蓝绿基础设施对城市气候韧性构建的作用
——基于共引文献网络的文献计量分析

The Contributions of Blue-Green Infrastructure to Building Urban Climatic Resilience
—Bibliometric Analysis Based on Co-citation Networks

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摘要

在全球气候变化与城市可持续发展背景下，构建气候韧性已经成为城市地区应对气候变化风险的重要发展战略，其中蓝绿基础设施被视为提升城市韧性的重要潜在工具。尽管一些研究提到蓝绿基础设施可以通过增加自身的多样性、灵活性、冗余度、模块化和分散性来促进城市韧性，但对于在哪些领域促进、具体通过什么途径促进，以及促进的程度还缺乏针对性研究，无法支撑从韧性理论到规划设计实践的推进。本文通过Citespace文献计量工具识别出蓝绿基础设施对城市气候韧性的主要作用领域为应对城市洪涝、海平面上升和高温热浪风险，并具体分析了蓝绿基础设施在这三个领域中对城市气候韧性的作用，进而指出蓝绿基础设施内在作用机制是其自身的生物－物理特性和与其功能相似的其他基础设施组成模块化单元来吸收城市系统遭受的干扰和冲击，依靠网络化结构和作为庇护所来帮助系统在干扰和冲击后尽快恢复物理功能和社会关系。同时，本文指出，上述作用原理尚缺数据支撑、缺乏对生态－社会－经济综合利益评估，以及难以取得决策者和公众的信任是目前蓝绿基础设施在应用过程中遇到的主要问题和挑战。最后，本文试从科学研究、规划设计和实施管理等方面提出应对策略，以期为构建城市气候韧性提供思路。

关键词

气候变化；气候韧性；蓝绿基础设施；共引文献网络；基于自然的解决方案；应用问题；应对策略

ABSTRACT

Against the backdrop of global climate change and in regards of urban sustainable development, enhancing climate resilience has become a critical strategy in adapting climate change for urban areas, where blue-green infrastructure is considered an important means. Although existing studies mention that blue-green infrastructure (BGI) can promote urban resilience by increasing its own diversity, flexibility, redundancy, modularization, and decentralization, questions like where to promote, by what specific means to promote and to what extent it could promote to are still lack of scientific exploration, leading insufficient support for applying resilience theory into planning and design practice. This research recognizes the role of BGI in building climate resilience in the key fields of functioning—urban floods, sea level rise, and high temperature and heat waves—and summarizes that the common functioning mechanisms include the bio-physical properties of BGI, forming modular units with other infrastructures of similar functions, and the reliance on networked structures to help the system restore its physical functions and social connections as quickly as possible after disturbances and attacks. This paper also analyzes possible obstacles that hinder the promotion of BGI solutions—the lack of data support to BGI functioning mechanism, the lack of comprehensive assessment on ecological-social-economic benefits, and the difficulty in gaining confidence from decision-makers and the public. Finally, this paper proposes countermeasures from aspects of theoretical development, planning practice, and implementation and management, in order to offer insights for building urban climate resilience.

KEYWORDS

Climate Change; Climate Resilience; Blue-Green Infrastructure; Co-citation Networks; Nature-Based Solutions; Applied Problems; Countermeasures

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1 引言

气候变化和城市化对人居环境造成的各种危害——洪涝和干旱、频发的极端天气、粮食和水资源短缺等正不断加剧，人类健康持续受损。近年来，“韧性”（resilience）的概念被引入城市规划和管理中，以期减少这些危害的负面影响[1][2]。韧性是指一个社会或生态系统在吸收干扰的同时保持基本结构和运作方式的能力、系统自我组织的能力，以及适应压力和变化的能力[3]。城市气候韧性是城市韧性的一个重要分支，关注城市系统对气候变化过程的长期影响与极端气候灾害的综合应对[4]。联合国气候变化专门委员会（IPCC）认为气候变化对城市的可持续发展构成了严重的威胁，倡导将构建“气候韧性途径”（climate-resilient pathways）作为减小城市地区气候变化影响的重要发展战略[5]。

蓝绿基础设施（blue-green infrastructure，以下简称BGI）是由蓝绿空间和相关构筑系统组成的自然或半自然基础设施，如森林、湿地、河流、公园、绿色屋顶、绿墙、生物滞留池等，它们通过提供一系列生态系统服务来提升生态系统的韧性和人类福祉[6]~[9]，被视为缓解和适应气候变化的一种通用有效途径。城市气候韧性不仅聚焦于适应气候变化，而且还注重加强城市预测、吸收已知和未知的威胁并进行重组的整体能力[10]~[13]，强调了城市系统的主动性和学习力。尽管一些研究提到BGI可以通过增加自身的多样性、灵活性、冗余度、模块化和分散性来促进城市韧性[14]~[19]，但对于在哪些领域促进、具体通过什么途径促进，以及促进的程度还缺乏针对性研究，无法支撑从韧性理论到规划设计实践的推进。此外，BGI作为一种基于自然的解决方案（Nature-Based Solutions，以下简称NBSs）已在世界上许多城市得到了应用，了解应用过程中遇到的共性问题有助于厘清未来研究方向，并促进NBSs的推广。

鉴于以上，本研究通过文献研究法系统梳理BGI在关键作用领域中对气候韧性构建的作用，了解其作用机制，以便为后续建立面向气候韧性提升的BGI策略和更细化的规划设计指标体系提供理论依据。此外，研究还探讨了BGI在过往应用过程中面临的问题，并从理论研究、规划设计和实施管理等方面提出应对策略，以期深入了解BGI在气候适应和风险管理中的作用，为城市气候韧性构建提供思路。

1 Introduction

The various hazards caused by climate change and urbanization on human living environments—floods and droughts, frequent extreme weather events, food and water shortages, etc.—are increasing and human health continues to suffer. In recent years, the concept of “resilience” has been introduced into urban planning and management to mitigate the impacts of such threats[1][2]. Resilience refers to “the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change”[3]. Studies on urban climate resilience, an important branch of urban resilience, focus on how urban systems holistically accommodate or respond to long-term impact of climate change and extreme climate disasters[4]. The Intergovernmental Panel on Climate Change (IPCC) emphasized climate change as a threat to sustainable development of cities, and “climate-resilient pathway” as an urban development strategy for mitigating and adapting to climate change[5].

Blue-green infrastructure (BGI) can be understood as a hybrid network of natural or semi-natural infrastructure of blue-green spaces and built systems, e.g. forests, wetlands, rivers, parks, green roofs, green walls and bio-retention ponds that can contribute to ecosystem resilience and human well-being through ecosystem services[6]~[9], thus is considered a widely adoptedand effective approach for climate change mitigation and adaptation. Besides of adaptation to climate change, urban climate resilience also focuses on strengthening a city’s overall capacity to systematically anticipate, absorb, and reorganize itself to known and unknown threats[10]~[13], which emphasizes the initiative and learning capacity of urban systems. Although studies mention that BGI can promote urban resilience by increasing its diversity, flexibility, redundancy, modularization, and decentralization[14]~[19], but questions like where to promote, by what specific means to promote and to what extent it could promote to are still lack of scientific exploration, leading insufficient support for applying resilience theory into planning and design practice. Furthermore, BGI as a Nature-Based Solutions (NBSs) has been applied in many cities around the world. Therefore, understanding common problems encountered in application will help clarify future research directions and encourage the promotion of NBSs.

In view of the above, this research systematically sorts out the role of BGI in building climate resilience in the key fields of functioning, and explores related mechanisms through literature review, so as to provide a theoretical reference to the development of BGI strategies and refined planning and design index systems for climate resilience enhancement. Additionally, this research also discusses about the problems in BGI implementation, and proposes countermeasures from aspects of theoretical development, planning practice, and implementation and management, in order to gain insight into the role of BGI in climate adaptation and risk management and provide ideas for building urban climate resilience.

