A lack of focus on data sharing, stakeholders, and economic benefits in current global green infrastructure planning

Tian Ruan [a, b, c], Jouni Paavola [d], Faith Ka Shun Chan [e, f], Yaoyang Xu [a, c, *], Chiara Baldacchini [g, h], Carlo Calfapietra [g]

[a] *Key Laboratory of Urban Environment and Health, Ningbo Observation and Research Station, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, Peoples R China*

[b] *University of Chinese Academy of Sciences, Beijing, 100049, Peoples R China*

[c] *Zhejiang Key Laboratory of Urban Environmental Processes and Pollution Control, CAS Haixi Industrial Technology Innovation Center in Beilun, Ningbo 315830, Peoples R China*

[d] *Centre for Climate Change Economics and Policy (CCCEP), School of Earth and Environment, University of Leeds, Leeds LS29JT, UK*

[e] *School of Geographical Sciences, University of Nottingham Ningbo China, Ningbo 315100, China*

[f] *Water@Leeds Research Institute, University of Leeds, Leeds LS29JT, UK*

[g] *Institute of Research on Terrestrial Ecosystem –National Research Council (IRET-CNR), I-05010 Porano, TR, Italy*

[h] *Department of Ecological and Biological Sciences (DEB), University of Tuscia, Viterbo 01100, Italy*

[*] *Corresponding author.*
E-mail addresses: yyxu@iue.ac.cn (Y. Xu).

Cite as: Ruan T, Paavola J, Chan F, Xu Y, Baldacchini C, Calfapietra C (2023) A lack of focus on data sharing, stakeholders, and economic benefits in current global green infrastructure planning. *Journal of Environmental Management*.

Abstract

Green infrastructure (GI) is increasingly popular in solving urban environmental challenges and enhancing ecosystem services. Yet the research status and challenges of GI planning have not been comprehensively benchmarked to date. We explored the GI types, actions, goals, and spatiotemporal characteristics of GI planning cases worldwide based on the available literature. The challenges of GI planning were also investigated by the cases included in this manuscript. Additionally, the urban governance solutions to address these challenges were proposed. We found that multi-type GI planning is the most popular. Data sharing, stakeholder participation, economic benefits and research funding for GI planning research were generally inadequate, although they have improved trend over time. Multiple-goal GI planning frequently has higher levels of data sharing, stakeholder participation and economic benefits than GI planning that just takes into account one purpose. We conclude that the future transformation of GI planning requires efficient data sharing mechanisms, effective co-design among stakeholders, systematic business models, and available research funding.

Keywords: Green infrastructure; Data sharing; Stakeholder; Economic benefits; Research funding; Transformation

1. Introduction

Green infrastructure (GI) is a long-standing concept, and its definition and connotations have diversified through continuous enrichment. In 1999, the US Conservation Foundation and the USDA Forest Service first defined GI as an interconnected network consisting of waterways, forests, greenways, parks and other protected areas that maintain the ecological environment and deliver quality of life for communities (Benedict et al., 2006). With the development of the concept of GI, many believe that GI refers to the strategic planning, creation and management of a network of interconnected green spaces, which can provide a range of social, ecological and economic benefits (Matthews et al., 2015; Tzoulas et al., 2007). Anthropogenic environmental pollution and large-scale construction of grey infrastructure have adversely affected green spaces and the ecosystem services they provide, with attendant threats to human well-being (Gashu and Gebre-Egziabher, 2019; Wang et al., 2018). GI is an important platform for providing interaction between human activities and natural systems, improving its service functions, which is a key measure for cities solving the social, economic, and environmental challenges of sustainable development (Grabowski et al., 2022; Tomson et al., 2021).

In the GI research, climate change mitigation is attracting increasing attention and there is a gradual shift towards climate adaptation strategies (Chan et al., 2021). Urban stormwater management has become one of the most important research topics, and ecosystem service enhancement strategies are also common in GI (Pace et al., 2021; Primmer and Paavola, 2021). Urban planners consider GI extensively already, but there are still challenges to overcome. Urban planners often design specific types of GI for specific goals. For instance, drainage systems were designed to manage floods, and green wastewater infrastructure was used to treat sewage (Hagen et al., 2017; La Rosa and Pappalardo, 2020). However, urban space is often limited, and single-purpose GI could be inefficient. Planning efficient GI in compact urban spaces requires multi-functionality. It is not a new concept (Hansen and Pauleit, 2014) as the research on the multi-functional GI was initiated a decade ago according to the EU Green Infrastructure Strategy (European Commission, 2013). However, the exploration of the challenges encountered in multi-functional GI planning has not yet been comprehensive. Multi-functionality seeks to combine several functions to make more effective use of the limited space and deliver multiple benefits to the society, ecology, and the economy (Tzoulas et al., 2007). Many believe that multi-functionality is key to the promotion of GI and that together with connectivity, should be a core element in GI planning (Zhang et al., 2019).

A well-thought-out GI planning approach is important for achieving urban sustainability (Kumar et al., 2022). Research on GI planning has focused on the theory of planning reform, innovation in planning methods and the impact of planning implementation, which has progressed with theory and practice in GI (Van Oijstaeijen et al., 2020). Most studies have drawn from a single case or a small number of cases to examine the theories, methods, and practices of GI planning (Wang et al., 2022). However, there are few studies based on a large number of GI planning cases and little comparative work exists worldwide. The global progress on case studies of GI planning, including the spatiotemporal characteristics, data sharing, stakeholder participation, economic benefits, and research funding, remains largely unknown. Data sharing can reduce the cost and improve the efficiency of GI planning (Alexander et al., 2019), while stakeholder participation enables more inclusive and equitable planning (O'Donnell et al., 2018). Achieving economic benefits is a powerful underpinning for the long-term development of GI (Melo et al., 2020), and access to funding can contribute to the accumulation and sharing of knowledge for GI planning research (Löfqvist and Ghazoul, 2019).

