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Green infrastructure: systematic literature review

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ABSTRACT

Green infrastructure can effectively coordinate environmental, social and economic development, and has become one of the important strategies to achieve sustainable development. This study used CiteSpace and VOSviewer to analyze 2194 papers in the field of green infrastructure published from 1995 to 2019 in the Web of Science database using the bibliometrics and visualization methods. Results demonstrate a substantial increase in the number of studies on green infrastructure in recent years, with European and American countries leading the study of green infrastructure. Landscape and Urban Planning, Urban Forestry & Urban Greening, and Journal of Environmental Management are the first three cited journals in green infrastructure study. By studying co-cited literature, the study of green infrastructure has been found to involve the relationship between green infrastructure and ecosystem and human health, construction, evaluation and management of green infrastructure, and analysis of a special aspect of green infrastructure, among others. Clustering analysis results of green infrastructure keywords indicate that the existing studies have concentrated on green infrastructure in stormwater management, ecosystem services, biodiversity protection, and climate change. This study provides references for green infrastructure for sustainable environment development.

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1. Introduction

In view of the contradiction and conflict between socioeconomic development and the natural ecosystem (Lu et al., 2020; Shan & Duchi, 2020; Solonenko, 2019), such ideas as sustainable development, circular economy, and smart growth have become the core of current environmental issues (Barbesgaard, 2017; Rodríguez et al., 2020; Thomas & Littlewood, 2010; Tran & Beddewela, 2020; Villate et al., 2020). Green infrastructure, as an effective method to coordinate environmental, social, and economic development, has become one of the important strategies to achieve sustainable development (Ahern, 2011; Apostolopoulou & Adams, 2015; Cortinovis & Geneletti, 2018; De Valck et al., 2019). The concept of green infrastructure is a crucial

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node in the exploration of “harmonious coexistence between human and nature,” and its formation has experienced lengthy concept preparation and accumulation (Benedict & McMahon, 2002). The design concepts of “protecting nature” and “respecting nature” have been recognized by the public previously, but nature is in a relatively passive state. By contrast, “green infrastructure” attaches considerable importance to the coordination between nature protection and human construction, as well as artificial facilities. Moreover, “green infrastructure” advocates actively maintaining, restoring, building, and even rebuilding green network (Ying et al., 2011; Zhai, 2012). Green infrastructure plays important roles in adapting to climate change (Geneletti & Zardo, 2016; Takács et al., 2016), improving stormwater management capacity (Pappalardo et al., 2017; Raei et al., 2019), alleviating heat island effect (Saaroni et al., 2018; Wang & Banzhaf, 2018), and reducing environmental pollution (Livesley et al., 2016). This type of infrastructure is the natural life support system of regional environment and lays an ecological security foundation for sustainable environment development. In terms of social culture, green infrastructure can improve the built environment, provide people with opportunities of getting close to nature, enhance landscape aesthetics, and promote social equality, thereby improving social well-being and human health (Coutts & Hahn, 2015; Ko & Son, 2018; Sun et al., 2019). In addition, green infrastructure can attract tourists, consumers, and investments by enhancing environmental quality, bringing effective economic benefits to surrounding areas, and promoting the prosperity and sustainable development of the regional economy (De-Miguel-Molina et al., 2019; Graça et al., 2017; Wolf et al., 2020).

The existing studies of green infrastructure involve a wide range of fields, such as environmental science, urbanology, geography, botany, architecture, and economics. The theories, methods, and technology of green infrastructure have been frequently discussed among researchers and formed different study branches. First, many studies have investigated the evolution of the concept and core value of green infrastructure. Wang and Banzhaf (2018) summarized the evolution of green infrastructure by searching papers on green infrastructure in four databases, including Web of Science (WOS), as well as books and documents published by international organizations, government agencies, and research institutions as of 2016; and emphasized the importance of multifunction for the study and development of green infrastructure (Wang & Banzhaf, 2018). Second, scholars have systematically reviewed a certain branch of green infrastructure. McFarland et al. (2019) discussed the stormwater management of green infrastructure and reviewed the relevant literature to provide storm-water management guidelines for different types of green infrastructures (McFarland et al., 2019). Brzoska and Späße (2020) investigated the evaluation of ecosystem services in green infrastructure, and analyzed 76 papers published from 2000 to 2019 in WOS and Scopus to obtain the main types and generalized methods of the evaluation of ecosystem services in green infrastructure (Brzoska & Späße, 2020). In addition, studies have analyzed the research hotspots and development trends of green infrastructure. Anastasia Chatzimentor et al. (2020) analyzed 313 papers published by 28 European Union (EU) member states from 2008 to 2019, and comprehensively summarized the theme clusters and latest academic frontiers of green infrastructure study in Europe (Chatzimentor et al., 2020).

The study of green infrastructure is based on concept development and evolution and focuses on the research trends of a certain branch of green infrastructure or certain region. Thus, the current research used the method of bibliometrics to conduct a multi-dimensional visual analysis of the distribution, frontier, and trend of the literature on green infrastructure (Latapí Agudelo et al., 2019; Lu et al., 2019; Sana Ben et al., 2020). This method aims to systematically expound the knowledge evolution and development frontier of green infrastructure from an extensive longitudinal perspective, expecting to provide references for the strategic study of green infrastructure that contributes to sustainable development.

2. Methodology and data sources

2.1. Methodology

Scientific knowledge map is an emerging study method in the fields of scientometrics and informatics in recent years. This method can reveal the knowledge sources and development law of a certain field and expresses the knowledge structure and evolution law in fields related to graphics. Scientific knowledge map has the properties and characteristics of “graph” and “spectrum.” That is, scientific knowledge map is a visual graph and a serialized knowledge pedigree (Liu et al., 2020).

The color of each node from blue to red in the graph of CiteSpace represents the progress of time, and the size of nodes and clarity of labels represent the occurrence frequency. The tree diagram and connection thickness between nodes reflect the information correlation degree, thereby providing additional analysis parameters, including the network mediation center degree and substantially complete diagrams, and time series analysis function (Zhang et al., 2020). VOSviewer is a visualization software developed by Van Eck and Waltman of Leiden University in the Netherlands. The software has outstanding clustering function, and the visualization effect is also conducive to exploring the fields involved in the subject and research hotspots in various fields (Song & Chi, 2016). The font size of the nodes in the graph represents their occurrence frequency, and different colors of the nodes represent the idea that they belong to different clusters (Van Eck & Waltman, 2010). The two types of software can complement each other's advantages, and have been widely used in scientometrics.

