Sustainable Cities and Society 98 (2023) 104845

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Green infrastructure sustains the food-energy-water-habitat nexus

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ARTICLE INFO

Keywords:
Green infrastructure
Food-energy-water-habitat nexus
Synergies and trade-offs
Ecosystem services
Framework

ABSTRACT

The ecosystem service potential of urban green infrastructure (GI) is increasingly appreciated, yet its underpinning role in the food-energy-water-habitat (FEWH) nexus is unclear. In order to explore the positive and negative impacts of GI on the FEWH nexus, this study asked three questions: 1) What are the research hotspots in FEWH for GI and what are the trends over time? 2) What ecosystem services can GI provide in terms of FEWH? 3) Can we quantify the ecosystem service potential of GI, and what are the synergies and trade-offs among the service types? By collating the research evidence which supports the ecosystem service potential of GI to contribute to FEWH, we developed a matrix to score the potential and to assess the synergies and trade-offs among ecosystem services. From this, a conceptual framework of the role of GI in supporting the FEWH nexus was developed. The results show that the potential of GI to sustain the FEWH nexus is significant and that multi-functional GI planning is necessary to minimize the trade-offs between them. This requires the application of new methods, theories, adaptation to new circumstances, and the development of appropriate business models within the planning domain, as well as compliance with policy directions and funding externally.

1. Introduction

Green infrastructure (GI) is increasingly being adopted to address urban environmental challenges. With rising human population and urbanization, sustainability has become a more pressing issue (Riffat, Powell & Aydin, 2016). While humans depend on nature and ecosystem services like production of oxygen, food, and water purification as well as energy production and mitigation of natural disasters (Hanes, Gopalakrishnan & Bakshi, 2017; Wang, Zhou, Pickett, Yu & Li, 2019), they increasingly put a strain on the environment through habitat destruction, change, fragmentation and pollution (Li, Fang, Wang & Sun, 2016; Naslund, Gerson, Brooks, Walters & Bernhardt, 2020). This has led to climate change, loss of biodiversity, and increased costs of potable water (McNeely, 1992; Stock, 2021). To offset some of the negative impacts, the idea to use GI more efficiently within an urban setting was developed a couple of decades ago (Benedict & MacMahon, 2002; Bolund, 1999; Van Oijstaeijen, Van Passel & Cools, 2020).

The concept of GI was formally introduced by the "Green Infrastructure Working Group" organized by the Conservation Fund and US Department of Agriculture Forest Service in 1999. GI usually refers to strategic planning, creation, and management of an interconnected network of green space within an urban environment and can provide considerable ecological, social, and economic benefits (Gashu & Gebre-Egziabher, 2019; Soga et al., 2017). In 2013, the European Commission Communication on GI laid the foundation for the strategic planning and management of GI, providing concrete suggestions on how to use GI as a tool through nature-based solutions (NBS), helping us maintain and enhance benefits in GI investments (European Commission, 2013). The concept of NBS was formally proposed by European Commission in 2015, considered as an evolution of the concept of GI. Compared with the specificity of GI, the concept of NBS is more extensive (Escobedo, Giannico, Jim, Sanesi & Lafortezza, 2019).

GI has great potential to supply four key elements of food, energy, water and habitat. Food, energy and water are essential and fundamental resources that support human survival and socioeconomic development (Djehdian, Chini, Marston, Konar & Stillwell, 2019).

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https://doi.org/10.1016/j.scs.2023.104845
Received 26 April 2023; Received in revised form 25 June 2023; Accepted 1 August 2023
Available online 2 August 2023

Policies for food, energy, and water are often in conflict with each other, optimizing one resource at the expense of another (Zhang et al., 2019). To maintain the sustainability of urban systems and avoid considering a single aspect that leads to trade-offs, scholars have proposed an integrated nexus approach to deal with the conflicts between the utilization of resources (Chang, Hossain, Valencia, Qiu & Kapucu, 2020). This approach has been widely welcomed especially after the formal presentation of food-energy-water (FEW) nexus studies at the Bonn conference in 2011 (Hoff, 2011; Romero-Lankao, McPhearson & Davidson, 2017). Simultaneously, biodiversity conservation is also important for urban sustainable development (Garrard, Williams, Mata, Thomas & Bekessy, 2018). Therefore, we extended the nexus to food-energy-water-habitat (FEWH).