Given the above, this study sought to answer the following three questions: 1) What is the current status of research on GI planning? 2) What are the challenges of GI planning? 3) What are the potential solutions to these challenges? To answer the questions, we systematically sorted out the GI types, actions, and goals of GI planning in the existing literature, and discussed the spatiotemporal characteristics of GI planning cases. Then we analyzed the progress in GI planning, including the degree of data sharing and stakeholder participation, as well as economic benefits and research funding. We also identify the challenges of GI planning and propose a number of urban governance solutions to efficiently address GI challenges.

2. Material and Methods

2.1. Data collection

We searched the literature by using the term TS= ((“green infrastructure*” OR “blue infrastructure*” OR “nature-based solution*”) AND “urban planning”) in the core collection database of the *Web of Science*, and Timespan = (1900-01-01~2021-12-31). The search yielded 437 publications, the first of them appeared in 2000, describing a green infrastructure (GI) planning case in 1999. Therefore, our research covered 21 years (2000-2021) of articles. Only research articles (355) were selected for further analysis. Other publications, such as editorials and reviews, were excluded from this study due to the lack of GI planning cases.

Through reviewing the abstracts of 355 research articles, we found that planning theories, planning methods and planning cases make up most of the research. Articles on planning theory do not involve specific planning sites or types of GI but focus on theoretical innovation (Hansen and Pauleit, 2014). Planning method articles in turn focus on the testing of methods or construction of frameworks (Petrisor et al., 2021). The research of GI planning cases refers to the realization of a planning vision using specific types of GI at a specific planning site and may involve planning theory and methodological elaboration but not primarily (Kirk et al., 2021; Lehnert et al., 2021). In addition, the selected articles also included other analyses of for example planning policies and barriers (Feltynowski et al., 2018; William et al., 2017).

A total of 145 planning cases were identified from 125 research articles. After reading the full text of these 125 articles, the location (continent, country, city or region, latitude and longitude), the types of GI (e.g., forests, greenways, water, parks, green roofs and walls), the actions of GI (e.g., carbon sequestration, cooling, stormwater management, food supply, air purification, recreation, habitat protection), the year of GI planning (If not mentioned in the article, the publication year of the article was used instead) among these cases were recorded. In addition, the degree of data sharing, stakeholder participation, and economic benefits was assessed, as well as the sources of research funding (e.g., universities, municipalities, EU projects) were also recorded. The specific information on planning cases can be found in the Supplementary Materials.

2.2. Data classification

GI can range from regional-scale initiatives (e.g., forests, rivers and riverbanks around cities) to local-scale ones (e.g., green roofs, green walls or street trees) (Bartesaghi Koc et al., 2016; Rolf et al., 2019). Therefore, the elements that makeup GI can also be considered as types of GI (Grabowski et al., 2022; Hansen et al., 2015). Following the typology developed by Jones et al. for categorizing GI (Jones et al., 2022), we integrated the less common categories in the cases of this study to avoid redundancy (see typology in Supplementary Materials). We classified the GI in this study into "parks/gardens", "hybrid GI for water/water bodies", "linear features/routes", "constructed GI on infrastructure/amenity areas", "other non-sealed urban areas", "other public space", and "multi-type GI" (see Table 1 for definitions). The specific categories are shown in the Supplementary Materials.

Table 1 Types of green infrastructure and their definitions (Jones et al., 2022).

GI types	Definition
Gardens	Mainly private space linked to dwellings
Parks	Mainly public space, but some access restrictions may apply
Amenity areas	Areas designed primarily for specific amenity uses
Constructed GI on infrastructure	Constructed green and blue space, added to infrastructure
Other public space	Areas designed primarily for specific uses (not leisure); some access restrictions may apply
Linear features/routes	Linked to routeways, geographical features and boundaries
Hybrid GI for water	Infrastructure designed to incorporate some GI components
Water bodies	Blue space features
Other non-sealed urban areas	Other un-sealed features without specified use, often on private land
Multi-type GI	More than one type of GI

The key goals of GI were grouped into enhancing climate resilience, conserving biodiversity, and improving human well-being. GI planning with more than two goals was classified as multiple-goal GI planning. Actions to enhance climate resilience aimed at stormwater management and heat mitigation. Habitat construction, policy development, and scientific research were all actions taken to conserve biodiversity. Provisioning services (e.g., water supply, energy supply), cultural services (e.g., recreation) and regulating services (e.g., prevention of mosquito diseases and allergies) were actions for improving human well-being. The major actions to achieve multiple goals of GI planning include the development of models/frameworks, surveys, and public involvement. Developing models/frameworks facilitates the understanding of the complex interactions between various elements such as GI and urban development. Surveys help collect essential data, information and identify risks of multiple-goal GI planning. Public involvement ensures that the diversity of stakeholder perspectives and needs are taken into account to develop multiple-goal GI planning.

Data sharing, stakeholder participation and economic benefits were scored for each planning case: the degree of achievement was assessed to be 0, 1, 2, and 3 for inexistent, low-level, medium-level, and high-level respectively (see Supplementary Materials). The degree of data sharing was assessed in a range from none to high-level, if the study did not disclose the data, disclosed some of the data, disclosed all data with access restrictions, and disclosed all data for free. The closer the communication between stakeholders, the higher the score for stakeholder participation in this study. Stakeholder participation involves not just identification of relevant stakeholders but also successfully communicating with them (Ferreira et al., 2021; Hendricks et al., 2022). We evaluated the economic benefits of GI planning cases by considering the number of stakeholders who benefited from them. If the reported economic benefits involved 1, 2, and 3 or more categories of stakeholders, we assigned a score of 1, 2, and 3 to economic benefits, respectively. A score of 0 was assigned if the case did not report economic benefits or if the reported economic revenues were lower than costs. That is, we assess how widely the economic benefits are distributed rather than assess their magnitude.