2 数据和方法

2.1 数据收集

本研究在参考相关研究[20]中检索词条设置结构的基础上，在Web of Science核心合集数据库中进行基础数据的检索（图1），检索式中关键词包括：

1）BGI类型——如“blue space”或“green space”（蓝绿空间）、“blue infrastructure”或“green infrastructure”（蓝绿基础设施）、“urban park”（城市公园）、“urban waterbody”（城市水体）和“urban tree”或“tree canopy”（城市树木）——以及它们所在的区位——如“urban”或“city”（城市）、“community”（社区）、“human settlement”或“living environment”（人居环境）。

2）气候变化和灾害，如“adverse event”（不良事件）、“extreme event”（极端事件）、“climate change impact”（气候变化影响）、“urban heat island”或“heat wave”（高温热浪）、“flood”或“waterlogging”（洪水内涝）、“fresh water or food shortage”（淡水或食物短缺）。

3）与韧性相关的重要概念，如“resilient”或“resiliency”（韧性）、“adaptation”（适应）、“disaster”或“hazard”（灾害）、“recover”（恢复）、“risk”（风险）、“response”（响应）。

最终在不限发文时间（默认1950年至检索日）的条件下对上述检索结果进行交集操作，文献类型为文章（Article），语言为英文。剔除了部分不相关学科文献及除重后，得到5 312条文献。数据检索与下载日期为2021年8月27日。

2 Data and Methodology

2.1 Data Collection

With reference to the search queries structure from previous study, the author made basic data search from the Core Collection Database in Web of Science (Fig. 1)[20] with the following keywords.

1) Types of BGI—such as “blue space” or “green space,” “blue infrastructure” or “green infrastructure,” “urban park,” “urban waterbody,” and “urban tree” or “tree canopy”—and their locations, such as “urban” or “city,” “community,” “human settlement” or “living environment.”

2) Climate change and disasters, such as “adverse event,” “extreme event,” “climate change impact,” “urban heat island” or “heat wave,” “flood” or “waterlogging,” and “fresh water or food shortage.”

3) Concepts related to resilience, such as “resilient” or “resiliency,” “adaptation,” “disaster” or “hazard,” “recover,” “risk,” and “response.”

Intersection was conducted to the searching results above, with default setting on the publication date (1950 to the searching date). The type of literature was set as Article, and the language English. After eliminating the results of irrelevant disciplines and deduplication, 5,312 pieces of results were obtained. The results were retrieved and downloaded on August 27, 2021.

2.2 Qualitative Bibliometric Analysis

This paper made bibliometric analysis of the above datasets with CiteSpace (5.8.R2). After title relevance screening, a total of 5,311 articles published between

# 5	5,312	#3 AND #2 AND #1 精炼依据: Web of Science 类别: (ENVIRONMENTAL SCIENCES OR SOCIAL SCIENCES INTERDISCIPLINARY OR WATER RESOURCES OR ENGINEERING MULTIDISCIPLINARY OR AREA STUDIES OR GEOSCIENCES MULTIDISCIPLINARY OR BIOLOGY OR SOCIAL SCIENCES MATHEMATICAL METHODS OR ECOLOGY OR METEOROLOGY ATMOSPHERIC SCIENCES OR ENVIRONMENTAL STUDIES OR ENGINEERING CIVIL OR GEOLOGY OR FORESTRY OR ENGINEERING GEOLOGICAL OR GREEN SUSTAINABLE SCIENCE TECHNOLOGY OR ENGINEERING ENVIRONMENTAL OR ARCHITECTURE OR FOOD SCIENCE TECHNOLOGY OR GEOGRAPHY PHYSICAL OR GEOGRAPHY OR URBAN STUDIES OR PUBLIC ENVIRONMENTAL OCCUPATIONAL HEALTH OR BIODIVERSITY CONSERVATION OR PLANT SCIENCES OR MULTIDISCIPLINARY SCIENCES OR REGIONAL URBAN PLANNING OR LIMNOLOGY OR POLITICAL SCIENCE OR REMOTE SENSING OR MANAGEMENT OR SOIL SCIENCE OR SOCIOLOGY OR CONSTRUCTION BUILDING TECHNOLOGY OR AGRICULTURAL ENGINEERING OR DEVELOPMENT STUDIES OR BUSINESS OR ECONOMICS OR AGRONOMY OR PUBLIC ADMINISTRATION) 索引=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC 时间跨度=所有年份
# 4	5,780	#3 AND #2 AND #1 索引=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC 时间跨度=所有年份
# 3	4,346,211	(TS=("resilient" OR "adaptation" OR "adaptive capacity" OR "coping capacity" OR "disaster" OR "hazard" OR "recover*" OR "resilienc*" OR "evacuat*" OR ("emergency" NEAR/2 "response") OR "risk" OR "closure" OR "congestion" OR "disrupt*")) AND 语种: (English) AND 文献类型: (Article) 索引=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC 时间跨度=所有年份
# 2	380,255	(TS=(("adverse" NEAR/2 "event*") OR ("extreme" NEAR/2 "event*") OR "wildfire" OR "urban heat island" OR "heat wave*" OR "high temperature weather" OR ("cool*" NEAR/1 ("impact*" OR "effect*")) OR "flood*" OR “waterlogging” OR "microclimate" OR “typhoon” OR (("fresh water" OR “food”) NEAR/1 "shortage") OR ("climate change" NEAR/1 ("impact*" OR "effect*")))) AND 语种: (English) AND 文献类型: (Article) 索引=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC 时间跨度=所有年份
# 1	170,159	(TS=("green space*" OR "blue space*" OR "greenspace*" OR "bluespace*" OR "green infrastruct*" OR "blue infrastruct*" OR "blue-green space*" OR "green-blue space*" OR "blue-green infrastruct*" OR "green-blue infrastruct*" OR "green area*" OR "blue area*" OR "green and blue space*" OR "blue and green space*" OR "urban park*" OR "forest*" OR "vegetated park*" OR "city park*" OR "tree canopy" OR "urban tree*" OR "street tree*" OR "urban green*" OR "urban vegetation" OR "green park*" OR "green corridor*" OR "grass-coverd" OR "tree-covered" OR "river*" OR "urban waterbody" OR "wetland*" OR "stream*" OR "lake*" OR "channel*" OR "reservoir*") AND TS=("urban" OR "city" OR "community" OR "human settlement*" OR "living environment")) AND 语种: (English) AND 文献类型: (Article) 索引=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC 时间跨度=所有年份

1. 数据收集策略

1. Search queries used for data collection

2.2 文献计量结合质性分析

本文使用CiteSpace（5.8.R2）对上述数据集进行文献计量分析。经过标题相关性筛查，最终用于计量分析的数据集包含1991~2021年期间发表的5 311条文献。CiteSpace的文献共被引分析功能可通过不同的算法对具有强共被引关系的文献进行聚类，并从聚类的施引文献标题、关键词或摘要中提取名词性术语对聚类进行命名，这个命名可被认为是该聚类所代表子领域的研究前沿[21]。在此基础上，研究通过对聚类文献的分析提取出BGI对气候韧性发挥作用的关键领域，即关键作用领域。然后，通过引文法对聚类中的文献进行向后追溯或向前发展得到的相关文献进行分析，归纳总结在关键作用领域中BGI对气候韧性产生的具体作用，以及BGI在既往实施案例中出现的问题。在具体作用和问题分析部分，所依据的材料在原始文献数据集及其共被引网络的基础上进行了必要的拓展和二次检索，以便能够更有针对性地阐述所研究的问题。

3 BGI对气候韧性的作用

3.1 作用领域识别

研究对文献集进行共被引分析，时间切片采用一年一分割，节点类型选择被引文献，提取节点阈值选择g指标（k=25），其他参数均为默认值。网络生成后用Pathfinder裁剪每个切片及合并后的网络，以突出重要的网络结构。最后共得到1 487条被引文献节点，2 401条节点连线。参考既有研究，图2中仅展示了前20条高被引文献。