In this study, knowledge map visualization used CiteSpace to generate the knowledge maps of publishing countries, publishing institutions, and co-cited magazines, and analyze the basic situation of foreign green infrastructure study. Moreover, the basic knowledge, research hotspots, and trends of foreign green infrastructure study were explored combined with the cited literature, subject distribution, and keyword co-occurrence knowledge maps generated by CiteSpace and the keyword clustering graphs generated by VOSviewer.

2.2. Sources of literature data

The basic data of this study was collected from the core collection of the WOS database with the keyword “green infrastructure” as the retrieval object. The first study on “green infrastructure” has been found to be included in the WOS database in

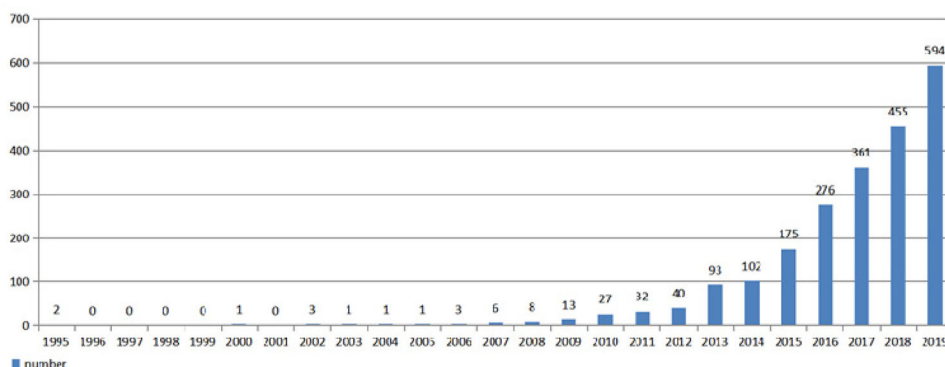


Figure 1. Studies on green infrastructure collected in the WOS database.

Source: Authors.

1995. Therefore, the time span of retrieval was “1995–2019,” and four types of Article, Proceedings Paper, Review, and Book review were selected. A total of 2194 papers were obtained, expecting to cover all study results on the basis of ensuring the quality of document retrieval.

According to the statistical analysis of the literature retrieval results, under 10 studies on green infrastructure were published from 1995 to 2008. However, a rapid growth occurred from 2009 to 2014, which exceeded 100 in a short period. An evident study upsurge has been noted since 2015, and the number of published studies has increased by the hundreds annually (Figure 1). Evidently, “green infrastructure” is a topic worthy of in-depth discussion and study.

3. Overview of green infrastructure study

3.1. Distribution of countries publishing studies on green infrastructure

In CiteSpace, the nodes were set as countries, and the time zone function was used to draw the time zone evolution map of countries and regions studying green infrastructure. By setting the threshold, the number of studies in the years when over 2 studies were published was summarized, and 62 key nodes were obtained (Figure 2). To date, 747 articles were published in the US, accounting for 34.05% of the global total and ranking first, followed by China (231, 10.53%), the UK (225, 10.26%), Italy (160, 7.29%), Australia (153, 6.97%), and Germany (141, 6.43%). The proportions of other countries are all below 5% (Table 1). Moreover, European and American countries have conducted numerous studies on green infrastructure, and their study results have substantial reference significance.

3.2. Distribution of countries publishing studies on green infrastructure

In CiteSpace, the nodes were set as Institutions, and the threshold was set to Top N=50 to visualize the knowledge map classified by institution. One node represents a scientific research institution, and the node size represents the number of papers published by the institution. The larger the node, the more evident the label font

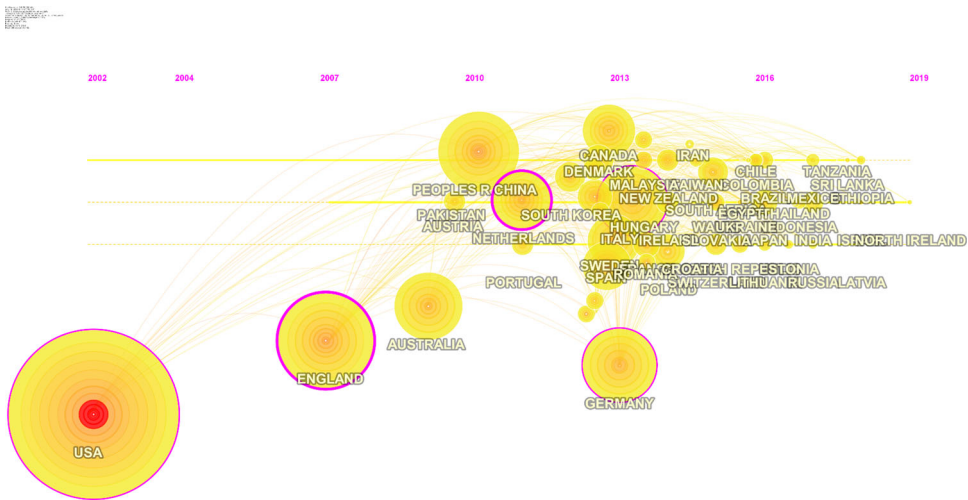


Figure 2. Time zone evolution map of countries and regions studying green infrastructure.
Source: Authors.

Table 1. Ratio of green infrastructure research literature to the total published studies in various countries from 2002 to 2019.

Country	Count	Percentage (%)
US	747	34.05
China	231	10.53
UK	225	10.26
Italy	160	7.29
Australia	153	6.97
Germany	141	6.43
Sweden	100	4.56
Canada	92	4.19
The Netherlands	89	4.05
Spain	79	3.60
Others	177	8.07

Source: Authors.

(font is weighed and opacity is high), thereby indicating that the institution has published numerous studies (Figure 3). The analysis results indicate that the top 6 institutions publishing papers on green infrastructure (including parallel ranking) are 49 papers by the US Environmental Protection Agency (EPA) with a centrality of 0.02; 31 by Swedish University of Science and Technology Agriculture, 0.12; 25 by UFZ Helmholtz Centre Environmental Research, 0; 19 by the University of Hong Kong, 0.04; 19 by the Chinese Academy of Sciences, 0.01; and 19 by Drexel University, 0.01. Three institutions have high suddenness: Drexel University, 7.02; Swedish University of Agricultural Sciences, 5.98; and Wageningen University, 4.50 (Table 2).