The sources of research funding for GI planning case studies were categorized into 1) institutional funding (e.g., universities, research institutes, experimental centers), 2) private funding (e.g., companies, individuals, civil society), 3) public funding (e.g., municipal funding, national funds, EU programs), 4) combined funding (multiple sources) and 5) unfunded.

2.3. Summary statistics

Sankey diagrams were used to provide a visual summary of the data we collected. The summarized information includes GI types, goals of GI planning, and actions taken to achieve these goals in 145 GI planning cases. Sankey diagram has been widely used for visual analysis of multidimensional data, and it can clearly portray the classification of data and the connections between each pair of objects (Lupton and Allwood 2017). To explore the spatiotemporal characteristics of GI planning cases, a global map of GI planning cases was produced based on their locations and goals. The time trend maps were created based on GI planning time across different continents, goals, GI types, research funding sources, as well as the degree of data sharing, stakeholder participation and economic benefits. As there are relatively few planning cases from outside of Europe, the Americas and Asia, the global regions were analyzed in four main sections. The degree of data sharing, stakeholder engagement and economic benefits of the planning case studies were expressed in terms of the cumulative sum of the scores assigned.

To better understand the overall characteristics of GI planning research, a radar bar chart was produced to characterize the number of cases with different goals (enhancing climate resilience, conserving biodiversity, improving human well-being and multiple goals) in terms of data sharing, stakeholder participation, economic benefits, and research funding sources. Stacked area maps were developed to illustrate the differences in data sharing, stakeholder participation and economic benefits under different funding sources for GI planning research.

Four additional radar bar charts were generated to provide more detailed information on the analysis of GI planning for different goals. This specifically includes case information on actions for GI planning to enhance climate resilience (stormwater management, heat mitigation, carbon sequestration), actions to conserve biodiversity (habitat construction, policy development and scientific research), actions of enhancement of human well-being (provisioning services, cultural services and regulating services) and actions to achieve multiple goals (developing models/frameworks, surveys, and public involvement). To conclude, we outlined solutions for the transition of GI planning alongside a summary of the GI planning cases we reviewed. This summary diagram consists of three parts: 1) the research status of GI planning presented by the Sankey diagram, 2) the GI planning challenges shown by the bar charts, and 3) the corresponding proposed solutions for each challenge.

3. Results

3.1. GI planning characteristics

The majority (32%) of cases involved "multi-type GI" planning, followed by "other non-sealed urban areas" (21%), and "hybrid GI for water/water bodies" (17%) (Fig. 1). "Hybrid GI for water/water bodies" were primarily used for stormwater management, while "linear features/routes", and "parks/gardens" were mainly implemented for heat mitigation. Only "other non-sealed urban areas" involve conserving biodiversity through policy development. Biodiversity conservation in "constructed GI on infrastructure/amenity areas", "linear features/routes", "parks/gardens", and "hybrid GI for water/water bodies" was still at the stage of scientific research. In terms of the actions in the cases, "constructed GI on infrastructure/amenity areas", "other non-sealed urban areas", and "multi-type GI" could provide regulating services, while "linear features/routes", "parks/gardens", and "hybrid GI for water/water bodies" enable provisioning and cultural services. More than half of the "multi-type GI" planning cases were tested and shown to achieve multiple goals. GI planning with multiple goals (34%) was more frequently used than enhancing climate resilience (28%), conserving biodiversity (17%), and improving human well-being (20%).

GI planning cases were distributed across all continents except Antarctica. Western Europe and Eastern North America accounted for 73% of the cases worldwide (Fig. 2). Asia, particularly in eastern Asia, comes in second at 12%. South America, Oceania, and Africa had the fewest GI planning cases overall. While planning cases with multiple goals were primarily found in Europe and North America, cases for enhancing climate resilience, conserving biodiversity, and improving human well-being existed in all continents.

The timeline of 145 GI planning cases revealed that North America pioneered GI planning in the 1990s and continues to work on GI planning research (Fig. 3a). Research on GI planning started in Europe around 2000 and became a core research stream on GI planning. Scholars started researching GI planning in Asia and other continents around 2015 (Fig. 3a). Research on GI planning with multiple goals started early and began to drop after peaking in 2019. Since 2018, the number of case studies on enhancing climate resilience and improving human well-being has gradually increased (Fig. 3b). The degree of data sharing, stakeholder participation and economic benefit in GI planning research was all on the rise over time (Fig. 3c). GI planning research initially received minimal financing, but since 2014, public and institutional funding has taken the lead, with unfunded research swinging upward (Fig. 3d). While planning for all GI types has fluctuated throughout time, planning for multi-type GI has been a prominent area of research (Fig. 3e).