Urban infrastructures are key determinants of FEWH security. gray infrastructure such as power plants, roads, and water supply systems tend to be stable and, once adopted, become path-dependent and difficult to change (Romero-Lankao et al., 2017). GI has gradually become a priority for urban planners due to its short establishment period and low cost (Bowler, Buyung-Ali, Knight & Pullin, 2010). The impact of GI on the FEW nexus has been studied and its importance in policy development has been noted (Bellezoni, Meng, He & Seto, 2021). There is also extensive evidence from scholars to quantify the impact of urban GI on the FEW nexus (Meng et al., 2023). Currently, we have found few studies that address GI and FEWH nexus. However, under the dual pressure of urbanization and climate change, it is necessary to strengthen the research on GI for coupling FEWH nexus to resolve the people-environment-infrastructure conflict. In order to address a key knowledge gap around people-environment-infrastructure interactions, it is necessary to better understand the role of GI in the delivery of food, energy, water and habitat, while taking into account their dependence and interaction with people and with built structures. Together these improve human living conditions (Emmanuel & Loconsole, 2015), but the role of GI can also be constrained within the local environment by limited resources such as energy, water and land (Sen & Khazanovich, 2021; Vijayaraghavan, 2016). Thus these interactions can be both positive and negative.

In order to explore the positive and negative impacts of GI on the coupling of FEWH nexus, this study was conducted based on the following three questions: 1) What are the research hotspots in FEWH for GI and what are the trends over time? 2) What ecosystem services can different types of GI provide in terms of FEWH, and in what proportion? 3) Can we quantify the ecosystem service potential of GI, and what are the synergies and trade-offs among the service types? To address the above questions, based on published literature, this study conducted time-series analysis and knowledge flow sorting on the research hotspots and ecosystem services of GI in terms of FEWH. In addition, a matrix was created to score the service potential of GI, and the synergies and trade-offs among service types were discussed through ordination analysis. Our research aims to elaborate on the challenges and priorities of GI in providing ecosystem services for coupled FEWH nexus, and to develop a conceptual framework which outlines solutions to guide GI implementation.

2. Data source and methodology

2.1. Data source

Data were searched in two parts in the web of science core collection database on December 20, 2022. One part of the data was searched with terms related to green infrastructure, urban, and FEWH (see Table S1 in Supplementary Materials), and a total of 3452 publications were obtained. Research terms in this part included blue infrastructure and nature-based solutions because 1) although some scholars classify blue infrastructure as GI as well, some scholars prefer to describe it separately; 2) nature-based solutions are based on planning and implementing GI, and the two concepts often appear simultaneously. The search terms include only the city-wide due to the conflict among population, resources and environment in cities, which are the main sites of GI planning and implementation, although there are also a small but limited number of GI plans in rural areas.

Another part of the data was retrieved considering that there are specific types of GI, such as city farms, green roofs and gardens, etc. A total of 16 types of GI related to FEWH were selected (see search terms in Supplementary Materials). In order to avoid obtaining a large number of irrelevant publications, only the top 50 most relevant publications for each GI were selected. Therefore, 800 publications were obtained in this part. Duplicates were removed from both parts of the data, which resulted in 3357 papers. Although other databases are also available, such as Scopus, the web of science literature is sufficient to support the analysis of GI (Bellezoni et al., 2021).

2.2. Methodology

2.2.1. Time series analysis

Time series analysis of keywords can better reveal the temporal evolution of GI research. The annual frequencies of the keywords in the obtained literature were extracted and the synonyms were combined. The Ward distance method was used to perform temporal cluster analysis of keywords, and the research period was divided into 2001–2016 and 2017–2022 (Fig. S1 in Supplementary Materials). By calculating the frequency of keyword occurrences in two periods, the trend factor of keywords can be derived (see Supplementary Materials for the calculation process). When the trend factor is greater than 0, it indicates an increasing trend of keyword research interest and vice versa (Zhu, Dressel, Pacion & Ren, 2021).

A bubble chart of GI research hotspots was created in the Origin software by selecting 200 high frequency keywords. The search terms "green infrastructure", "blue infrastructure", and "nature-based solutions" were excluded because their frequency was too high and would have overshadowed other keywords. Emerging keywords with high frequency (frequency > 3) that only appear in 2017–2022 were also listed separately in the bubble chart.

2.2.2. Knowledge flow

Knowledge flow has been widely used for visual analysis of multidimensional data (Lupton & Allwood, 2017). By reviewing the abstracts of obtained publications, the main types of FEWH-related ecosystem services of GI were identified. The literature involved in GI types and the services it provides were counted separately to produce a knowledge flow. In this case, a publication may be duplicated for counting, as there are cases where a single publication includes multiple GI types and multiple ecosystem services.

Food-related services of GI were divided into food provision and food safety. Food is the basic material needs of human beings, and food provision affects social stability (Goldstein, Hauschild, Fernandez & Birkved, 2016). Food safety means that food is safe to eat, meets the due nutritional requirements, and does not cause any harm to human health (Carvalho, 2017). Food provision and food safety reflect the ecosystem service potential of GI in quantitative and qualitative terms, respectively.