从图2可见，整体网络呈现较为明显的团簇结构，说明文献中存在若干共同主题。进一步对共被引网络进行聚类后得到22个子集群（图3），聚类的模块性指数Q值和加权平均轮廓性指数S值分别为0.9369和0.9661，表明聚类结构显著且结果合理[21]。在Citespace软件提供的文献数量大于50的八大聚类中，结合用潜在语义索引和对数极大似然率提取的聚类标签以及聚类中的高被引文献识别，发现这些聚类可被归纳为五大主题，分别为“城市洪涝”（urban flood and waterlogging）、“森林野火”（forest wildfire）、“海平面上升”（sea-level rise）、“城市高温热浪”（urban high temperature and heat wave）和“NBSs”（表1）。五大主题的前四项可被认为是目前与BGI相关的气候韧性研究中最受关注的四类风险，也即是BGI对气候韧性的关键作用领域。四个风险主题中，城市洪涝主题下的聚类具有最早的文献平均发表年度（2008年），可见在气候变化的背景下，应对城市洪涝风险是全球范围内较早受到高度关注的话题，而在距今更近的时间点（2016年）出现热点的原因可能与“承洪韧性”（flood resilience）概念最近在灾害管理领域受到的

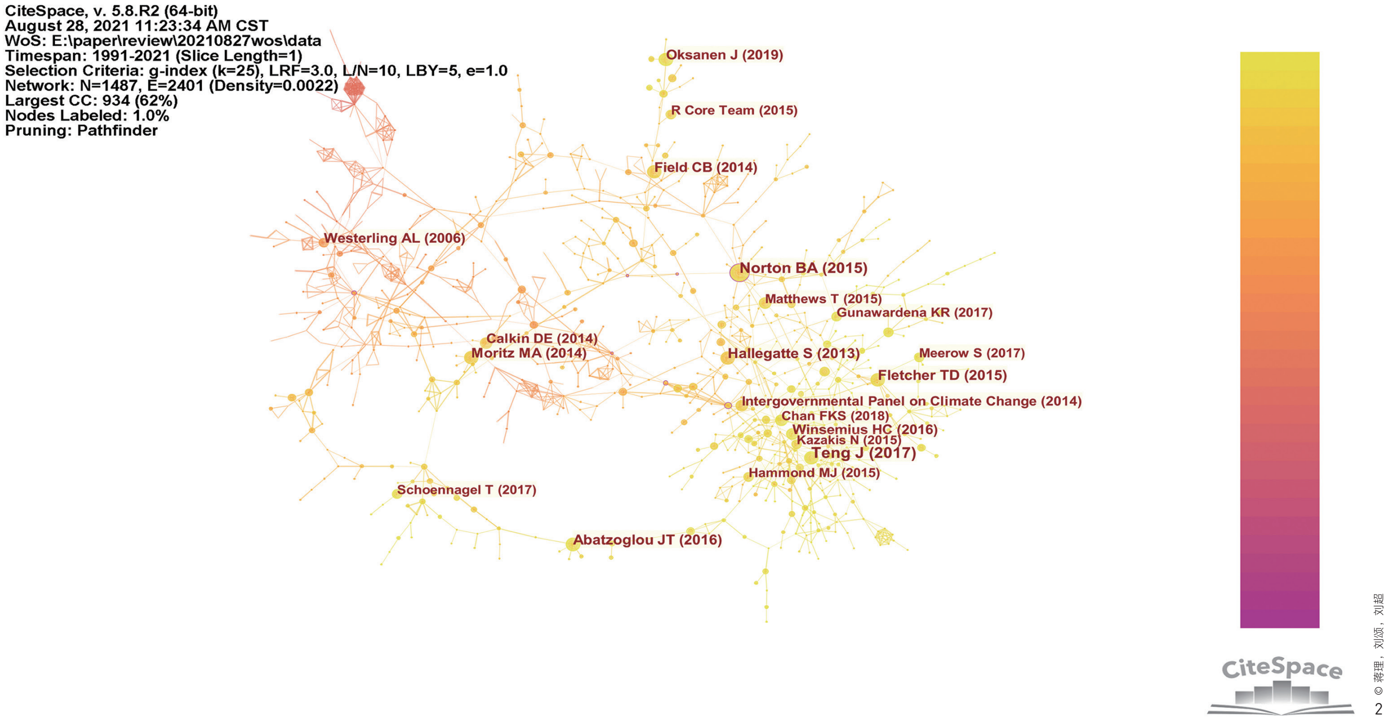
1991 and 2021 were retained for bibliometric analysis. The literature co-citation analysis function of CiteSpace can cluster literature with strong co-citations via different algorithms, and then name the literature clusters with the extracted nominal terms from the titles, keywords or abstracts. Each cluster's name can be considered a frontier research interest in its corresponding subfield[21]. By analyzing the clustered literature, the research extracted the key fields where BGI plays in climate resilience, i.e. key fields of functioning; Based on the review of the citing and cited articles of the clustering literature, the specific impact of BGI on climate resilience in key fields of functioning, as well as the problems found in BGI practice cases were summarized. Further review and supplementary search were conducted on the existing literature dataset and the co-citation network, for better understanding the specific problems in current research.

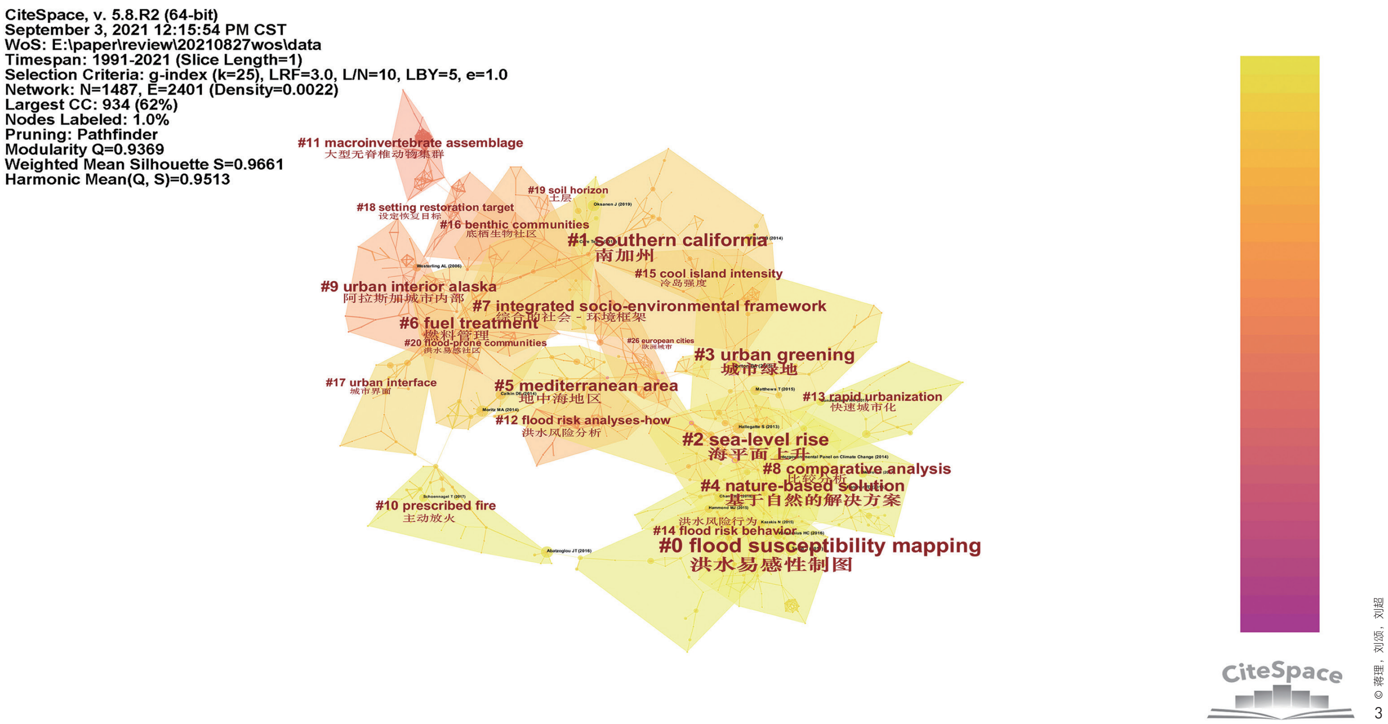
3 The Role of BGI on Climate Resilience

3.1 Identification of Key Fields of Functioning

The co-citation analysis was carried out on the literature dataset with annual segmentation for Time Slicing, Cited Reference for Node Types, g indicator (k=25) for Node threshold extraction, and default values for other parameters. After the network was generated, Pathfinder was activated to crop each slice and the merged network to highlight important network structures. Finally, 1,487 citation nodes were obtained with 2,401 connection lines. Figure 2 shows the top 20 highly cited articles.