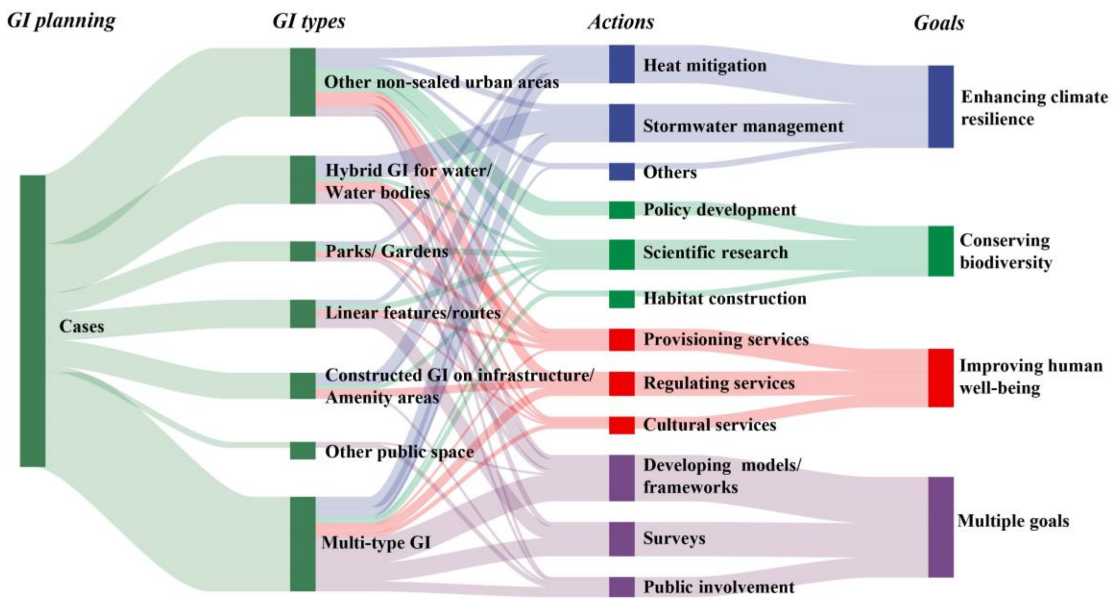

Fig. 1. Sankey diagram of green infrastructure planning research

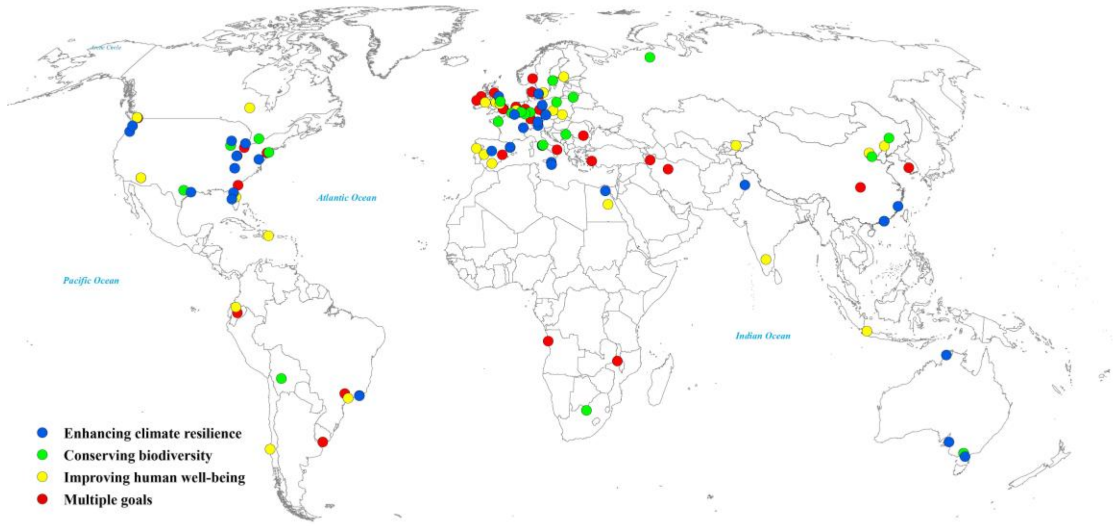

Fig. 2. Spatial distribution of green infrastructure planning cases.