Energy-related services of GI were divided into energy provision, carbon storage and heat mitigation. Energy is an important material basis of the national economy (Almeshaiei, Al-Habaibeh & Shakmak, 2020). Energy consumption is the main source of carbon emissions. Reducing energy consumption or increasing carbon sequestration are effective measures to alter carbon storage (Kavehei, Jenkins, Adame & Lemckert, 2018). Relying on GI for heat mitigation can reduce the energy consumption of machine cooling (Chen, Haase, Qureshi & Firozjaei, 2022). Energy provision, carbon storage and heat mitigation directly and indirectly reflect the relationship between GI and energy.

Water-related ecosystem services of GI mainly include water provision, water quality improvement and water flow management. Water is also a basic human need, and water quality improvement is an important measure to ensure water security (Guzman, Wang, Muellerklein, Smith & Eger, 2022). Water flow management is an essential way to prevent and control water disasters (Ibrahim, Bartsch & Sharifi, 2020). From water provision to water quality improvement and water flow management reflecting the strong regulatory ability of GI from passive to active.

GI services to habitats have focused on providing habitat for wildlife and thus conserving biodiversity (Aiken, Mulloy, Dwane & Jackson, 2021). The supply of food, energy and water represents the provisioning services of ecosystem services. Food safety, carbon storage, heat mitigation, water quality improvement, and water flow management are among the regulating services of ecosystems. Biodiversity conservation belongs to ecosystem supporting services. In addition to ecosystem services, the economic impact of GI in terms of FEWH was investigated. GI primarily provides ecological benefits, however economic benefits can influence and even determine the choice of GI by urban planners (Isaifan & Baldauf, 2020).

2.2.3. Ordination analysis

The scoring of GI services enables the quantitative measurement of their potential to serve food, energy, water and habitat. A matrix was introduced to describe the service potential of GI for FEWH (see Supplementary Materials), following the approach used by Jones et al. to assess the ecosystem service potential of GI (Jones et al., 2022a). In the matrix developed by Jones et al. the types of GI were systematically classified and the ecosystem service benefits were scored (negligible ~ very high = 0 ~ 4) for each type of GI. Original scorings in Jones et al. (2022a) were based on evidence in the literature, and using first principles based on understanding of ecological processes and social behaviours to score GI elements which are currently under-researched. Since the matrix developed in this study was targeted to explore the ecosystem services of GI for food, energy, water, and habitat, only 16 essential GI types were emphasized. The matrix takes into account both the positive and negative effects of GI on ecosystem services in our research, as it has been stated that the disbenefits of GI should not be ignored either (Bellezoni et al., 2021).

The scoring process for this study included 1) While referring to Jones et al.'s (2022a) scoring criteria, for each score in the matrix, an additional representative literature was provided to support the scoring (see Table S2 in Supplementary Materials). The degree of negative and positive impacts was assigned separately (high negative impact ~ high positive impact = −3 ~ 3, Table 1). 2) The proposed scoring matrix was sent to other co-authors to discuss the validity of the scores until a consensus was formed on the final matrix. We believed the matrix to be reasonable because all of the authors came from diverse scientific backgrounds.

A principal component analysis mapping was performed to analyze the synergies and trade-offs of GI on FEWH. Principal component analysis (Coskun-Hepcan & Hepcan, 2018) is one of the ordination analysis methods. In this study, each GI type was used as a sample point and each ecosystem service type was used as a species for mapping. In addition, correlations between ecosystem services were calculated to complement the judgment of synergies and trade-offs. The quantification of ecosystem service potential can provide a reference basis for the planning and implementation of GI.

3. Results

3.1. Research hotspots and trend

Ecosystem services were the most important research theme for GI in relation to FEWH since 2001 (Fig.1). In terms of supporting services of GI, biodiversity conservation received more research interest from scholars from 2001 to 2016 and less interest after 2017. In the area of regulating services, there was considerable interest in urban planning as a means of applying GI for climate change mitigation and adaptation, particularly for stormwater management and urban heat mitigation. Flood and low impact development associated with stormwater management accounted for a relatively large number of literature reports. However, surface temperature and cooling effect as correlates of heat mitigation were reported less but with high trend factors.

In respect to specific GI types, green roofs received comparable attention over the two research periods. The trend factors for green walls and city farm were high, indicating that they were in the spotlight for 2017–2022. Urban woodland was only a hotspot for research from 2001 to 2016. In addition to the focus on FEWH, the trend factors for air pollution and air quality were high. Emerging keywords reflected the hotspots of GI research in recent years. Hotspots in GI research methods included machine learning, random forest, analytic hierarchy process, and decision support system. COVID 19 and sustainable development goals were emerging keywords in a socio-environmental context. Stakeholder and co-create were a focus in the co-design and implementation of GI.

Table 1
The matrix with scores of services provided by GIs for food, energy, water, habitat.

