or functional utilization.

(2) Proactive Conservation Models: the traditional salvage conservation mode, activated post-destruction, is proving insufficient. It is now imperative to explore viable preventive conservation methods and concepts. Recent scholarly work is increasingly employing technologies like 360° imaging to create digital models of cultural heritage, integrating detailed data through 3D recording and storage. This approach focuses on preempting the destruction of heritage through preventive maintenance and scientific management, to maintain heritage in optimal condition and achieving comprehensive conservation.

(3) Enhanced Public Engagement: embedding the Web-GIS platform and Public Participation GIS (PPGIS) model into the information dissemination and decision-making processes has revolutionized how geospatial data are distributed, retrieved, shared, and analyzed. Remote querying, analysis and export of spatial data via the Internet have strengthened public participation, facilitating data integration and collaborative assessment from multiple perspectives. This enhancement has increased the feasibility of implementation and the comprehensiveness of results, promoting the transmission and development of cultural heritage in contemporary society.

This paper enhances the understanding of research focus and development trends in the application of GIS in cultural heritage conservation. Future research should transcend merely integrating basic data with GIS for the creation of information databases, spatial analysis, and visualization. As indicated earlier, it should adopt a spatial humanities perspective, utilizing GIS, remote sensing, and other digital technologies to address complex spatiotemporal correlation challenges across multiple scales, dimensions, and levels that cannot be resolved by traditional, single-discipline, qualitative methods. Spatial humanities, through the digitization and spatialization of raw materials, uncover

Liu *et al. Heritage Science*   (2024) 12:139

Page 12 of 14

underlying historical and cultural phenomena, complementing conventional research methodologies. This approach emphasizes spatial history and human, social, and spatial interactions, enabling scholars from various disciplines to propose new research questions, apply novel analytical methods, and develop new models based on their expertise, thereby deepening research in this field.

It is also indispensable to adopt a historical perspective to trace the origins, understand the evolutionary processes, and perceive the historical applications of GIS in cultural heritage conservation. Creating spatial historical maps can enhance the granularity and richness of the research. Before establishing the database, it is necessary to standardize the processing of diverse data on cultural heritage in terms of formats, storage, and entry, following different standards. In system integration, differences in technical operations between systems necessitate the establishment of model standards for the analysis and management system platform to enhance system compatibility.

Moreover, the completed database and information management system should serve as a robust platform for multi-dimensional information comparison and collaborative efforts, supporting the application of various data analysis methods and models to improve the comprehensiveness and accuracy of literature analysis.

In recent years, the global pandemic has limited access to cultural heritage in terms of visitation, monitoring, and maintenance, which in turn unpredictably impacts cities, societies, and economies. Therefore, digital technologies are crucial in innovating cultural heritage conservation during such crises, requiring the integration and analysis of data from diverse sources and formats to produce visual research outcomes. The application of GIS not only fosters public participation by non-professionals, but also promotes interdisciplinary cooperation and virtual displays among different professional institutions. This digital approach provides the public with an operational platform to access cultural heritage sites from various countries at any time, offering rich spatial landscapes from diverse perspectives throughout the conservation process [66].

Despite its contributions, this paper acknowledges certain limitations. The primary limitation arises from the exclusive use of the WoS Core Collection database to extract complete reference texts and citation lists. In CiteSpace, when WoS Core Collection is used in alongside multiple databases, automatic filtering, and deduplication cannot be performed, potentially leading to discrepancies between cited results and actual situation [67]. Furthermore, reliance mainly on co-citation for bibliometric studies may introduce biases, as literature that is highly cited or centrally co-cited may not necessarily be of the highest quality [68].

Supplementary Information

> **Additional file 1: Figure 1.** Domain-level citation patterns in cultural heritage conservation research. **Figure 2.** Detail focus on most important clusters of the co-citation reference networks (1999-2022). **Table 1.** Cited references and citing articles of Cluster #0 cultural heritage assessment. **Table 2.** Cited references and citing articles of Cluster #1 conservation management plan. **Table 3.** Cited references and citing articles of Cluster #2 preventive conservation. **Table 4.** Cited references and citing articles of Cluster #6 degrees photography. **Table 5.** Different module values for different years. **Table 6.** Articles published in 2013 with subsequent citation bursts. **Table 7.** Articles published in 2018 with citation bursts. **Table 8.** Articles that cite Ortiz R et al.'s 2016 and their citation counts as of December 2022.

Author contributions
Beibei Liu: conceptualization, Visualization, Writing—original draft, Writing—review & editing. Cong Wu: funding acquisition, Supervision. Weixing Xu: Writing—original draft. Fengliang Tang, Yingning Shen:writing—review & editing.

Declarations

Ethics approval and consent to participate
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Authors declare that the manuscript is not submitted to any other journal at the time of submission for simultaneous consideration, that the submitted work is original and has not been published elsewhere in any form, that this work is not part of a single study, that results are presented under the principles of honesty, without fabrication falsification or inappropriate data manipulation.

Consent for publication
Both authors have read and agreed to the published version of the manuscript.

Competing interests
The authors declare no competing interests.

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Liu *et al. Heritage Science*   (2024) 12:139

Page 13 of 14

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Page 14 of 14

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