The following points can be obtained by analyzing the results of visualization map. (1) From the perspective of institution distribution, the argument that institutions in European and American countries lead the study of green infrastructure is supported, among which Drexel University and the US EPA are the main representatives. European and American countries, as well as some regions in Asia, have previously conducted studies on green infrastructure, thereby showing a good development

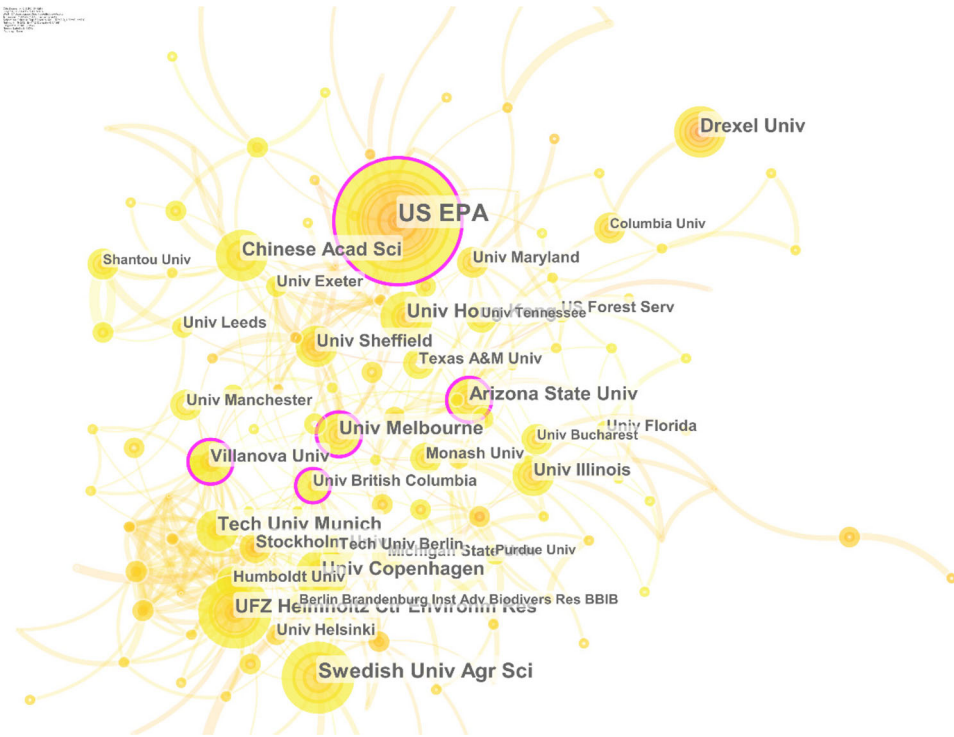


Figure 3. Number of papers published by green infrastructure research institutions and the centrality network of the papers.
Source: Authors.

Table 2. Top 8 institutions with the strongest citation bursts.

Institutions	Year	Strength	Begin	End	1995–2019
Drexel Univ	1995	7.0184	2010	2013	
US Forest Serv	1995	3.3544	2010	2013	
Stockholm Univ	1995	3.6774	2013	2016	
US EPA	1995	3.555	2014	2015	
Wageningen Univ	1995	4.4974	2015	2016	
Arizona State Univ	1995	4.1075	2016	2019	
Swedish Univ Agr Sci	1995	5.9818	2017	2019	
Chinese Acad Sci	1995	4.1213	2017	2019	

Source: Authors.

trend. (2) According to the structural analysis of the map, clusters are generated according to the cooperative relationship among different institutions. Institutions that have published the most number of papers are scattered in the dense cluster groups. In general, each cluster has institutions that have published a substantial number of studies. Therefore, the generation of each cluster may be directly related to institutions with considerable influence. (3) The analysis of various indicators has indicated that 15 and 38 institutions have centralities above 0.12 and above 0.04, respectively. The highest

Table 3. Frequently cited journals of the green infrastructure study.

Serial number	Name of Journals	Number of citations	Impact factors	Half-life period
1	Landscape and Urban Planning	1338	5.441	12
2	Urban Forestry & Urban Greening	728	4.021	8
3	Journal of Environmental Management	701	5.647	10
4	Ecological Economics	525	4.482	7
5	Science of the Total Environment	493	6.551	8
6	Landscape Ecology	460	3.385	11
7	Science	439	41.845	8
8	Land Use Policy	418	3.682	10
9	Environmental Management	415	2.561	11
10	Environmental Pollution	409	6.792	8

Source: Authors.

centrality of the six institutions that have published the most number of studies is 0.12, and the remainder has centrality below 0.04. This result indicates that institutions that have published numerous papers have low centrality. According to the definition of centrality, this phenomenon can reflect that institutions with numerous papers have weak direct correlation with other institutions, and the connectivity in the network of the institutions is low. This situation is partly the result of such institutions having complete research systems and strong scientific research capabilities. However, the cooperation between institutions with the same discipline and varying research directions and even different disciplines and diverse research directions has significance for academic exchange and development (Liu, 2018; Lu et al. 2019).

3.3. Distribution of cited journals

In CiteSpace, the nodes were set as Cited Journals to generate the knowledge map of the co-cited journals. Table 3 lists the top 10 cited journals of green infrastructure research, and summarizes the impact factors and half-life period. Green Infrastructure Finance: Leading Initiatives and Research is a book that is not listed on the table. The citation frequency is 250 times, which has high reference value. The following conclusions can be drawn after comprehensively analyzing the fields covered by the 10 journals and other journals with high centrality. (1) At present, the majority of the green infrastructure journals focus on the environment, ecology, or refined types (e.g. forestry and water resources), and are often closely related to cities. (2) Journals with high citation frequency have strong impact factors (indicating that the published papers have strong influence in academia) and long half-life period (indicating that the published studies have long timeliness; that is, numerous papers published many years ago continue to be cited). The three indicators show that the following journals lead the academic sector of green infrastructure study.