Name	Food provision	Food safety	Energy provision	Carbon storage	Heat mitigation	Water provision	Water quality improvement	Water flow management	Biodiversity conservation	Economic benefits
City farm	3	2	−1	0	1	−3	−2	1	2	3
Woodland	1	1	1	3	3	−1	3	3	3	1
Garden	2	2	0	3	2	−1	2	2	3	1
Park	1	0	0	3	3	−2	3	2	3	1
Green corridor	1	1	0	1	2	0	1	1	2	−1
Green roof	1	1	1	2	2	−1	−1	1	2	−2
Green wall	0	0	1	1	1	0	0	1	1	−3
Lake	2	1	1	2	3	2	3	2	3	0
Pond	1	−1	0	1	1	2	1	2	3	−1
Reservoir	1	−1	3	2	2	3	−1	2	−1	2
Coast	3	1	2	3	2	0	3	0	3	−1
River	1	1	0	1	3	2	2	2	3	0
Drainage	0	0	−1	1	1	1	1	3	1	−1
Green swale	0	0	0	2	1	0	2	2	2	−1
Wetland	0	1	0	2	2	1	3	3	3	1
Protected area	1	2	0	3	3	1	2	2	3	1

Note: negative impacts (high, medium, low), negligible, positive impacts (low, medium, high) = −3, −2, −1, 0, 1, 2, 3.

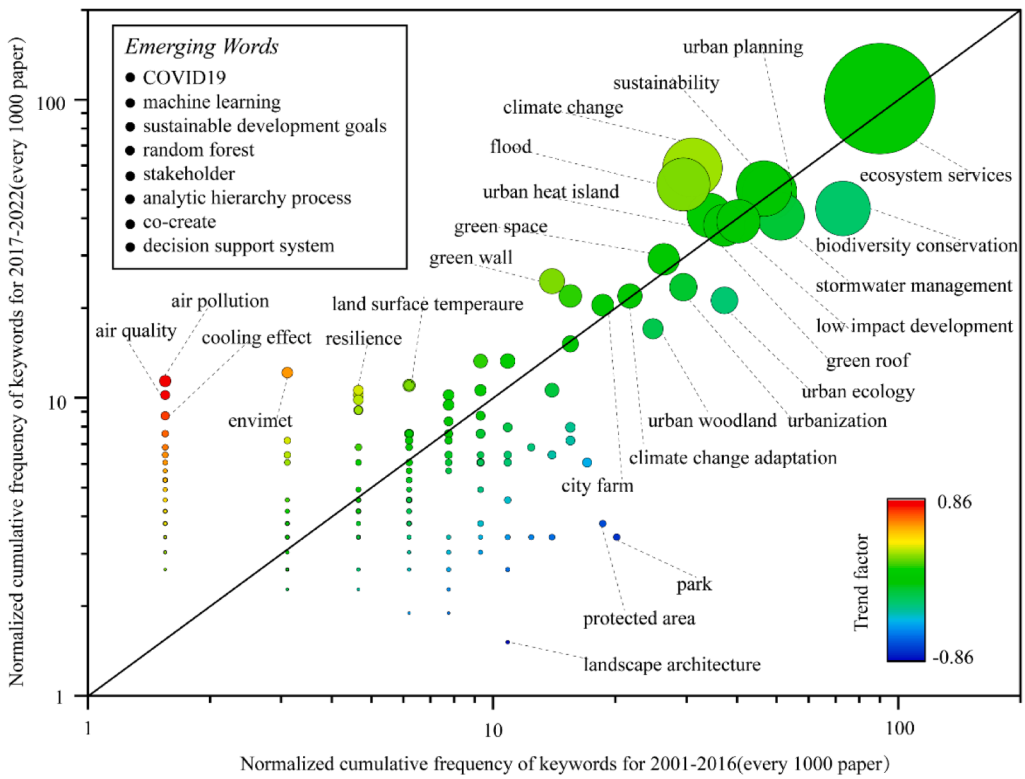

Fig. 1. Top 200 frequently occurring keywords (bubbles) based on time trend distribution of past (2001 - 2016) and recent (2017 - 2022) normalized cumulative frequencies (some bubbles with the same trend factor as the normalized cumulative frequency appear superimposed). The shade of color indicates the magnitude of the trend factor value of the keyword. The size of the bubble indicates the cumulative frequency of the keyword.

3.2. Ecosystem services

There were differences in the research focus on FEWH for different types of GI (Fig.2). The percentage of GI research on food was only 10%, with food provisioning being the main type of service. City farm was the most frequently mentioned source of food provision, followed by gardens and parks. Food safety has received relatively little focus in GI research, accounting for about 1.3% of papers. A total of 21.6% of papers mentioned energy, where energy provision was less reported, and the main source of supply was lake, pond and reservoir. Carbon storage and heat mitigation were of high interest in GI research, at 8% and 11.8%, respectively. The greater potential for carbon storage was in woodlands, while heat mitigation research mentioned green roofs, green walls, gardens and parks most frequently.