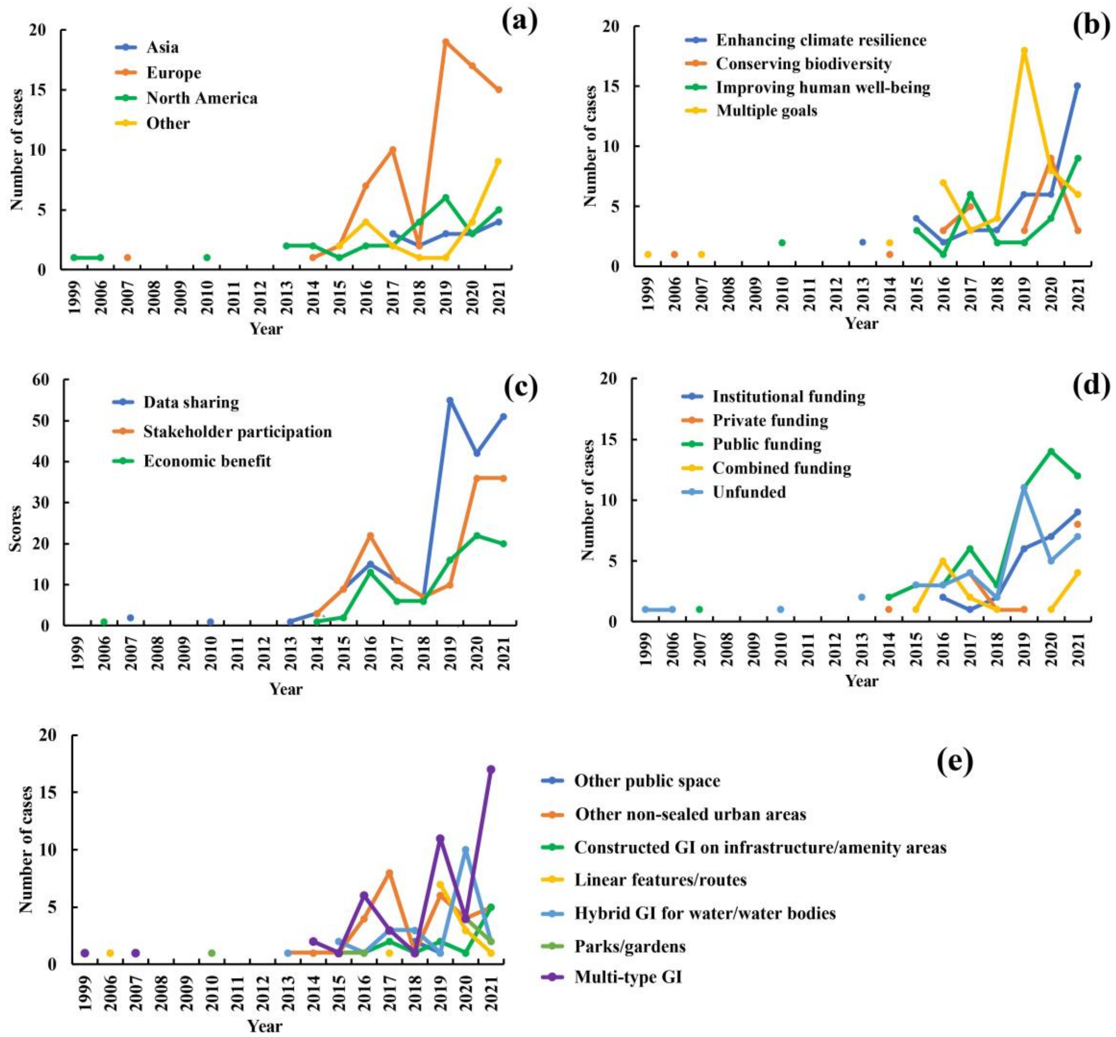

Fig. 3. Temporal trends of green infrastructure planning cases. (a: region; b: goals; c: the realization degrees of data sharing, stakeholder participation and economic benefit; d: sources of research funding; and e: GI types)

3.2. Data sharing and stakeholder participation

Data sharing occurred in 65% of the 145 GI planning cases, but only 29% of them involved high-level data sharing (Fig. 4a). Data sharing occurred in over 60% of case studies for enhancing climate resilience and improving human well-being, but high-level data sharing was involved in only 20% of the cases (Fig. 4b and c). The proportion of data sharing in biodiversity conservation cases was the lowest (40%), but among them, cases involving habitat construction all contained data sharing (Fig. 4d). The multiple-goal GI planning case study had the largest proportion (80%) of data sharing and 42% of cases involved high-level data sharing. All cases where multiple goals were achieved through public involvement shared data (Fig. 4e).

Stakeholder participation in GI planning was weak overall. No stakeholders were involved in 60% of GI planning cases (Fig. 4a). Although stakeholder interests were taken into account in half of the multiple-goal GI planning cases, high-level stakeholder participation occurred in just 28% of these cases (Fig. 4e). Stakeholder participation for other GI goals was poorer: stakeholder views were considered in around 35% of the cases and high-level stakeholder engagement was involved in less than 20% of the cases (Fig. 4a). Only 5% and 10% of the planning cases for stormwater management and heat mitigation involved high-level stakeholder engagement (Fig. 4b). High-level stakeholder participation in policy development and habitat construction was absent for biodiversity conservation cases (Fig. 4d).

3.3. Economic benefits and research funding

Economic benefits were not generated or considered in 63% of the 145 cases of GI planning (Fig. 4a). But 46% of the multiple-goal GI planning cases involved some economic benefits, although less than 10% of the cases involved wide economic benefits (Fig. 4e). Less than 30% of GI planning cases for enhancing climate resilience and improving human well-being provided economic benefits, especially cases for enhancing human well-being through cultural services omitted mention of economic benefits (Fig. 4b and c). Around 44% of biodiversity conservation cases involved economic benefits, but none of them involved widely shared benefits (Fig. 4d).

GI planning research with public funding (39%) and institutional funding (18%) involved a higher degree of data sharing, but studies with combined funding (10%) involved greater stakeholder participation (Fig. 4f). Poor levels of data sharing and stakeholder participation and limited economic benefits characterized cases that received only private funding (5%) or were unfunded (28%). Less than 15% of the unfunded studies involved data sharing, stakeholder participation and economic benefits, and all were only partially realized. In the case of planning for improved climate resilience, there were no privately sponsored studies, and in the case of privately funded planning, there was limited stakeholder participation (Fig. 4f). Research on GI planning for improving human well-being through regulating services, conserving biodiversity through habitat construction, and achieving multiple goals through public involvement were all funded (Fig. 4c, d, and e).