4. Trend of green infrastructure study

4.1. Main knowledge base

4.1.1. Distribution of disciplines

CiteSpace was used to draw the knowledge map of discipline distribution structure of 2194 documents, in which 73 nodes were obtained (Figure 4). The analysis results are

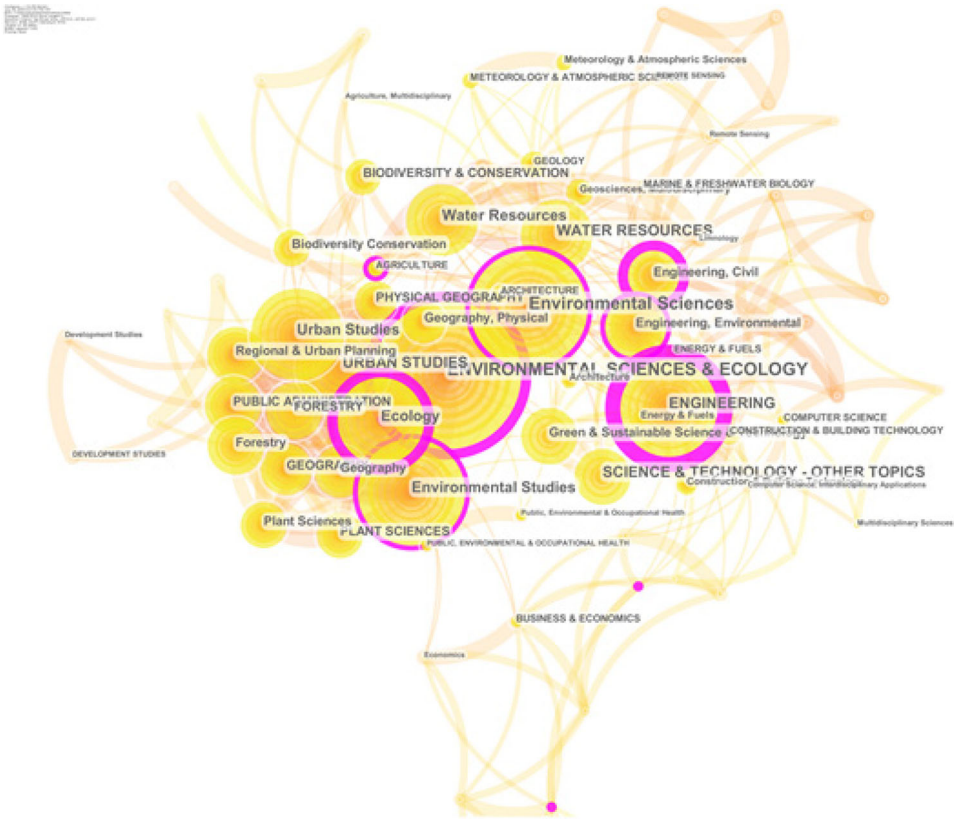


Figure 4. Disciplinary distribution structure of green infrastructure research.
Source: Authors.

as follows. (1) Analysis of mainstream disciplines: Environmental sciences is the discipline with the most number of studies, which account for over 50%, and environmental sciences is the mainstream discipline. The citation frequencies of urban studies, engineering, ecology, and water resources are above 200 times, thereby showing strong centrality. This result indicates that numerous studies of green infrastructure have been conducted in the aforementioned disciplines. (2) Time distribution and clustering analysis of disciplines: Timeline View in CiteSpace was used, the keywords were taken as the clustering elements, and the burst function was used. With the passage of time, the discipline distribution of “green infrastructure” study has become increasingly extensive. The basic trend of discipline distribution was summarized according to the visualization analysis. From 2006 to 2007, the studies mainly focused on “environmental science” and “urban research.” From 2007 to 2010, engineering and agriculture were studied. Thereafter, the discipline distribution showed evident scattered trend, among which geological geography, botany, architecture, and business economics were frequently investigated. Note that “green infrastructure” has an extensive study scope, and the study depth in different disciplines should be further developed. (3) Analysis of research directions with development potential. The analysis results of CiteSpace were derived and analyzed from three aspects. First, the occurrence time, frequency, and centrality of research directions were taken as

comprehensive analysis indicators. Meaningful research directions with frequency above 15 times or centrality over 0.1 in the recent 5 years (i.e. 2014–2019) were selected. The following directions were summarized: remote sensing, meteorology and atmospheric science, operational research and management, and computer science. Second, the subjects with high centrality (≥ 0.3) but low frequency (≤ 50 times) before 2014 were selected. Moreover the following directions were obtained: business and economics, materials science, and public administration. This fields had not been fully developed but had considerable research significance. Third, the disciplines with strong burst (≥ 3) but low frequency (≤ 50) were screened, and two directions were obtained, namely, limnology and marine and freshwater biology. In summary, increasing studies that prove green infrastructure can maintain multiple values and benefits have been conducted (Meerow & Newell, 2017). However, people have insufficient abilities to acquire knowledge and understand specific types of green infrastructure values (Karanikola et al., 2016). By contrast, the existing studies on green infrastructure have caused considerable repercussions in the ecological environment. The study branches of biophysics (biodiversity) and commercial economy (roof greening and stormwater management) are expanding, but only a few quantitative analysis systems can provide strong evidence of the impact of green infrastructure on these two aspects (Tao et al., 2017). In addition, the study of the social, cultural, and insurance values of green infrastructure is scarce and remains in the “blind zone” (Gómez-Baggethun & Barton, 2013).

From the analysis of disciplinary distribution, it can be seen that green infrastructure has its own research emphasis in different disciplinary areas and has different understandings of the concept of green infrastructure (Zhang & Chui, 2019). Therefore, diversified concepts of green infrastructure have been formed based on different disciplinary perspectives, which can be summarized into three types of concepts. The first category is the concept of green infrastructure defined from the perspective of ecosystem protection, mainly including Environmental Sciences, Environmental Ecology, Biodiversity Conservation, etc. (TEEB, 2010; Termorshuizen & Opdam, 2009). The second category is the residential environment disciplines such as Urban Studies, Regional&Urban Planning, etc., and the definition of green infrastructure from the perspective of serving the needs of human settlements (De la Barrera et al., 2016; Parker & Simpson, 2018; Venkataramanan et al., 2019). The third type focuses on municipal Engineering disciplines such as Engineering, Water Resources and Architecture, and defines green infrastructure from the perspective of greening municipal Engineering facilities (Hoover & Hopton, 2019; Venkataramanan et al., 2020) (Table 4).

4.1.2. Analysis of literature co-citation

Highly cited literature is often the knowledge base of theme development, and thoroughly analyzing highly cited literature can reveal the origin and orientation of the “green infrastructure” research. Data were input into CiteSpace, and “cited reference” was selected to obtain the co-citation network map (Figure 5). When the threshold value was adjusted to 50, the node labels (authors and years of cited documents) with over 50 cited times displayed. Cluster labels (#0–#6) were generated by keywords by

Table 4. Green infrastructure related disciplines and key definitions.