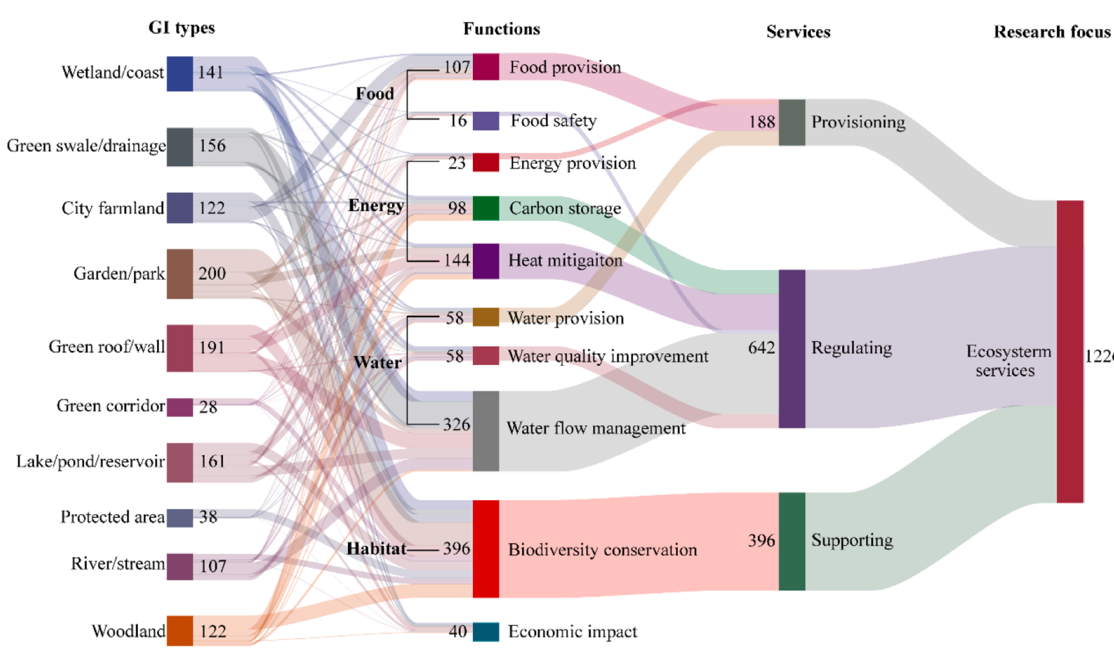

Fig. 2. Knowledge flow of GI and FEWH, the numbers represent the quantity of publications.

Water research was the biggest for GI research at 36.1%. Of these, the percentage of water supply and water quality studies was the same, both at 4.7%, while 26.7% of studies focused on water flow management using green swales and drainage systems. GI providing habitat for wildlife for biodiversity conservation was also a hot topic, accounting for 32.3%. Almost all GI types were able to provide habitats for wildlife, with gardens, parks and woodlands getting more attention for biodiversity conservation research.

The ecosystem services of GI for FEWH reported in the literature represented that the regulating services (52.4%) had greater coverage in the literature than that of provisioning (15.3%) and supporting services (32.3%). Cultural services were not counted here because they were mentioned rarely. Apart from ecosystem services, the economic impact studies of GI accounted for 3.3%. The main GIs involved in economic impact studies were green roofs, lakes and drainage systems.

3.3. Contribution and correlation

There was a large variation in the ability of GI to serve FEWH. In the PCA diagram, the first principal component (PC1) and the second principal component (PC2) contributed 30.27% and 26.77% of the variance, respectively (Fig. 3a). The types of services provided by GI for FEWH were indicated by arrows. The length of the arrow indicated the correlation between the service type and the ranking axis, for example, water provision and food safety contributed the most to the first and second ranking axes, respectively. The direction of the arrow indicated the direction of the fastest growing value, and the angle between the arrows indicated the correlation between the service types. For example, food provision was positively correlated with economic benefits and negatively correlated with water provision (Fig. 3a).

Each GI type was represented by points, and the size of the points indicated the total score, which could be interpreted as the overall contribution of GI (Fig. 3a). Lakes had the highest total score, followed by woodland. It shows that lakes and woodlands contribute more to FEWH. Green walls, green roofs and drainage systems have lower total scores, indicating their lower overall contribution. The colors of the points characterize the green and blue features of GI, respectively. Points close together indicate high similarity between GI, such as gardens and parks, wetlands and lakes that were close together, which have similar GI characteristics.

The relationship between GI and service type is the relationship between points and arrows (Fig. 3a). For a service type, a vertical line was made from each point to the line where the arrow was located, and the points were ranked according to the direction of the arrow growth. For example, for food provision, city farm has the highest score while reservoir has the lowest score. According to the correlation among service types (Fig. 3b), there were negative correlations between food provision and water flow management (−0.55) and between water provision and food safety (−0.47). For water quality improvement, there was a positive correlation with biodiversity conservation (0.67) and with carbon storage (0.63). The correlation coefficient between economic benefit and each service type was less than 0.5.