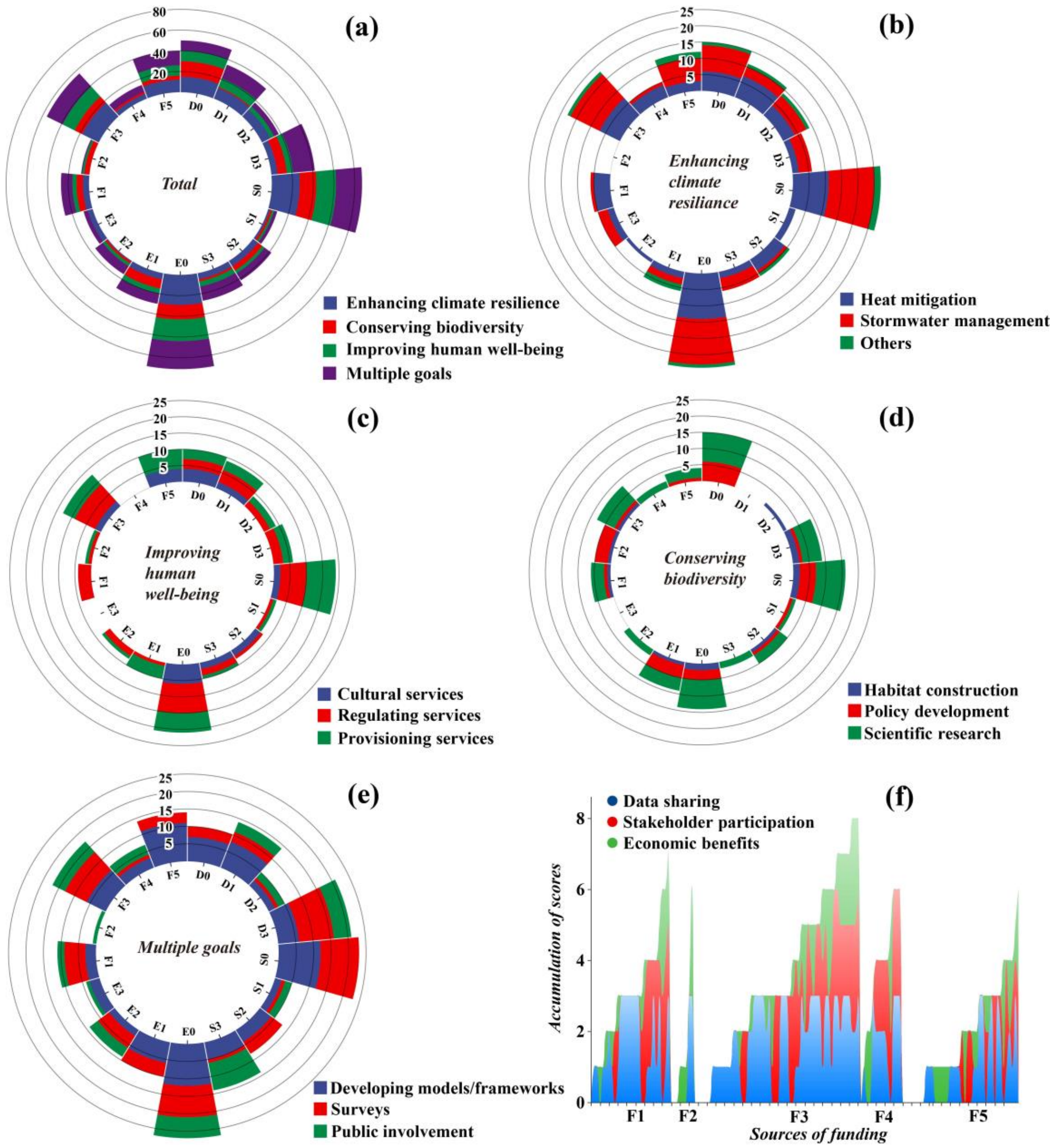

Fig. 4. General characteristics of GI planning (a), GI planning for different goals (b, c, d, e) and research funding (f). (D0-D3, S0-S3, and E0-E3 indicate data sharing, stakeholder participation, and economic benefits from none, low-level, medium-level to high-level respectively. F1-F5 indicate institutional funding, private funding, public funding, combined funding and unfunded, and the numbers in the figure indicate the number of GI planning cases.)

4. Discussion

A summary of research results and proposed solutions for the future transformation of GI planning is provided in Fig. 5. The summary diagram consists of three parts (Fig. 5): 1) the research status on GI planning. The research status was presented by a Sankey diagram that includes the types of GI, the related actions, and the ultimate goals achieved involved in the planning cases; 2) the challenges of GI planning. The challenges were analyzed and summarized through data sharing, stakeholder participation, economic benefits, and research funding of GI planning cases; and 3) solutions. Solutions were proposed for each of the four major challenges of GI planning identified in the study to provide ideas for future GI planning.

4.1 Research status

"Multi-type GI" was typically applied to achieve multiple goals (Fig. 5a). Probably because "multi-type GI" is more effective than a single one, whether in terms of water management or cooling, planners are more inclined to use "multi-type GI" to deal with environmental issues (Mazhar et al., 2015; Myint et al., 2017). "Other non-sealed urban areas" and "hybrid GI for water/water bodies" were the most popular GI types (Fig. 5a). The former might be popular due to its high potential for ecological restoration and the simplicity of implementation (Angelstam et al., 2020; Bonilla-Duarte et al., 2021). The popularity of "hybrid GI for water/water bodies" may in turn be due to the frequency of flooding caused by climate change and urbanization, which makes water management increasingly urgent (La Rosa and Pappalardo, 2020).

The key goal of GI was to enhance climate resilience (Fig. 5a), as humans need to address life-threatening natural disasters in changing climate (Li et al., 2019). Heat mitigation and stormwater management are key to enhancing climate resilience (Fig. 5a). Global warming and hard urban surfaces exacerbate urban heat, whereas GI is welcomed by city managers for its sustainable cooling effect (Sen and Khazanovich, 2021). Extreme rainfall causes flooding and poses a threat to human beings, while urban planners can manage urban stormwater by installing GI (Cuthbert et al., 2022).

Biodiversity conservation through scientific research became a preferred action (Fig. 5a). Science and technology have enhanced the efficiency of GI in protecting biodiversity, changing the way in which habitats were originally protected through isolation (Anderson and Minor, 2020). Provisioning and regulating services of GI were major actions to enhance human well-being (Fig. 5a). Primarily by providing food, energy, and water, controlling the spread of disease, and regulating mental health (Maes et al., 2021; Van Vuuren et al., 2019). There is a trend to develop models/frameworks to achieve multiple goals in GI planning (Fig. 5a). With the development of computer science, GI planning sets up multiple scenarios through modeling methods to select the optimal solution for multiple goals (Zhao et al., 2021).