As shown in Figure 2, overall, the co-cited network presents a prominent cluster structure, indicating several common interests of research. The network was further clustered and gained 22 subclusters (Fig. 3). The Modularity Q and Weighted Mean Silhouette S values of the clusters are 0.9369 and 0.9661, respectively, indicating significant clustering structure and reasonable results[21]. From the 8 major clusters recognized by Citespace with literature counts greater than 50, five topics were identified after reviewing the clustering tags extracted by Latent Semantic Indexing (LSI) and Long-Likelihood Ratio (LLR) algorithms and the highly cited literature in the clusters. These topics were named as "urban flood and waterlogging," "forest wildfire," "sea-level rise," "urban high temperature and heatwave," and "NBSs", respectively (Table 1). The former four topics could be considered current risk categories with the most attention in BGI research related to climate resilience, i.e. the key fields of climate resilience BGI is contributing to. Among the four topics, urban flood and waterlogging has the earliest average publication year (2008), suggesting that in the context of climate change, coping with urban floods has been a worldwide concern for a longer period of time, while the recent attention re-rise (since 2016) may be related to the broad discussion about the concept of "flood resilience" in the field of disaster management[22]. In addition, the average publication year of the articles under the topic of NBSs is 2016, indicating that BGI, as an integrated, nature-based approach responding to the challenges in sustainable development,





2. 共被引网络及前20篇高被引文献的第一作者及发表年份
3. 共被引网络聚类可视化

2. The first authors and publication years of the top 20 highly cited articles in the generated co-cited network
3 Visualization of the subclusters in the further clustered co-cited network

广泛讨论有关[22]。NBSs主题下的文献平均发表年份也相对较近（2016年），说明BGI作为一种利用自然应对可持续发展挑战的综合途径，近年来也成为了研究和实践热点。

需要说明的是，由于在识别出的森林野火灾害文献中，BGI（森林）仅作为灾害的发生地而并不具备缓解与适应灾害的作用，在本文中仅作为与气候变化紧密相关的一个领域进行展示，不纳入之后的分析。

has also become a research and practice hotspot in recent years.

It should be noted that in the articles under the topic of forest wildfire, the involved BGI terms (mostly forest) are not related to BGI's role in mitigation and adaptation to disasters—only mentioned as the places where disasters occurred. Thus, this paper simply presents this topic as a field closely related to climate change, which is not included in later analyses.

表1：共被引网络五大主题聚类信息
Table 1: Literature clusters under the five classified topics in the co-cited network

主题 Topic	聚类号 Cluster ID	文献数量 Size	轮廓度 Silhouette	标签 Labels	平均发表年份 Average publication year
城市洪涝 Urban flood and waterlogging	0	88	0.975	洪水易发性制图；洪水易发性建模；城市洪水风险；城市内涝 Flood susceptibility mapping; flood susceptibility modeling; urban flood risk; urban waterlogging	2016
	7	51	0.963	综合的社会 – 环境框架；案例研究；人口 Integrated socio – environmental framework; case study; human population	2008
森林野火 Forest wildfire	1	70	0.957	南加州；防火隔离带；荒地-城镇交界域；房屋损失；土地管理实践；国家森林 Southern California; fuel break; wildland-urban interface; house loss; land management practice; national forest	2010
	5	56	0.966	地中海地区；多尺度方法 Mediterranean area; multiscale approach	2013
	6	54	0.932	燃料管理；多尺度方法 Fuel treatment; multiscale approach	2009
海平面上升 Sea-level rise	2	69	0.95	海平面上升；洪水风险；水利部门；社会经济变化 Sea-level rise; flood risk; water-based sector; socio-economic change	2013
城市高温热浪 Urban high temperature and heatwave	3	64	0.951	城市绿地；城市森林；绿色基础设施；绿色屋顶；全球变暖；适应途径；应对城市过热 Urban greening; urban forest; green infrastructure; green roof; global warming; adaptation approach; tackling urban overheating	2014
基于自然的解决方案 NBSs	4	57	0.965	基于自然的解决方案；缺少灾害数据；城市增长 Nature-based solution; lacking disaster data; urban growth	2016

3.2 关键作用领域分析

3.2.1 促进应对洪涝的韧性

全球气候变化与降水和洪水事件的变化密切相关。据世界资源研究所预测，到2030年，全球范围内将有7.58亿人暴露在百年一遇的洪水淹没区[23][24]。而由强降水或连续性降水引发的城市内涝每年都给全世界许多城市造成严重的生命和财产损失[25][26]。应对洪水和内涝风险长久以来都是城市可持续发展的重要议题。

（1）通过对雨水的截留和吸收抵御洪水冲击

大量研究表明，滞留池、可渗透路面、雨水花园、河流走廊和城市林地等可渗透的地表，在降雨或洪水到来时可以有效地吸收和储存雨水，植被的冠层和根茎也可以拦截地表径流[27][28]，从而在场地、社区和流域范围内减少径流和洪峰流量[29]~[31]。在设施个体层面上，下凹绿地和更健康或更密集的植被可以更有效地拦截和储存雨水径流[25][32]。在景

3.2 Analysis of Key Fields of Functioning

3.2.1 Enhance Resilience to Floods

Global climate change is closely related to fluctuations of precipitation and flood events. According to the estimation by World Resources Institutes, globally 758 million people will be exposed in 100-year flood zones by 2030[23][24]. In addition, urban waterlogging caused by heavy rainfall or continuous precipitation has resulted in severe loss of life and property in many cities worldwide every year[25][26]. Coping with flood and waterlogging risks has long been critical to urban sustainability.

(1) Reduce flood impact through interception and absorption of rainwater

A number of studies prove that the permeable surface such as detention ponds, permeable pavement, rain garden, river corridor, and urban woodland can effectively absorb and store rainwater, and vegetation canopy and roots can help with runoff retention[27][28], reducing runoff and flood peak flow at site, community, and watershed scales[29]~[31]. For individual BGI measures, sunken green spaces and healthier or denser vegetation can more effectively detain and store rainwater runoff[25][32]. At landscape scale, spatial configurations of landscape (i.e. the size, shape, isolation, and connectivity) potentially impacts runoff reduction: larger,

观尺度上，景观格局（大小、形状或空间排列）对减少径流有潜在的影响，较大的、连接性更强的BGI格局可能会降低平均年径流峰值[29]。一项针对广州和深圳的研究发现，当流域内BGI的比例分别为24.4%和72.1%，斑块面积分别为1.9hm^{2}和2.8hm^{2}时，缓解内涝的效率达到最大，意味着在土地紧张的都市区，可通过研究BGI对内涝作用的规模阈值来避免资源浪费[25]。

（2）提供集中式雨水基础设施的可替代方案

引入分散式、模块化的BGI能够减少城市对集中式雨水基础设施的依赖。随着暴雨强度的增加，部分BGI措施对径流消减的表现是不稳定的，而综合配置不同类型的BGI措施能够提供相对可靠的性能保障[32]。模拟研究显示，在单次强度较大的暴雨事件中，综合性的BGI配置对社区尺度上的总径流减少率可达到85.0%~100%，峰值流量减少率达到92.8%~100%[27]。对于城市整体排水系统来说，将灰绿基础设施结合使用可使其不容易发生灾难性故障，更易于应对气候的变化和不确定性[15][16][33]。研究发现，不同的BGI措施在影响下水道洪水和合流制下水道溢流的规模和持续时间方面表现出差异化的空间自相关和集聚特征[34]，说明规划BGI时需要考虑它们与原有排水设施在空间上的联合效性。

（3）作为灾后庇护所与社会—生态系统衔接

社会系统恢复方面，历史灾害事件证明，公共绿地和广场等公共开放空间可以作为救援和庇护的主要场所，为灾后需要恢复的灾民提供基本的生命支持和适应性响应条件[35]。一些研究指出，易涝区的保留空地有潜力被转化为野生动物栖息地和人类娱乐活动空间[35][36]；在规划设计中要考虑到这些BGI能够提供的多样化服务，兼顾应急管理和恢复与城市日常生活的需要[35]；最关键的是，它们必须与社会—生态系统紧密相连，建立服务流能够迅速到达的网络，以加强两个系统之间的反馈[22]。

3.2.2 促进应对海平面上升的韧性

研究预测至2050年世界上将有约71%的人口居住在低海拔沿海地区[37]。气候变化与海平面上升引发的洪水、海啸、风暴潮等极端天气事件及对生态系统和社会经济系统的间接影响，已经给全世界的沿海地区带来了极大的危害和风险[38][39]，采取有效策略来减轻自然灾害和提高沿海地区的韧性刻不容缓。

less fragmented, and more connected BGI patterns likely to mediate the average annual peak runoff[29]. For example, a study on Guangzhou and Shenzhen found that when the area proportion of BGI at watershed scale is 24.4% and 72.1%, and the area of BGI patches is 1.9 hm^2 and 2.8 hm^2, respectively for the two cities, the mitigation effect of urban waterlogging would reach the maximum. It means that in metropolitan areas with land shortage problems, land resource waste can be avoided by analyzing the size threshold of BGI effectiveness on waterlogging[25].