Disciplines	Objects	Key definitions
Environmental ecology (e.g. Environmental Sciences, Environmental Ecology, Biodiversity Conservation)	Capacity of an ecosystem to provide ecosystem services	The subset of the interactions between biophysical structures, biodiversity and ecosystem processes that underpin the capacity of an ecosystem to provide ecosystem services, including supporting, provisioning, regulating, and cultural services (Termorshuizen & Opdam, 2009; TEEB, 2010).
Human Environment (e.g. Urban Studies, Regional & Urban Planning)	Maintaining and improving human well-being	Well-structured vegetated pieces of land located in a city with differentiations in vegetation cover. Considered as public goods which allow free access to all citizens and represent pockets of nature for all residents (De la Barrera et al., 2016; Chatzimentor et al., 2020; Parker & Simpson, 2018).
Municipal Engineering (e.g. Engineering, Water Resources, Architecture)	Greening of municipal facilities	A set of green strategies in built environments that serve a variety of municipal needs such as managing flooding, improving water quality, reducing environmental pollution, and, adapting to climate change (Hoover & Hopton 2019; Venkataramanan et al., 2020)

Source: Authors.

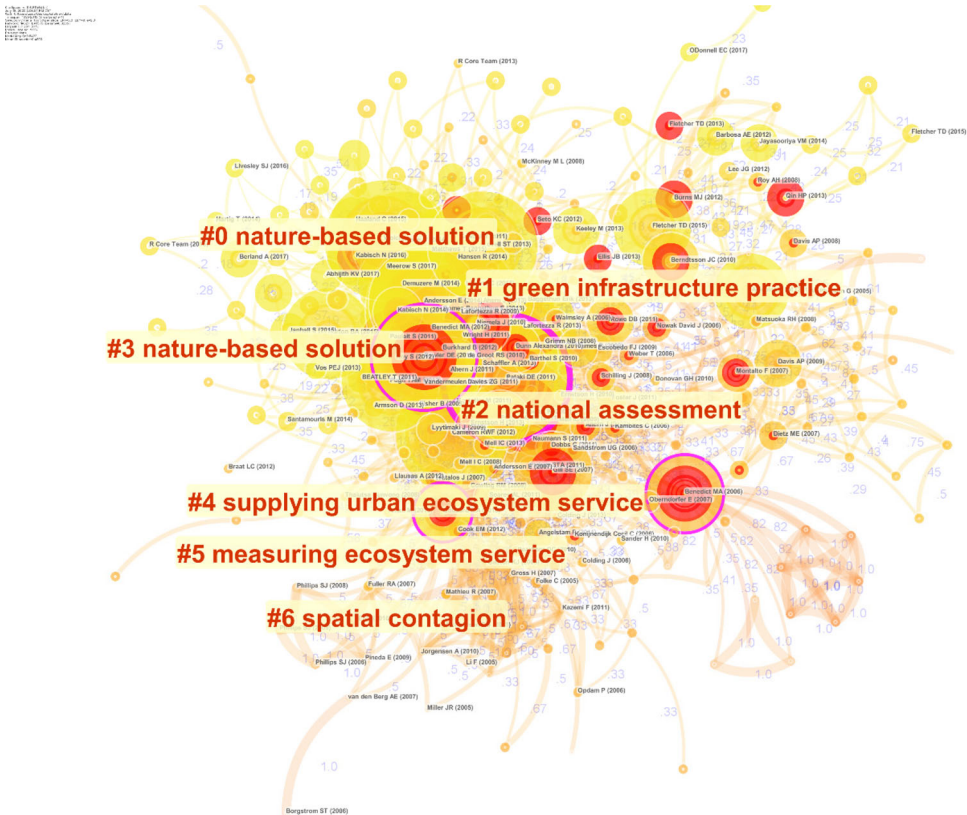


Figure 5. Distribution of highly cited literature on green infrastructure.

Source: Authors.

using clustering function. The highly cited studies are concentrated in #0, thereby indicating that the reference group of #0 is the core of the current green infrastructure research.

The visualization results in the map were analyzed and summarized. From the time perspective, the clusters generated by the early studies on green infrastructure were relatively concentrated. Over time, the studies spread around with the early clusters as the center, and new research clusters were generated. The highly cited studies were in the core areas with dense clusters, thereby further verifying that the cited literature had relatively laid the knowledge foundation of the subject research. According to the correlation degree of each cluster, the research on green infrastructure developed rapidly. The research situation mapped by co-citation networks before 2009 showed a typical initial state of research. The research network had strong concentration and high overlap degree, with only a set of clear branches and single direction. Various problems of the traditional development model (e.g. biodiversity and resource utilization) were considered from the urban economy perspective. Through further refinement and extension in this cluster, research topics on green infrastructure and stormwater management occurred (This clustering was developed and enriched in the later period). From 2009 to 2013, the cited literature were supplemented and expanded on the basis of previous clustering, in which network overlap occurred. However, more development direction occurred, thereby laying the foundation for the subsequent theoretical research. Since 2013, evident multi-directional research branches have emerged and new clusters have been generated on the basis of the previous literature accumulation to comprehensively and thoroughly discuss the combination of green infrastructure and different fields. From the content perspective, the study of green infrastructure was centered on human health embodied in two aspects. One aspect is the direct influence of green infrastructure on human physical and mental health. The other aspect is the indirect influence of green infrastructure on human health by influencing human living environment. Many studies have focused on the key word “city.”

Table 5 lists 8 classic studies on green infrastructure, which have been cited over 50 times. By analyzing the eight studies, three contents can be summarized. (1) Relationship among green infrastructure, ecosystem, and human health. “Promoting ecosystem and human health in urban areas using green infrastructure: A literature review published by Tzoulas et al. (2007) is the most influential and representative. The definitions of ecosystem health and human health are expounded, and the influence of green infrastructure is further analyzed. The discussion is supported by the mass literature. Different conceptual models are dialectically analyzed, and a conceptual framework combining green infrastructure, ecosystem, human health, and well-being is developed, thereby laying the foundation for interdisciplinary “concept convergence” (Tzoulas et al., 2007). (2) Construction, evaluation, and management of green infrastructure. This aspect has a large content span and is mentioned in all studies. First, “Millennium Ecosystem Assessment” is mentioned in five studies, indicating that the assessment system is extremely authoritative. Second, considerable focus is provided to land issues. Gill et al. (2008) argued that local land use and coverage are direct driving factors of ecosystem service change in the urbanization















Table 5. Highly cited literature of the green infrastructure research.