4. Discussion

4.1. Research trends

The topic of multi-functionality of GI in FEWH research is gradually increasing. At the beginning of the 21st century, urban planners were primarily concerned with the connectivity of GI. GI can provide a sound green network for wildlife migration and ecological processes (Weber & Wolf, 2000). Therefore, biodiversity conservation became the main function of GI and received high focus. As climate change intensifies, the thinking and research around GI has been gradually transitioning to multi-functionality, expanding to consider other ecosystem services such as stormwater management and heat mitigation (Meerow & Newell, 2017).

The high potential for services but resistance to implementation, as well as a lack of space in cities, has led to more research attention on green roofs, green walls, and city farms. Roofs and walls tend to be privately owned, but allow retro-fitting, or clever incorporation into new building designs. By contrast, city farms take up significant amounts of urban land, water, and other resources. Despite the various environmental benefits that these GI can provide, lack of land access, poor technological maturity and long payback cycles limit their popularity to a certain extent. Research on production intensification, technology upgrading, community participation and economic growth is increasing to address some of these barrier issues such as land, technology and finance (Alim et al., 2022).

Among the ecosystem services of GI for FEWH, coverage of

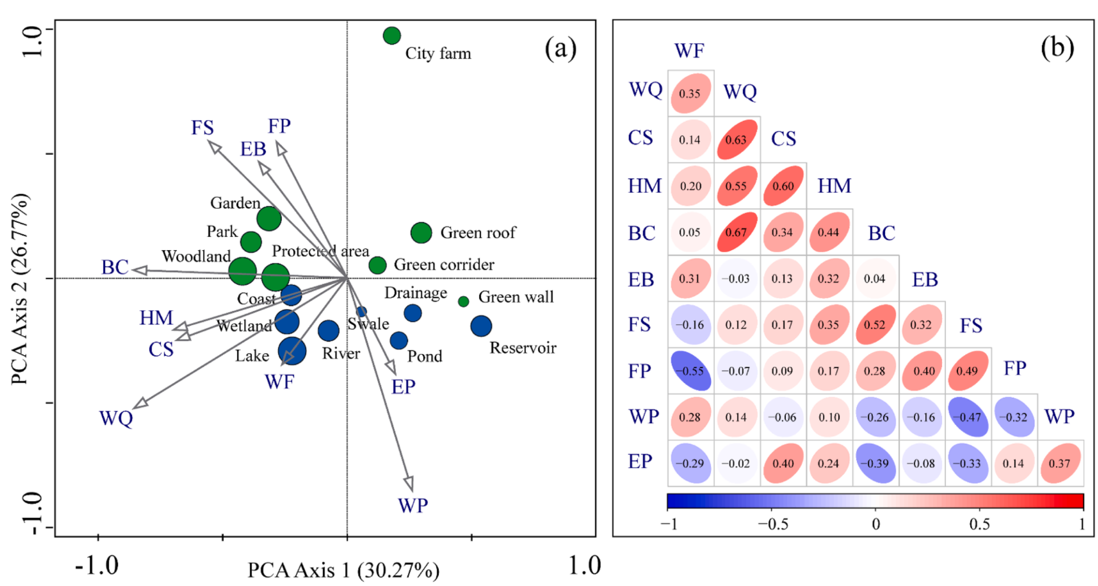

Fig. 3. Principal components analysis showing relationships among GI types (a) and correlations between ecosystem service types (b). FP - Food Provision; FS - Food Safety; CS - Carbon Storage; EP - Energy Provision; HM - Heat Mitigation; WP - Water Provision; WQ - Water Quality Improvement; WF - Water Flow Management; BC - Biodiversity Conservation; EB - Economic Benefits.

regulating services in the literature was greater than provisioning and supporting services. This is possibly because provisioning and supporting services of GI require higher technical and financial inputs, such as solar energy and urban agriculture construction (Chen & Chen, 2021; Weidner, Yang, Forster & Hamm, 2022). In contrast, GI that provides regulating services is less costly to establish, such as managing vegetation and controlling runoff (Ab Azis & Zulkifli, 2021). Moreover, provisioning and supporting services often require more complex management and maintenance. However, forests, parks, and wetlands have better cooling, stormwater management, and biodiversity conservation effects along with relatively less maintenance (Garcia-Herrero et al., 2022; Oldfield, Warren, Felson & Bradford, 2013). Another factor behind this trend is that it is often easier to quantify regulating services, and they offer a level of direct mitigation of many urban pressures such as flooding or cooling (Jones et al., 2022b).