(2) Provide alternatives to centralized stormwater infrastructure

The introduction of decentralized, modularized BGI can reduce the city's reliance on centralized stormwater infrastructure. However, as the intensity of the storm increases, the performance of some BGI measures on runoff reduction will become unstable. Diversified configuration of different BGI measures can enhance the overall performance[32]. Simulation research shows that in single intensive storm events, integrated BGI configuration can reduce the total runoff at community scale by 85.0% to 100% and peak flow by 92.8% to 100%[27]. Furthermore, for the overall urban drainage system, the combination of grey and green infrastructures can make the city less vulnerable to catastrophic failures and easier to cope with climate change and uncertainties[15][16][33]. Research reveals that different BGI measures present differences in spatial autocorrelation and spatial cluster results in terms of the magnitude and duration of sewer flooding and combined sewer overflows[34], demonstrating the need to consider their spatial co-efficiency with the original drainage facilities in BGI planning cases.

(3) As post-disaster shelters to connect with socio-ecological systems

From the perspective of social system recovery, past disaster events evidence that public green space, squares, and other public open spaces have significant potential to contribute to disaster management as shelters to rescue and agents of recovery, and to provide essential life support and adaptive response[35]. In addition, some studies emphasize that reserved open spaces as flood prone areas can be potentially converted to public open spaces promoting wildlife habitat and recreational activities[35][36]. Moreover, planning and design of BGI as public open spaces should consider the diversity of the services that these BGI can provide, balancing the needs of emergency management and recovery as well as the daily urban life[35]. Most importantly, BGI must be closely linked to the socio-ecological systems by building a network of service flows so that the feedback between the two systems can be strengthened[22].

3.2.2 Enhance Resilience to Sea-level Rise

It is predicted that the population living in the low elevation coastal zone will increase to 71% by 2050[37]. However, extreme weather events caused by climate change and sea-level rise (including floods, tsunamis, and storm surges) and their indirect impacts on ecosystems and socioeconomic systems have brought huge hazards and risks to coastal regions all over the world[38][39]. It is imperative to adopt effective strategies to mitigate natural disasters and improve the resilience of coastal areas.

（1）作为海岸缓冲带抵御海啸、风暴潮等冲击

田野调查和数值模拟研究发现，包括沿海树木、红树林、湿地、草场、盐沼等在内的沿海植被可以减轻海岸侵蚀并稳定海岸线[40]。其中，沿海树木和红树林因其对极端海浪的衰减作用而广为人知。树林在水流方向的长度，树木枝干的粗细、密度和根系结构，以及树下的灌木丛是减少海啸能量的重要因素[41][42]。由于密集的树冠和树叶会大幅减少湍流能量，沿海森林还可以在飓风来临时提供一定的屏障作用[43]~[45]。湿地对浪涌的衰减率因湿地类型、风速、风暴压力、海拔、周围景观、水体连通性和植被而异[43][46]~[49]。对于中度的海平面上升率，建设海草草场将有效减弱海平面上升对防波堤倾覆的影响[50]。另外，沿海植被（如红树林和盐沼）可通过捕获和保留沉积物缓解海岸线因海平面上升带来的退化，且与单一物种相比，不同根部结构的物种组合或能导致更高的沉积效率[40][51]~[53]。

（2）提供沿海工程防护措施的可替代方案

植物的减灾潜力也可能随时间发生退化（自疏导致群落密度下降、树冠高度超过海啸深度等），因此需要通过如引入异质性的森林来增加海岸生态系统对抗冲击的冗余度[41][54]。同时，BGI也存在一些空间局限性，例如，研究观察发现，海水必须穿过4~60km的湿地，才能实现1m的浪涌衰减[49]；它们大幅减少风暴潮的能力还有待验证。越来越多的海岸保护项目将生态解决方案（BGI）与工程结构（灰色基础设施）相结合来减轻极端天气事件的影响[55]~[58]，尤其常见于那些没有足够海岸空间的沿海城市。

（3）为逃生争取时间和提供帮助

在社会系统响应方面，沿海植被在极端自然事件中可作为缓冲，具有延长避灾时间的巨大潜力，因此应该保留居民点前方的缓冲植被区，如枝叶茂密、根系发达的红树林[59]。相反，在居民点后方保留密集的植被会增加建筑物的损坏和人身伤亡，但可以种植一些树枝直径较大的低矮的阔叶树种，通过拦截房屋等损毁后产生的碎片减少冲击带来的二次伤害，并为人们提供可供攀登支撑物和软着陆的逃生空间[41][42][60]。

3.2.3 促进应对高温热浪的韧性

近年来，全球气候变化增加了极端高温事件的频率、强度、规模和持续时间[61]，而预测的极端温度在城市热岛效应的影响下被进一步放大[62]，热应力已成为一种公认的城市气候风险[63]。

(1) As coastal buffers against tsunamis and storm surges

Studies with field observations and mathematical/numerical models found that coastal vegetation, including coastal trees, mangroves, wetlands, seagrasses, and salt marshes, can mitigate coastal erosion and stabilize shorelines[40]. Specifically, coastal trees and mangroves are well known for their attenuating effect on extreme waves. The length of a forest in the streamwise direction, the size and density of trees, and the undergrowth are critical factors to tsunami energy reduction[41][42]. As dense canopies and foliage can cause the energy loss of turbulent flows, coastal forests can substantially reduce damage during hurricanes through wind attenuation[43]~[45]. Research suggests the exact rate of wetlands on wave attenuation varies by wetland type, wind speed, storm forcing, elevation, the surrounding landscape, waterbody connectivity, and vegetation[43][46]~[49]. For coastal areas of moderate sea level rise rates, the use of seagrass meadows would be effective to attenuate breakwater overtopping[50]. Research also evidences that coastal vegetation, including mangroves and salt marshes, would counteract sea level rise by trapping and retaining sediments, and a mix of species would yield a higher efficiency of sedimentation than using one species alone[40][51]~[53].

(2) Provide alternatives to coastal engineering protection measures

Since the mitigation potential of coastal vegetation declines with age due to self-thinning (decreased density) or tree crown height exceeds the tsunami water depth, there is a need to increase the redundancy of coastal ecosystems against shocks by, for example, introducing heterogeneous forests[41][54]. Additionally, BGI also has requirements on spatial conditions. For instance, studies found that the range of surge attenuation rates of wetlands is 1 m per 60 km to 1 m per 4 km[49], suggesting that coastal wetlands' ability to significantly reduce the energy of storm surges is still not clear. Nevertheless, more and more coastal protection projects combine ecological solutions (BGI) with engineering structures (grey infrastructure) to mitigate the impact of extreme weather events[55]~[58], especially in cities with limited shores spaces.

(3) As aids for disaster evacuation

In terms of social system response, coastal vegetation, as bioshields during extreme natural events, demonstrates its great potential in extending disaster avoidance time. Therefore, vegetation buffers (e.g. mangroves with dense foliage and roots) in front of human settlements should be reserved[59]. In contrast, keeping dense vegetation behind settlements would endanger human lives and increase structure damages. Research also proves that vegetation, especially low broad-leaved trees with large diameter branches, can reduce the secondary damage from disasters by trapping building debris, and help people escape, climb, and make soft landings[41][42][60].