4.2 Challenges

GI planning is challenged by low-level of data sharing, inadequate stakeholder participation, limited attention to economic benefits, and underfunded research (Fig. 5b). High-level data sharing occurred in only 29% of the GI planning case studies (Fig. 5b). The difficulty and cost of generating data may make data owners less willing to share (Alexander et al., 2019). And the data standards are not uniform, different urban green space datasets are based on different definitions, data sources, sampling techniques, periods and scales (Feltynowski et al., 2018). Some practices towards this have started in Europe, such as urban data-sharing platforms and nature-based solutions case-sharing websites, but the spatial and temporal scale of data is small and its scope is still limited (Bick et al., 2018).

The majority (60%) of GI planning cases did not involve stakeholder participation (Fig. 5b). First, the relevant stakeholders of GI planning are not clearly understood and identified (Guenat et al., 2021). Second, the responsibilities of stakeholders are not clearly defined: it is not understood which status the stakeholders have in the planning and what role they should play (Patra et al., 2021). Third, asymmetric communication among stakeholders, as well as significant imbalance of power and resources, create challenges for collaboration (Ferreira et al., 2021; Hendricks et al., 2022).

Around 63% of the cases omitted to attend to economic benefits (Fig. 5b).GI can involve higher research and development expenditures as GI solutions are less established and developed than traditional infrastructure solutions (Epps and Hathaway, 2019). Additionally, GI projects are frequently impacted by policy changes and natural hazards, which increase maintenance costs (Jongman et al., 2014). The multi-functionality of GI complicates "benefit capture" and highlights the importance and centrality of public provision of GI (Paavola and Primmer, 2019): GI is commonly intended for non-profit and public purposes, such as biodiversity conservation and leisure activities in parks and greenways (Tzoulas and James, 2010). In addition, GI often provides indirect economic benefits that are hard to quantify (Granoff et al., 2016).

About 28% of GI planning cases were unfunded (Fig. 5b). GI research is challenging to fund owing to its technological immaturity and long payback periods compared to traditional infrastructure. Insufficient funding and resources may lead to inadequate project management and organizational capacity, absence of partners and supporting institutions, and limited research objectives and scope. This can result in poor data sharing, stakeholder participation, and limited economic benefits (Takakura and Massi, 2022). Funding for GI case studies primarily came from the public sector, private funding being rather limited (Fig. 5b). This is because, in contrast to profit-driven private businesses, the public sector has a wider social responsibility and greater resources and capabilities (Wunder et al., 2018; Staccione et al., 2021).

4.3 Solutions

From an environmental management perspective, the solutions proposed in this study for the four major challenges of GI planning provide scientific guidance for future cities in management of GI (Fig. 5c). The priority of data sharing entails relevant institutions or individuals to have the sharing awareness. Compensation procedures, whether from governments or individuals, is proven as a feasible way to increase the awareness of sharing among data owners (Blume et al., 2018). In addition, an effective sharing mechanism should ensure the smooth progress of data acquisition, analysis and utilization, which is a guarantee for maintaining data security (Raymond et al., 2017). Pan-urban data management platforms across sectors and disciplines must be developed to better understand and interpret different types of data to ensure effective management of urban environments and to be able to support citizen participation in collecting and accessing relevant data (Sorensen et al., 2021).

Achieving co-design with stakeholders requires identifying relevant stakeholders and clarifying their responsibilities and roles (Fig. 5c). Identification of stakeholders needs a judgement by users, beneficiaries, local authorities and service providers who will be involved in the implementation of the GI (Patra et al., 2021). The primary or secondary status of stakeholders is determined based on their influence or interest. Stakeholders can be engaged at four distinct levels: inform, involve, consult and collaborate. The views of the stakeholders should be fully considered at the collaborative level (O'Donnell et al., 2018). Workshops, interviews, and investigations can help generate an understanding of what stakeholders expect from the GIs to ensure that GI planning can benefit all relevant stakeholder groups (Ugolini et al., 2018).

The creation of locally relevant business models is necessary to increase the economic advantages of GI (Fig. 5c). Cost-effectiveness, political considerations, and business strategies must all be taken into account. GI should be integrated with urban planning and land use planning. New technologies and materials are needed for GI to conserve energy to help reduce construction and maintenance costs as well as improve resource efficiency (Nordman et al., 2018). Policies and regulations are critical to the business model of GI. Governments can ensure the effectiveness of GI construction and operation by providing tax relief, reducing regulatory restrictions, establishing financial support mechanisms, and offering regulatory mechanisms (Afionis et al., 2020). Profit models of GI can increase the value of property and land to attract investment by improving the quality and aesthetics of the surrounding environment (Garcia-Lamarca et al., 2022), as well as selling energy and water, managing waste, and creating green jobs (Wang et al., 2020). In addition, efficient cost-benefit analysis methods need to be developed to effectively quantify the economic benefits of GI (Wise et al., 2022).

Overcoming the insufficient funding for GI research necessitates collaboration among multiple parties. Society, government, and international organizations can work together to provide financial and technical support for GI establishment (Fig. 5c). Social capital can provide financial support for GI research through donations and investments (Löfqvist and Ghazoul, 2019), and can also cooperate with the public sector to develop and invest in GI research projects, such as establishing joint ventures, setting up joint research institutes, or establishing funds (Cheng et al., 2023). Governments can fund GI research through grants to research institutions and fiscal transfers (Busch et al., 2021). International organizations, multinational corporations, or international funds can support GI research through international collaborative projects or by providing technology transfer and professional support (Klaaßen and Steffen, 2023).