4.2. Synergies and trade-offs among ecosystem services

If carbon sequestration, biodiversity conservation, water quality regulation and cooling are required at the same time, then the best choices for GI are woodlands, protected areas and wetlands. It can be seen that there are significant synergistic effects of GI in carbon storage, habitat provision, water quality improvement and heat mitigation (Fig.3a and 3b). Moreover, woodlands, protected areas and wetlands contributed more to these four service types. In agreement with Jones et al., the more natural habitats (woodlands, the coast, lakes) are more multi-functional, while the more constructed habitats (green roofs, and constructed wetland features) are less multi-functional (Jones et al., 2022a). This is likely because constructed features tend to be designed with a primary purpose in mind. However, some features, particularly green roofs, are increasingly designed to be multi-functional, for example with the aim of storing carbon and supporting biodiversity in addition to water management and providing thermal stability to buildings (Knapp, Schmauck & Zehnsdorf, 2019).

While the potential for GI to sustain FEWH nexus is significant, it simultaneously raises new trade-offs (Fig. 4a). In particular, the trade-offs between water and food are stronger (Fig. 4b). GIs capable of water supply and water flow management have difficulty providing food and ensuring food safety, such as drainage systems and reservoirs (Jokinen, Hillman & Tymensen, 2019). Vice versa, food production causes high water consumption and GIs capable of producing food were less capable of water flow management. For example, city farms were less resilient to floods due to changes in the original ecology (Alberti et al., 2022). As food straw can be converted into biofuel and waste from energy production may be used as fertilizer for crop development, there is a rather high synergy between food and energy (Tilman, Socolow, Foley, Hill & Larson, 2009). Additionally, there is a strong synergy between habitat and food, with good habitat luring pollinators to disperse pollen for crop production and food production sites also serving as excellent habitats for both plants and animals (Carvalho, 2017).

The objects that have both trade-offs and synergies include: 1) Energy and water, where water can provide hydropower, but water transport consumes energy (Chang et al., 2020). 2) Habitat and water, where habitat needs water supply and is also threatened by flooding, and although the habitat can purify the water, it may also be affected by water pollution (Scheffers & Paszkowski, 2013). 3) Habitat and energy, GIs that supply energy such as solar farms can provide habitat for plants and animals, but at the same time the establishment of energy infrastructure may destroy the biodiversity of habitat (Semeraro, Pomes, Del Giudice, Negro & Aretano, 2018). Exploring the synergies and trade-offs among ecosystem services of GI can provide knowledge to enhance positive impacts and avoid negative impacts when planning GI for the future adaptation of people to urban environment.

The economic benefits of the services provided by GI to FEWH have still received relatively little study effort. Compared to the ecological benefits, the economic benefits of GI have not been quantified as extensively. Unlike the material abundance in developed countries, there is often resistance to building GI in a large number of developing countries because of the increased cost, and low direct economic benefits and unclear beneficiaries (Manso, Teotonio, Silva & Cruz, 2021). This occurs despite the large number of indirect economic and societal benefits provided by GI (Bowen & Lynch, 2017; Fletcher et al., 2022; Mell, Henneberry, Hehl-Lange & Keskin, 2016).

PCA and correlation analysis provide a more comprehensive investigation of the synergies and trade-offs among ecosystem services provided by GI, and identify issues that need to be focused on to promote the coupling of FEWH nexus in the future. The visualization of synergies and trade-offs within FEWH nexus provides important knowledge support for the development of the conceptual framework and forms an important part of it (Fig. 4b). This has led to the proposed final solution