3.2.3 Enhance Resilience to Heat Waves

In recent years, adverse trends in the frequency, intensity, geographical, and temporal spread of extreme heat caused by global climate change have already been observed[61], and the predicted extreme temperatures are magnified due to the urban heat island effect[62]. Heat stress is now an accepted urban climate risk[63].

（1）通过蒸发、蒸腾和遮蔽提供降温效应，缓解热应力

世界各地都发现植被和水体对缓解城市热岛效应、解决城市过热问题有积极影响[64][65]。城市中的BGI主要通过水面的蒸发、植被的蒸腾和遮蔽作用来改变城市地表的热通量，进而影响城市的小气候[66]。在不同的气候区和城市背景下，树冠下的环境温度要比非树冠下低0.7~5℃[63][67][68]。另一实证研究结合荟萃分析显示，城市公园能使公园内白天和夜间的平均温度分别降低0.94℃和1.15℃[69]。BGI不仅本身形成城市"冷岛"，还可以给周边一定范围的区域带来降温的效果[70][71]。有研究表明，绿地的降温距离在白天和夜间分别可以水平延伸300m和200~300m[72]。

研究发现BGI的热环境调节作用与其覆土组成（类型和垂直结构）、配置（模式和形状）、绿量和养护水平（浇灌）紧密相关[6][27][73][74]。目前较为一致的结论是蓝绿空间的规模越大，调节作用越强，但超过某一阈值后其单位面积降温效率可能下降[75][76]。一项针对香港城市典型街区的模拟研究发现，当树木覆盖率达到20%~30%时可获得最佳降温效率[77]。在珠江三角洲城市案例中，水体斑块大小的降温效率阈值在低、中、高三种社会经济发展背景下分别为0.49hm^2、0.55hm^{2}和0.70hm^2[78]。对比不同植被类型／群落结构的绿地，发现以树木为主的绿地在夏季降温或冬季增温量／距离都优于以草地为主的绿地[75]。另外，BGI的区位、周边的建成环境和背景气象条件也是不可忽视的影响因素，如，公园、河流和湖泊的下风向地区比上风向地区的降温作用更加显著[71][79][80]。

（2）提供降温措施可替代方案

多种类型的BGI降温措施能够产生互补或协同增益的效果。例如，公园中开阔的草地在白天可能会因接受了大量的太阳辐射而抵消其蒸腾散热的效果[81][82]，此时可以结合喷泉等景观水体的布置来增加地表的显热转换，降低环境温度[83]；再如，有研究发现滨水林地的空气降温幅度要比单纯的林地和水域降温的总和高[80]。BGI虽然有巨大的降温潜力，但也存在一些局限：例如，夜晚可能变成"热岛"[84]，植被在过高的温度下会因叶片气孔关闭失去效力，排放植物源挥发性有机物造成空气污染[85]，因此需要和其他降温措施结合使用。

(1) Provide cooling effect and relieve heat stress through evaporation, transpiration, and shading

It has been found worldwide that vegetation and water bodies contribute to alleviating urban heat island effect and urban overheating[64][65]. BGI affects urban microclimate by changing the heat flux of urban surface mainly through evaporating of water bodies, as well as transpiration and shading of vegetation[66]. Simulations for various urban contexts of different geo-climate zones report that the observed reduction in ambient temperature beneath tree canopy ranges from 0.7 °C to 5 °C[63][67][68]. A meta-analysis on the cooling effect of parks shows that, on average, a park was 0.94 °C cooler in the day, and 1.15 °C at night[69]. BGI not only can serve as an urban "cold island," but also brings cooling effect to a certain area around it[70][71]. In addition, a study has the cooling effect exceeded 300 m from the edge of the green area during the day and reached 200 ~ 300 m during the night[72].

Furthermore, studies have suggested that the thermal regulation effect of BGI is closely related to its land cover composition (type and vertical structure), configuration (pattern and shape), vegetation quantity, and maintenance level (irrigation)[6][27][73][74]. It is accepted that the larger the size of the blue-green space, the stronger its regulating effect, but there may be a threshold value of efficiency (TVoEs) above which its cooling efficiency per unit area may decrease[75][76]. For example, a simulation study on typical urban neighborhoods in Hong Kong reveals that when tree coverage ratio reaches 20% to 30%, the optimal cooling efficiency of trees were achieved[77]. In another study case on cities in the Pearl River Delta, TVoEs of water body patch size were 0.49 hm^2, 0.55 hm^2, and 0.70 hm^2 in levels of local socioeconomic development as low, medium, and high, respectively[78]. Comparing green spaces with different vegetation types/community structures, it was found that tree-dominated green spaces outperformed grass-dominated green spaces in terms of the magnitude and distance of cooling in summer or warming in winter[75]. The cooling effect of BGI is also affected by factors such as location, surrounding built environment, and local meteorological conditions. For instance, downwind areas of parks, rivers, and lakes can obtain more cooling benefits than upwind areas[71][79][80].

(2) Provide alternatives to cooling measures

Multiple types of BGI cooling measures can lead to complementary or synergic benefits. For example, open grassed areas in parks may receive a large amount of solar radiation during the daytime that may offset its cooling effect through transpiration[81][82], where the sensible heat conversion can be increased by combining with waterscapes (e.g. fountains) to decrease the air temperature[83]. A study found that the air temperature reduction of a waterfront forest was higher than the sum of the separate forest and water terms in the daytime[80]. Meanwhile, BGI sees drawbacks despite its outstanding cooling potential. For example, BGI would become a "heat island" at night[84]; during extreme temperatures, the cooling effect of vegetation would decrease due to the stomatal closure of leaves, and the emission of BVOCs (biogenic volatile organic compounds) of vegetation would resulting in air pollution[85]. Hence, other cooling measures need to be used in combination with BGI.

（3）提供躲避高温热浪的凉爽环境

具有开放空间属性的BGI是城市高温热浪天气中优秀的庇护所，使游人得到从生理到心理的恢复并最终适应外部环境[64][86]。热舒适和环境行为学调查发现，这些庇护场所需要提供多样的微气候环境，如同时具备开放的、阳光直射、半阴和阴凉的场地，以适应不同的使用需求和变化的气候条件[87][88]。在规划层面，应该同时考虑BGI场所的可达性和可获得性，从公平和可持续的角度优化设施布局[89][90]。

4 BGI在应用中面临的问题与对策

尽管BGI在促进城市气候韧性方面具有巨大的潜力，近年来，部分学者开展了针对性研究来分析BGI作为一种NBSs在适应气候变化方面的适用性以及未来所面临的挑战，也指出其在实际应用中尚存在诸多问题。

4.1 现存问题

4.1.1 BGI的作用原理缺少足够的数据支撑

不管是基于实测数据还是模型推演，目前对于BGI的气候韧性作用的认知大多基于离散的个案。考虑到地方差异及气候变化的不确定性，积累多样化的地方案例仍然是分析BGI的作用原理的一项重要前提。当前学界对提升BGI系统内在干扰抵御力上较为关注，但其中普遍存在高估BGI的生物—物理能力的现象，这一问题也需要引起足够的重视。在气候韧性构建中，BGI的独立作用是有限的，且其效果取决于干扰强度，设施数量、位置、材料，以及使用模式等[91]–[93]。尽管将不同措施结合使用能够更好地保障系统安全，然而，如何确定不同设施的数量及搭配方案，以使系统功能冗余的程度满足平衡城市安全和经济的需求还缺乏更多的数据支持。

另外，评估城市韧性不仅要考察系统受到干扰后功能的损失情况，也要考察系统功能恢复的速度。BGI的自适应、自组织特性与系统功能的恢复之间是否存在关联，能否为缩短系统功能恢复到稳定状态的时间做出贡献，也需要进一步的实证研究。

4.1.2 缺乏生态—社会—经济综合效益评估

虽然BGI解决方案具有多功能性的优势，但相关研究和实践多基于单一效益视角[16]，这种情况将会影响投资者对BGI的理解，并最终影响投资决策。已有不少学者关注到BGI应对部分气候危害的目标具有潜在

(3) As cooler environment to escape from heat waves

As open spaces, BGIs are urban shelters against heat waves that can strengthen visitors' physical and mental resilience, until being adapted to local hot and dry conditions[64][86]. Studies on thermal comfort and environmental behavior found that such shelter places need to provide diverse microclimatic conditions—open, sun exposed, sheltered, and shady spaces—to adapt to different usage needs and changing climatic conditions[87][88]. Consequently, the accessibility and availability of BGI should be considered to optimize spatial layout from the perspective of equity and sustainability in planning practice[89][90].