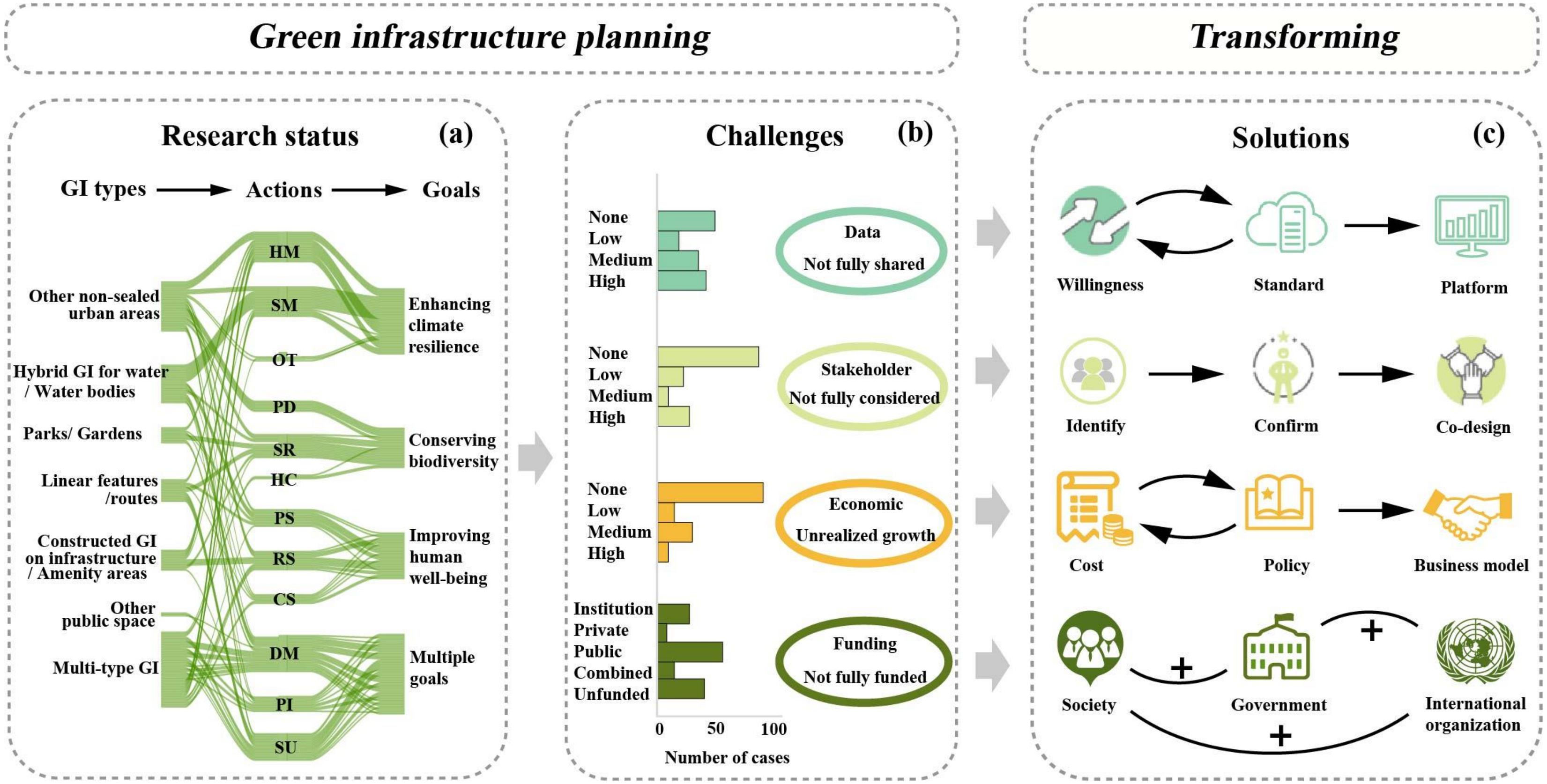

Fig. 5. Research status, challenges, and solutions for the transformation of green infrastructure planning. (HM- Heat Mitigation, SM-Stormwater Management, OT-Others, PD- Policy Development, SR- Scientific Research, HC- Habitat Construction, PS- Provisioning Services, RS- Regulating Services, CS- Cultural Services, DM- Developing Models/Frameworks, PI- Public Involvement, SU- Surveys)

5. Conclusions

We identified a total of 145 urban planning cases from 125 articles in the literature on GI. The three primary goals of GI planning are to enhance climate resilience, conserve biodiversity, and improve human well-being. GI planning with single purpose has been unable to support comprehensive management of ecologically damaged space and multiple-goal GI planning is becoming a trend. Data sharing and stakeholder participation in GI planning case studies need to be improved, and so do the quantification of economic benefits and research funding. The following are essential for the transformation of GI planning: 1) the establishment of data sharing mechanisms and platforms, the unification of data standards, and the improvement of data availability; 2) full participation of stakeholders to ensure the fairness and inclusiveness in GI planning; 3) the creation of locally appropriate business models to enhance economic benefits; and 4) the collaboration among society, government and international organizations to increase research funding.

Due to the diversity of GI planning cases covered in the literature, the approach taken in this study in order to quantify data sharing, stakeholder participation, and economic benefits in the cases under uniform criteria is relatively simple, and the precise assessment of GI cases can be strengthened in the future with the help of methods such as machine learning. If there is sufficient funding to support research on GI planning and implementation, the investigation and analysis of stakeholder co-design in GI planning, as well as other benefits of GI implementation (e.g., human health), and the business models adopted by GI projects could be further developed.

Acknowledgements

This work was supported by Ministry of Science and Technology of China (MSTC) with National Key Research and Development Programs (grant numbers 2021YFE0193100, 2017YFE0119000). Any opinions, findings, and conclusions or recommendations expressed in this work are those of the authors and do not necessarily reflect the views of MSTC.

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