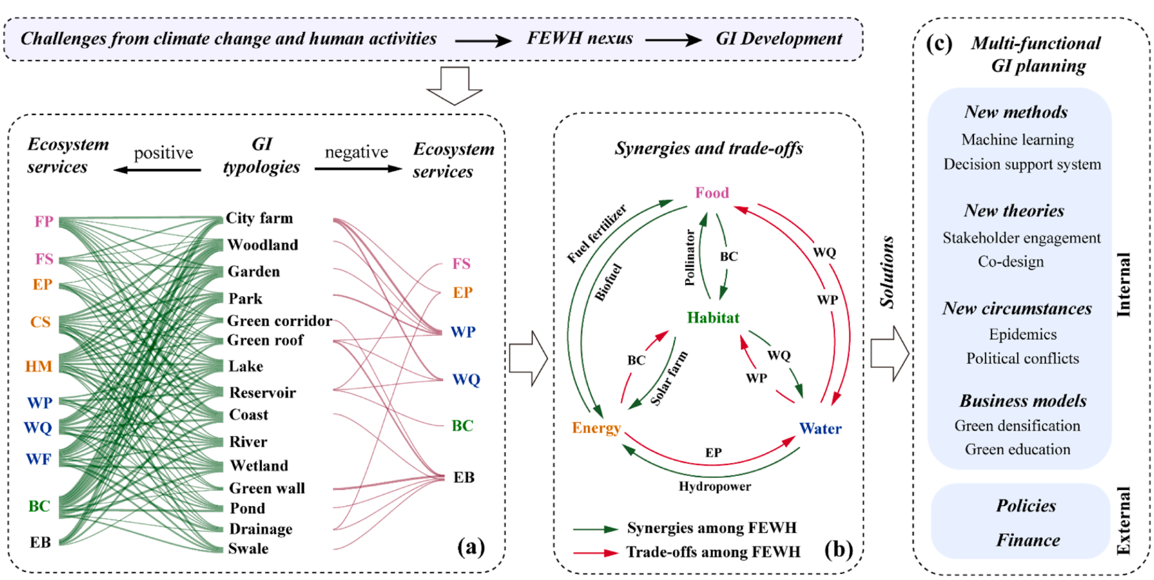

Fig. 4. Conceptual framework for green infrastructure (GI) to sustain food-energy-water-habitat (FEWH) nexus. (a): positive and negative impacts of GI on FEWH. (b): synergies and trade-offs among FEWH. (c): solutions to reduce trade-offs among FEWH. FP - Food Provision; FS - Food Safety; CS - Carbon Storage; EP - Energy Provision; HM - Heat Mitigation; WP - Water Provision; WQ - Water Quality Improvement; WF - Water Flow Management; BC - Biodiversity Conservation; EB - Economic Benefits.

in the framework, which is necessary to resolve the people-environment-infrastructure conflict in future cities.

4.3. Solutions

Utilizing a nexus approach to synergistically address the negative impacts of climate change and human activities on FEWH has become an efficient solution. Moreover, GI has greater positive benefits for ecosystem services in the FEWH nexus and is an effective tool for sustaining the nexus. To address emerging trade-offs and enhance synergies among FEWH, multi-functional GI planning is necessary. This requires applying new methods and theories, adapting to new circumstances, and developing appropriate business models within planning, and seeking policy and funding support externally (Fig. 4c).

New methods, new circumstances and new theories make the development of GI promising. With regard to new methods, developments in the computing have brought new technologies, from machine learning to decision support systems, that make the research, planning and implementation of GI more intelligent, precise and comprehensive (Guzman et al., 2022). In terms of new circumstances, in the context of the COVID-19 outbreak, there has been recognition of the great potential of GI to help with mental health regulation in addition to basic material supply and ecological protection (Zhang, Zhang & Zhai, 2021). On the new theories side, under the framework of co-design theory, the rights and interests of stakeholders are maintained, which stimulates co-creation and promotes the sustainable development of GI (Patra et al., 2021), while the idea of multiple overlapping and interacting domains of influence, termed 'sheds' allows better informed spatial planning both within cities and their surroundings (Jones et al., 2022b).

Developing the appropriate business model is an important internal support for the sustainability of GI. While certain GIs, like city farms and reservoirs, have the potential to boost the local economy, other GIs, like green roofs and walls, that are costly but difficult to achieve economic benefits (Fig. 4a). In order to sustain GI in the long term, its commercial value needs to be realized. This requires the development of locally appropriate business models, such as increased urban greenery to enhance real estate value, health management value for healing gardens, tourism value for heritage site reuse, and environmental education value for green spaces (Cilliers et al., 2018; Coombes & Viles, 2021; Sohn, Kim, Kim & Li, 2020).

Obtaining policy and financial support is an important external guarantee for GI. Policy-oriented GI planning responds to regional and national development trends, effectively avoids political barriers. Effectively accessing policy support needs to be based on local conditions and clarify the government's positioning for local development (Harrington & Hsu, 2018). External finance is the source of funding for GI in the planning and implementation stages, and it determines whether GI can be established satisfactorily. External funding acquisition needs to fully consider the rights and interests of funders and maximize their benefits (Davies et al., 2018).

5. Conclusion

As semi-natural facilities, GIs can reduce human pressure on the environment, thus maintaining a positive interaction among people, environment, and infrastructure. Information on the multi-functionality of GI has gradually increased over time as its potential to provide multiple services to people is increasingly understood. A major knowledge gap in the literature remains on the quantification of the economic benefits of many GI types. For improving the ability of GI to facilitate a coupled FEWH nexus, future multi-functional GI planning should employ computer systems-based approaches such as machine learning to improve efficiency; utilize stakeholder engagement theories such as co-design to ensure green equity; and continually adjust planning priorities to address the major challenges facing society. Additionally, in order to maintain the sustainability of GI, appropriate business models and external policy and financial support are needed.

The innovations of this study are 1) proposal to apply the FEWH nexus approach to help address conflicts in resource allocation, 2) developing a matrix of ecosystem service potential for GI to explore the synergies and trade-offs between services, and 3) creating a conceptual framework for GI for coupling the FEWH nexus. The nexus approach and matrix provide methods for resolving the mutual exclusion of resource use and quantifying the interactions between people-environment-infrastructure, and the conceptual framework offers a systematic solution for dealing with future urban people-environment-infrastructure contradictions. One potential weakness is that only 10 typical ecosystem services were chosen for the study, since additional types of ecosystem services may bring additional effects on the FEWH nexus. Future research and evaluation of the synergies and trade-offs between additional GI ecosystem services and these representative services can offer more comprehensive evidence for urban GI development.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2023.104845.

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