4 Problems and Countermeasures in the Application of BGI

Despite the great potential of BGI in promoting urban climate resilience, some scholars have conducted studies in recent years to analyze the applicability and future challenges of BGI as an NBS in climate change adaptation, and pointed out that there still exiting many problems in its application.

4.1 Existing Problems

4.1.1 Lack of Data Support to BGI Functioning Mechanism

Current knowledge about the role of climate resilience of BGI, whether with measured data or through model simulation, is mostly acquired from discrete individual cases. Considering local differences and the uncertainty of climate change, the accumulation of diverse local cases remains an important prerequisite for analyzing the functioning mechanism of BGI. The current academia pays more attention to improving the internal disturbance resistance of BGI systems, but the common overestimation of their biology-physical capability to be addressed with future efforts. Furthermore, the contribution of individual BGI measures to climate resilience building is limited, and the effectiveness is determined by the intensity of disturbance and the amount, location, material, and use pattern of specific measures[91]–[93]. While combining different measures can better ensure the security of the systems, the related data is still insufficient to inform detailed configuration schemes that support functional redundancy to balance the needs for urban security and economic growth.

Furthermore, the assessment of urban resilience should examine not only the loss of system function after disturbance, but also the recovery speed of the system function. Further empirical research is required on whether there is a correlation between the adaptive and self-organizing characteristics of BGI and the recovery of system function, and on whether it can contribute to accelerate this recovery.

4.1.2 Lack of Comprehensive Assessment on Ecological, Social, and Economic Benefits

Although BGI solutions hold the advantage in multi-functionality, it is frequently researched and implemented from the perspective of a single benefit[16], which would affect investors' understanding and decisions on multi-functional BGI

的协同和权衡关系[94]，但多数限于生态环境方面，如洪水和热岛效应缓解[95]、空气质量提升和碳固存[96]等，鲜有结合经济和社会视角的讨论。一方面，BGI的社会生态效益在指标选取和衡量标准设定上存在重大困难[97][98]，这些效益难以货币化、具有高度不确定性，或需要长期观察来评估[99]；另一方面，目前还比较缺乏对BGI战略中的公平和利益相关者参与议题的研究讨论[96][100]，尚无法准确界定利益主体和主体间的利益矛盾，导致相关评估脱离于现实。

4.1.3 难以取得决策者和公众对BGI解决方案的信任

相对于技术上的挑战，社会和政治制度或许是在气候变化适应背景下推行BGI解决方案面临的更大障碍[101][102]。一些社会性调查发现，自然风险暴露地区的民众认为BGI这类NBSs在降低风险方面的效果不如传统的技术解决方案[103][104]。这种信心的缺乏除了来自于他们对风险管理技术和工程方面不确定性的担忧，更多的是出于对此类项目是否能够在多个机构之间取得协调、在广泛的地区得到实施和持久性维护的怀疑[105]。这种情况下，单纯依靠教育宣传或经济激励的手段显然不能从根本上赢得决策者和公众的支持。

4.2 应对策略

4.2.1 基于系统视角开展多维度研究

面对复杂的城市系统，未来研究需要从对单一干预措施的绩效评估拓展到考虑要素与要素（不同BGI措施）、系统与系统（如灰色基础设施与BGI）、系统与外部环境条件（如城市系统与气候变化）之间相互作用关系的整体性评价。建立系统性分析框架，将危害来源、潜在影响、城市系统中的具体干预措施，以及预期效果明确联系起来，从而为相关部门提供决策支持。

BGI是一类有生命的城市基础设施，也可以借鉴工程韧性中的相关评价方法，对BGI的韧性构建作用展开更多维度的研究。有研究基于韧性的四个特征——稳健性（robustness）、冗余性（redundancy）、快速性（rapidity）、资源性（resourcefulness）①——制定了适应洪水的绿色

① 稳健性是指系统（元素、系统或其他分析单元，下同）承受特定水平的压力而不遭受退化或丧失功能的强度或能力；冗余性表示系统在多大程度上存在可替代性，即在遭受干扰、退化或机能丧失时系统整体仍能不间断提供服务的能力；快速性代表系统及时完成优先事项和既定目标以控制损失、抵御后续干扰的能力；资源性指的是系统在面对重大干扰时识别问题、确定优先次序和调动资源的能力（来源：参考文献[106]）。

① Robustness refers to the strength or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function. Redundancy refers to the extent to which elements, systems, or other units of analysis exist that are substitutable, i.e., capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality. Rapidity is defined as the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption. Resourcefulness means the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some elements, systems, or other units of analysis (Source: Ref. [106]).

measures. Many scholars have focused on the potential synergies and trade-offs brought by BGI in responding to climate risks[94], most of which, however, center on ecological environmental benefits, such as flood and heat island effect mitigation[95], air quality improvement, and carbon sequestration[96], with few discussions from economic or social perspectives. That is because, on the one hand, there are significant difficulties in identifying appropriate indicators and metrics for the social–ecological benefits of BGI[97][98], which are difficult to monetize and of high uncertainty, or require long-term monitoring[99]; On the other hand, few studies considered issues of equity or stakeholder participation in the development of BGI strategies[96][100], and it is challenging to clearly define stakeholders and the conflicts among them, often leading to impractical existing assessment results.

4.1.3 Difficulty in Gaining Confidence From Decision-Makers and the Public in BGI Solutions

Rather than technical challenges, socio-political barriers may more significantly impact the implementation of BGI solutions in the climate change adaptation[101][102]. For example, some social surveys have found that nature-risk exposed residents prefer technical solutions over BGI, as a NBS, as the latter were perceived as less effective in reducing risks[103][104]. This lack of confidence comes from people's concerns about technological or engineering uncertainties in risk management, and largely, from doubts about whether such projects can be well coordinated across multiple agencies, implemented broadly, and maintained sustainably[105]. Under such circumstances, it is clear that the support of policy-makers and the public cannot be gained simply through educational or economic incentives.

4.2 Countermeasures

4.2.1 Encourage Multi-Perspective Systematic Research

In the face of complex urban systems, future research needs to expand from performance evaluation on single interventions to holistic evaluation that considers the interactions among elements (different BGI measures), systems (e.g. gray infrastructure and BGI), and systems and external environmental context (e.g. urban systems and climate change). The establishment of a systematic analytical framework that integrates hazard sources, potential impacts, specific interventions on urban systems, and expected effects is encouraged to better inform related decision-making.