Serial number	Citation frequency	The first author	Year	Title	Literature source	Clustering label
1	90	Tzoulas K	2007	Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review	LANDSCAPE AND URBAN PLANNING	0
2	85	Gomez-baggethun E	2013	Classifying and valuing ecosystem services for urban planning	ECOL ECON	4
3	62	Bowler DE	2010	Urban greening to cool towns and cities: A systematic review of the empirical evidence	LANDSCAPE AND URBAN PLANNING	1
4	57	Wolch JR	2014	Green Alley Programs: Planning for a sustainable urban infrastructure?	LANDSCAPE AND URBAN PLANNING	13
5	55	Pataki DE	2011	Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions	FRONT ECOL ENVIRON	3
6	55	Gill SE	2007	Characterising the urban environment of UK cities and towns: A template for landscape planning	BUILT ENV	0
7	51	Andersson E	2014	Reconnecting Cities to the Biosphere: Stewardship of Green Infrastructure and Urban Ecosystem Services	AMBIO	1
8	50	Cameron RWF	2012	The domestic garden—Its contribution to urban green infrastructure	URBAN FOR URBAN GREE	4

Source: Authors.

process (Gill et al., 2008). Bowler et al. (2010) also explained that although green infrastructure projects have extensive theme and spatial scale, they have the common goal of realizing sustainable land management planning (Bowler et al., 2010). Moreover, the services and hazards of ecosystem and green infrastructure are dialectically analyzed and evaluated. Pataki et al. (2011) conducted a detailed analysis and found that the costs and benefits and services and hazards of an ecosystem should be weighted in green infrastructure construction (Pataki et al., 2011). Moreover, the various benefits of green infrastructure should be quantitatively analyzed to lay the foundation for construction planning. Lastly, sufficient attention should be given to people's active role in management. Andersson et al. (2014) recommended that the service of urban ecosystem is generated by the complex interaction between ecological process and human activities. Therefore, the synergy between ecology and society should be emphasized, thereby enabling ecosystem managers across different scales, departments, and administrative boundaries to play their roles (Andersson et al., 2014). Note that management is restricted by human demands and social, economic, and cultural conditions. (3) Analysis of the special contents of green infrastructure. The representative scholars are Cameron et al. (2012) and Newell et al. (2013). Green infrastructure is composed of multiple components. "Family Garden" (Cameron et al., 2012) and "Greenway" (Newell et al., 2013) are illustrated in the literature.

Table 6. Keyword burst detection in the green infrastructure research.

Keywords	Year	Strength	Begin	End	1995–2019
Sustainability	1995	3.7258	2009	2012	
Urban area	1995	6.7832	2010	2014	
Stormwater management	1995	3.6779	2010	2012	
Ecological network	1995	3.3545	2010	2013	
Urban ecosystem	1995	3.4451	2011	2013	
Energy	1995	4.0205	2011	2013	
Permeable pavement	1995	4.2854	2013	2015	
Landscape architecture	1995	3.4263	2013	2015	
Pattern	1995	3.6918	2014	2015	
Water quality	1995	3.3666	2014	2015	
Park	1995	7.2528	2014	2016	
Urban green infrastructure	1995	3.9008	2015	2019	
Restoration	1995	5.9485	2015	2016	
Green roof	1995	4.8968	2016	2019	

Source: Authors.

4.2. Analysis of the green infrastructure research trend

Keywords were selected from the titles, abstracts, and texts of the papers. High-frequency keywords can reflect the popular research fields (Li, 2010). Investigating the centrality and mutation of keywords in keyword co-occurrence analysis of CiteSpace is significant to the analysis of research hotspots. VOSviewer can cluster keywords with similar research topics into one class and mark them in the same color. Different views can express diverse information. This study used CiteSpace and VOSviewer to make the analysis results substantially comprehensive and reliable.

4.2.1. Analysis of research evolution

In CiteSpace, the visual map was generated with keywords as nodes, and the following results can be obtained by using the burst function (Table 6). Based on the keywords, the results were analyzed combined with the literature review. The study of green infrastructure can be divided into the following stages.

(1) 2009–2012. In 2009, the burst word “sustainability” appeared, and the study mainly explored sustainable development. In 2010, the burst words “urban area,” “stormwater management,” and “ecological network” appeared. In 2011, the burst words “energy” and “urban ecosystem” occurred. The research is in the stage of “explosive exploration.” A series of problems brought by rapid urbanization has become the bottleneck of urban sustainable development (Votinov et al., 2020), and the “sustainable development concept” contained in green infrastructure has been widely recognized. In 2009, the theme of the International Federation of Landscape

Table 7. Spatial scale of green infrastructure research based on the 865 scientific publications analyzed in this paper.

Spatial scale	Constituent elements	No of academic publications
Region/Macro-scale	Green corridors, green patches, wildlife migration corridors, green countryside	217
City/Meso-scale	Green alley and street, public park, urban wetland, urban forest, urban waterfront, urban greenway	355
Site/Micro-scale	Rain garden, grass channel, retention ponds, permeable pavement, ecological parking, green roof	293

Source: Authors.

Architects (IFLA) was “Green Infrastructure.” In the same year, the British Landscape Design Association also issued a statement, emphasizing the benefits of “green infrastructure” and its important role in coping with environmental challenges and the important role of landscape architects (Zhang et al., 2009). Under such a social background, “green infrastructure” has been endowed with important social value.

(2) 2013–2014. In the transitional stage, the research on green infrastructure was continuously developed and deepened. For example, the concept of green infrastructure has attracted continuous attention in the field of “landscape architecture” and reflected in “park” design. The research on green infrastructure in the field of storm-water management gradually developed into the stage of engineering measures, and “permeable pavement” was thoroughly explored. Meanwhile, substantial focus was attached to “water quality.”

(3) 2015–2019. Keywords in this stage included “urban green infrastructure,” “restoration,” and “green roof.” In 2015, the 6th International Conference on Restoration Ecology was held in Manchester, with the theme “Improving the Rapid Restoration Ability of Ecosystem: Restoring Cities, Villages and Countryside (Peng & Wu, 2015).” Roof greening and green building became emerging hot spots.

It can be seen from the evolution of the research that the practice of green infrastructure has been widely applied in three scales: site, city and region. Through the analysis of the literature abstracts, we found that there were 865 articles involved in different research scales (Table 7). Site scale is the micro—scale of green infrastructure research, which refers to a kind of ecological cycle of stormwater control and rainwater utilization facilities. The urban scale, as the meso—scale of green infrastructure, is essentially the natural system which can be relied upon to maintain the sustainable development of urban environment. The city and its residents can get nature services from it. Macro-scale regional green infrastructure refers to the natural continuous green network structure, which can maintain spatial stability, protect species diversity and have overall ecological benefits. “Urban area,” “park,” and “restoration” have considerably higher burst intensity than other keywords, thereby indicating that urban ecological restoration is one of the core objectives of green infrastructure research on city scale (Wu et al., 2019). Park planning design is an important link in urban ecological restoration (Gu et al., 2008).

4.2.2. Analysis of main knowledge domains

The following figure is a cluster view with co-occurrence keywords as clustering units in VOSviewer. The minimum display frequency of keywords is 5. The more obvious

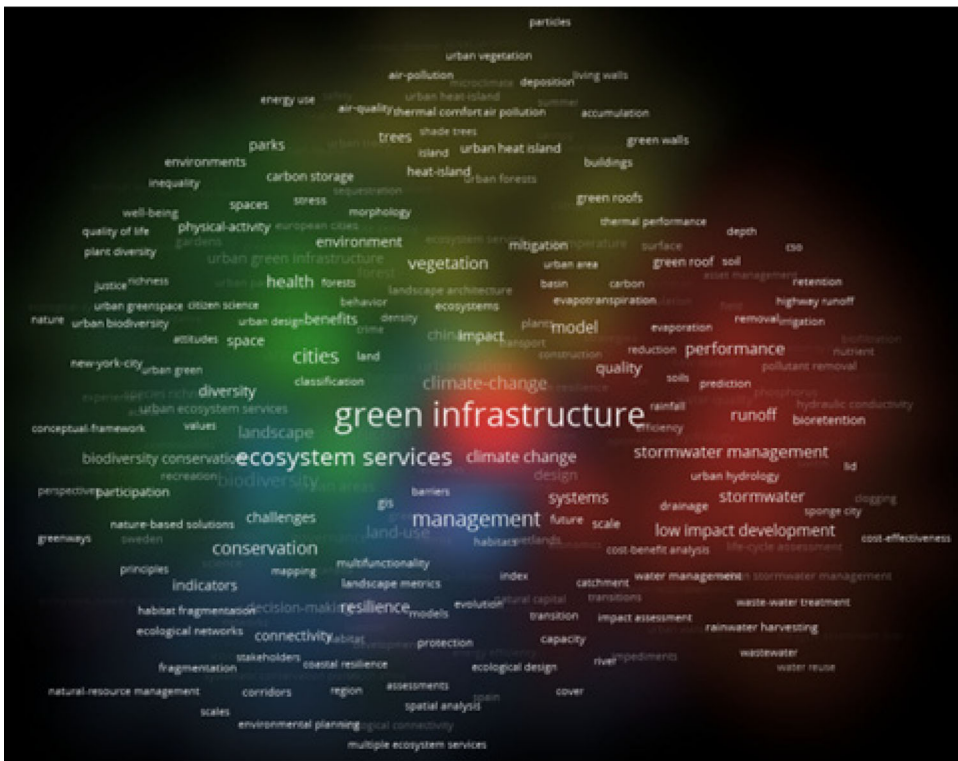


Figure 6. Cluster view of the green infrastructure research.
Source: Authors.

the font (i.e. large font size and high opacity), the higher the frequency (Figure 6). When the frequency of some keywords is above 5 times but in a lower state, they will not be displayed clearly because of high opacity. In Figure 6, the keywords with similar topics are clustered into one category and represented by one color. The four core clusters are as follows: red (green infrastructure and stormwater management), green (green infrastructure and ecosystem services), blue (green infrastructure and biodiversity protection), and yellow (green infrastructure and climate change) clusters.

(1) Green infrastructure and stormwater management. This cluster has the highest number of keywords and an important direction of the green infrastructure research. Traditional rainwater management aims to realize the rapid discharge of urban rainwater runoff, and the main carrier is an urban rainwater pipe system (gray infrastructure). With the rapid development of urbanization, building density gradually increases, the area of impervious pavement expands, and the natural storage and drainage system and hydrological cycle have been substantially damaged. Traditional stormwater management mode separates the relationship between human and nature, and its drawbacks are constantly exposed. In this case, an increasing number of cities begin to combine traditional stormwater pipe network with new green infrastructure, and explore multifunctional and sustainable stormwater management modes (Zhang & Chui, 2019), which are represented by “low-impact development,” “water sensitive urban design,” and “sponge city,” among others. These modes attach importance to

the application of “green elements” in stormwater management, such as “green roofs,” “rain gardens,” and “wetlands.”

“Low-impact development” originated in the US. It was originally intended to compensate for the economic and environmental limitations of traditional rainwater management measures through plant retention and absorption of infiltration rainwater (Luo & Li, 2014). This type of development’s basic idea is to use small-scale and low-cost green ecological technologies, and reduce runoff and water discharge via infiltration, filtration, evaporation, and flood detention to realize effective hydrological design (Bhatt et al., 2019). Such measures as “bioretention,” “green roofs,” and “permeable pavement” are taken to simulate the hydrological process of nature. The idea is to make the hydrological function of an urban development area to be as close as possible to the natural state.

“Water sensitive urban design” originated in Australia, and combines the entire hydrological cycle with urban development and construction to minimize the negative influence of urban development on the hydrological environment (Castonguay et al., 2018; Morison & Brown, 2011). This design emphasizes the combination of the best planning practice and management practice, and can be applied in urban districts, blocks, and even plots (Romnée et al., 2015). Best planning practice refers to site assessment and land use planning. Given that land use planning has an impact on sites (e.g. drainage mode and water quality), impact assessment is of immense importance. Best management practice is generally divided into engineering and non-engineering practices (Wang, 2016), with emphasis on leadership and knowledge management development in the latter ones (Jankurová et al., 2017; Mishchuk et al., 2016; Poór et al., 2018). The principle of engineering is similar to that of low-impact development, whereas non-engineering means to achieve the goal of stormwater management through non-technical means, such as management, system, or education.

The concept of “sponge city” was proposed under the background of increasingly severe stormwater disasters in China, combined with the excellent experience of other countries and existing technical foundation of stormwater management in China (Shi, 2018). The metaphor of “sponge” for stormwater management reflects the concept of stormwater management that respects and conforms to nature. Sponge city construction includes three directions: protection, restoration, and development. Protection refers to protecting the ecosystem that has not been destroyed. Restoration indicates restoring the damaged natural environment via human intervention. Development means the construction of ecological environment (urban ecological environment) (Han & Zhao, 2016).

(2) Green infrastructure and urban ecosystem services. Keyword density in a cluster should be analyzed. Figure 6 shows two evident small clusters. One cluster comprises the keywords “ecosystem services” and “cities.” The research on ecosystem services appears frequently in highly cited literature, thereby demonstrating the viewpoint that “highly cited literature lay a knowledge foundation for research hotspots.” The research on “green infrastructure” is closely related to the research on “ecosystem services,” both of which are broad and highly comprehensive concepts. The relevant studies have mainly focused on “cities” and analyzed the issues closely related to human health and environment protection.