BGI is living urban infrastructure. With reference to existing methods of engineering resilience evaluation, it is possible to make multi-perspective research on the role of BGI in resilience building. The "4Rs" in the concept of resilience—robustness, redundancy, rapidity, and resourcefulness①—have been used in scenario simulation studies to develop strategies of green infrastructure planning responding to flooding[22] and resilience improvement plan for natural disasters in a coastal area[107]. Resilience level is defined in a study as the ratio of the anticipated performance of recovery to the desired performance, which was used to establish an overall resilience system for communities[108]. Other scholars proposed a resilience

基础设施规划战略[22]，进行了针对沿海地区抗灾韧性提升的情景模拟[107]。有学者定义韧性水平为预期功能恢复与目标功能恢复的比值，以此来建立社区整体的韧性体系[108]。也有学者从全过程设计管理的角度提出了绿色基础设施的韧性设计范式，突出促进系统的自组织、自调节和学习演进能力[93]。多维度研究既要关注BGI系统在吸收冲击的过程中维持基本功能的内在力量，也应涉及从干扰中快速重组并恢复功能的能力，以及城市生态和社会系统方面在干扰后的响应、反馈和适应[93]。

4.2.2 面向共同利益开展评估研究

NBS是一种兼顾社会—经济—环境的可持续发展方式，分析、评价和展示NBSs的共同利益是一项复杂的挑战。鉴于BGI具备广泛效益的本质是其能够提供多样化的生态系统服务，因此未来可以将生态系统服务之间的协同和权衡关系与供需视角下的公平性研究相结合，建立一个涵盖多目标评价体系的综合规划模型，以审查在不同尺度和领域中BGI解决方案的潜在生态、社会和经济效益，促进具有共同利益的气候韧性行动。

4.2.3 基于韧性机制指导规划设计

从最大程度发挥BGI对气候韧性作用的角度，在规划设计时需在场地尺度上考虑个体BGI的面积、形态和不同的植物搭配对不同干扰的吸收能力，从邻里到区域尺度都需关注BGI规模影响与面积阈值效应。结构上应建立相互连接的BGI网络、规划合理的绿色枢纽和廊道以提高系统遭受干扰或冲击后的恢复效率，重视BGI在城市气候风险管理中的重要性。庇护场所应能提供多样化、灵活的空间以兼顾平时和灾时所需，且有良好的可达性，与其他灾害响应措施（如救济物资、灾害预警系统）和开放空间相连接，同时需综合考虑危害、暴露和社会脆弱性优化BGI布局。

4.2.4 创新体制建设适应实施管理

社会政治因素限制了BGI解决方案在提升城市气候韧性方面的应用，突破口可能在于对传统的城市治理和管理体制的创新和改革，包括明确部门间的职责，为发展当责制和集体责任制提供有利条件，调整激励措施，以及创新融资渠道和公私合作模式等。过往的经验表明，只有在对技术革新的认知、体制适应、规范准备和监管到位都满足的情况下，才有可能加快BGI解决方案的推广速度并实现BGI的预期效益。

design paradigm of urban green infrastructure from the perspective of whole-design-process management, highlighting the self-organization, self-adjustment, and evolution by learning of systems[93]. Multi-perspective research should focus on both the inherent power of systems to keep its basic functions in the process of absorbing disturbances, as well as the ability to rapidly reorganize and restore functions from disturbances, and the response, feedback, and adaptation of urban ecological and social systems after disturbances[93].

4.2.2 Conduct Assessments on Co-benefits

NBS is a means of sustainability with social, economic, and environmental benefits. It is challenging to analyze, evaluate, and demonstrate the co-benefits of NBSs. Given that the essence of BGI's multi-benefits is its ability to provide diverse ecosystem services, the synergies and trade-offs among ecosystem services can be combined with supply–demand equity studies, establishing a comprehensive planning model with a multi-objective evaluation system, which can examine the potential ecological, social, and economic benefits of BGI solutions at different scales and in varied domains, thereby encouraging climate resilience actions with co-benefits.

4.2.3 Plan and Design Based on Resilience Mechanism

In planning and design practice, to maximize the effect of BGI on climate resilience, the size and form of individual BGI measure and the absorption capacity of different plant combinations for different disturbances should be considered; The size impact and area threshold effect of BGI should be valued from neighborhood to regional scale; An interconnected BGI network and properly planned green hubs and corridors should be established to boost the recovery efficiency of systems after disturbance or attack, and highlight the critical role that BGI plays in urban climate risk management. By improving the accessibility and connections with other disaster response actions and resources (such as relief supplies and disaster warning systems) and open spaces, shelters should be able to provide diversified and flexible spaces to meet both daily life and disaster needs, while optimizing BGI layouts to address related hazards, exposure, and social vulnerability.

4.2.4 Establish Innovative Systems for BGI Implementation and Management

For the socio-political factors that limit the application of BGI solutions in improving urban climate resilience, innovations should be made to reform the traditional urban governance and management systems. Specific measures include clarifying the responsibilities of departments—providing favorable conditions for the development of accountability systems and collective responsibility systems, adjusting incentives, and introducing new funding sources and public–private partnership modes. Can BGI solutions be promoted at a faster pace to achieve expected benefits only if technological innovation, system reform, standard preparedness, and supervision measures are all in place.

5 结语

本文通过Citespace文献计量工具识别出BGI与气候变化相关领域的前沿主题，发现BGI对城市气候韧性的主要作用领域为应对城市洪涝、海平面上升和高温热浪风险。研究具体分析了BGI在这三个领域对城市气候韧性的作用，而BGI的生物—物理特性、与功能相似的其他基础设施组成模块化单元吸收遭受的干扰和冲击、依靠网络化结构帮助系统在干扰和冲击后尽快恢复物理功能和社会关系是BGI发挥韧性促进作用的共同机制。在具体应用中应考虑BGI的种类、规模、空间位置的综合影响，并根据不同的干扰类型、强度等来选择合适的BGI并进行相应的规划设计。此外，BGI的连接性、多样化和可达性也需要得到重点关注。

本文还分析了目前阻碍BGI解决方案推广的几个原因：BGI的作用原理还缺少足够的数据支撑、缺乏对生态—社会—经济综合利益评估，以及难以取得决策者和公众的信任。可能的应对策略包括以系统的、多维的角度和共同利益为目标开展机制与评估研究，从韧性的促进机制出发指导规划设计，并在体制上克服资金的限制、部门间和利益相关者合作等方面的障碍。

鉴于文献检索策略的原因，本文主要从实体系统方面讨论了BGI对构建城市气候韧性的贡献，并未涉及其在促进社会韧性方面的作用（如恢复性的绿化实践、灾后社区重建和心理恢复等），未来可加强对该方面的探索，为构建和提升城市整体的韧性提供更全面的科学依据。此外，研究只针对三类目前主要关注的气候灾害风险进行了分析，今后需要将空气污染、干旱和缺水、生物多样性和人类健康等其他相关议题纳入研究范畴，丰富人们对BGI作为构建气候韧性途径的理解。

未来城市的规模、人口和复杂性还将继续增长，城市对抗极端气候灾害的脆弱性也将随之增加，城市必须更迅速、更有效地做出响应以减少相关损失，构建与促进城市系统的气候韧性或将成为人类社会面对气候变化和一系列不确定挑战的有力武器。**LAF**

5 Conclusions

This paper uses CiteSpace to identify the cutting-edge topics about BGI and climate change, and finds that BGI helps enhance urban climate resilience in responding to urban floods, sea level rise, and high temperature and heat waves. The research specifically analyzes the role of BGI on urban climate resilience in these key fields of functioning, and summarizes that the common functioning mechanisms include the bio-physical properties of BGI, forming modular units with other infrastructures of similar functions, and the reliance on networked structures to help the system restore its physical functions and social connections as quickly as possible after disturbances and attacks. In practice, the type, size, and location of BGI should be carefully designed or selected based on the disturbance type, intensity, etc. Besides, the connectivity, diversity, and accessibility of BGI need to be valued as well.

This paper also analyzes possible obstacles that hinder the promotion of BGI solutions: the lack of data support to BGI functioning mechanism, the lack of comprehensive assessment on ecological-social-economic benefits, and the difficulty in gaining confidence from decision-makers and the public. Countermeasures may include conducting mechanism and evaluation research on co-benefits from a systematic, multi-dimensional perspective, guiding planning and design practices by exploring the resilience-enhancement mechanisms, introducing new funding methods, and facilitating collaboration across departments and stakeholders.

Subject to the data collection strategy, this paper mainly discusses the contribution of BGI to building urban climate resilience in terms of physical systems. Future research is expected to incorporate its role in promoting social resilience (e.g., restorative greening practice, post-disaster community reconstruction, and psychological recovery), so as to provide a more comprehensive and sounder basis for BGI solutions in building and improving the overall urban resilience. In addition, this research only discusses three types of climate disasters, issues such as air pollution, drought and water shortage, biodiversity, and human health need to be included in future studies to enrich public awareness on BGI as a pathway to enhancing climate resilience.

In future, cities will continue to grow in size, population, and complexity, which will increase their vulnerability to extreme climate hazards. It requires cities to respond to such risks more quickly and effectively to reduce losses. By building or strengthening climate resilience of urban systems, the human society will be better prepared for future climate change and other uncertainties. **LAF**

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