Table 8. Key gaps on green infrastructure research and provide suggestions for future research.

Focus areas	Research gaps	Future research
Publication performance	The GI research literature was mostly from highly developed countries, except China.	It is necessary to study in these developing regions. They are currently experiencing a rapid urbanization process, which is related to the severe ecological environment crisis in developing countries.
Disciplinary distribution	The understanding of GI concept in different academic disciplines leads to the diversity and ambiguousness of GI conceptualization.	Interdisciplinary research needs to be considered to form a recognized definition of green infrastructure.
Type of functions	There are many GI studies that consider environmental and social functions, but the economic valuation practices at GI are rare.	More thorough and extensive economic function studies of GI are needed.
Spatial scale	A strong focus on city scale, a clear research emphasis on ecosystem services and a limited emphasis on the social, economic aspects of GI.	In-depth study on the multi-functional green infrastructure in urban sustainable development.

Source: Authors.

(3) Green infrastructure and biodiversity protection. This selected the following representative keywords from the keywords with the highest frequency: “management,” “biodiversity,” “GIS,” “land-use,” “connectivity,” “ecological network,” “fragment,” and “corridors.” By analyzing the keywords, the following conclusions were drawn. (1) One of the important development goals of green infrastructure is to protect biodiversity (Savas et al., 2016). (2) Spatial analysis of species via GIS technology is significant to land use and habitat protection. (3) Green infrastructure is an interconnecting green space network, which consists of hubs and links. The restoration of “fragmentation” in ecological environment in the construction of green infrastructure is a critical and arduous task (Zhou & Yin, 2010).

(4) Green infrastructure and climate change. The keywords in this cluster are divided into three clusters. From the perspectives of location and content, the keywords in the cluster closely related to the theme word “green infrastructure” include “vegetation,” “ecosystem,” and “landscape architecture.” This cluster is broad and closely related to gardens. With this cluster as a starting point, two other clusters have been developed. One cluster studies how green infrastructure can alleviate climate problems, such as “urban heat island effect” and “air pollution.” The other cluster is specific engineering measures, such as “green roofs,” “green walls,” and “green buildings.”

5. Discussion

This study used CiteSpace and VOSviewer to analyze and interpret 2194 studies on green infrastructure collected in the WOS database from 1995 to 2019 from the aspects of issuing countries and institutions, highly cited journals and literature, discipline distribution, research evolution and keyword clustering. In what follows, we discuss our key gaps on green infrastructure research and provide suggestions for future research (Table 8).

In this study, the performance of publications was quantitatively analyzed based on bibliometric methods, and it was found that the US ranks first in terms of the number of publications and publishing organizations, followed by the UK, Italy, and Sweden in Europe. With the exception of China, there are few studies in Africa, Asia and South America, which may limit the universality of the green infrastructure findings. Therefore, it is necessary to study in these developing regions. They are currently experiencing a rapid urbanization process, which is related to the severe ecological environment crisis in developing countries. Moreover, green infrastructure research remains in its initial stage, and green infrastructure practice has considerable demands. In the future, numerous researches on green infrastructure will be conducted in the developing regions, and these countries and regions will also provide a broad practical space for green infrastructure development.

From the disciplinary distribution of green infrastructure research, its concept comes from different disciplines, such as environmental ecology, regional & urban planning, and engineering. Therefore, green infrastructure involves a wide range of ecosystems and targets, and has been adopted in various disciplines related to design, protection, and planning. However, no recognized definition and evaluation standard of green infrastructure is provided in the existing literature. The understanding of green infrastructure in various disciplines based on the corresponding research background makes the conceptualization, thereby weakening the effectiveness and multi-function of green infrastructure. The definition of green infrastructure is the basis of scientific research and planning strategy and has important authority. The clear definition and evaluation criteria of green infrastructure are conducive to in-depth and comprehensive interdisciplinary research on the basis of unified understanding. Therefore, interdisciplinary research needs to be considered to form a recognized definition of green infrastructure.

Green infrastructure can provide environmental, economic and social benefits simultaneously. According to the high-frequency keyword analysis and keyword cluster analysis in the previous sections, there are many studies that consider environmental and social benefits, as well as the valuation is often defined in biogeophysical terms. Although it is widely recognized that green infrastructures can influence several economic outcomes (De Groot et al., 2010; Kim & Song, 2019; Van Oijstaeijen et al., 2020), the absence of co-occurring keywords and clustering information related to economic benefit, indicates a lack of economic related research. A systematic review found that the economic valuation practices at green infrastructure are rare, leading to uncertainty of economic benefit and impact (Van Oijstaeijen et al., 2020). Our results confirmed this opinion from a scientific and quantitative perspective. In practice, comparing alternatives between green or grey infrastructures is often based on their relative economic benefits. However, there are no extensive scientific researches about these issues, and more thorough and extensive studies are needed to fill this gap. In particular, a comprehensive green infrastructure assessment could guide policy makers in this area (Turturean et al., 2019).

By analyzing the research hotspots, even though the research and practice are mainly concentrated in the region scale, city scale and site scale, we observed a clear focus on urban areas, a clear emphasis on ecosystem services and a limited emphasis

on the social, economic aspects of green infrastructure. Under the background of global urbanization, and a series of environmental problems brought about by rapid urbanization has become major challenges to urban sustainable development. Many of them are caused by intensive migration (Jędrzejowska-Schiffauer & Schiffauer, 2017; Mishchuk et al., 2019; Yang et al., 2016a, 2016b), particularly due to reasons of insufficient well-being in living environment (Bilan et al., 2020). In urban landscape with dense population, satisfying multiple demands for ecology, society, and human health is particularly urgent. In the future Green infrastructure research should be highlighted in the ecological, social and economic effects of urbanization, giving full play to the multi-function green infrastructure in dealing with the urban sustainable development, such as alleviating urban environmental problems (Lu et al. 2019), improving residents' living standards, and enhancing urban resilience.

6. Conclusion

This study conducted an in-depth analysis of green infrastructure research from different perspectives, expecting to explore the evolution of green infrastructure in vertical development trend and provide a reference for green infrastructure research. This study also has some shortcomings. On the one hand, only the core data set of WOS was selected, and some research results may be omitted. On the other hand, although the theme context, knowledge evolution, and research hotspots were comprehensively discussed, this study failed to thoroughly analyze the contents of interdisciplinary because green infrastructure is a typical complex system involving different disciplines. This aspect will be the promotion and development direction in the follow-up research.

Disclosure statement

No potential conflict of interest was reported by the authors.

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