Food-Energy-Water Nexus and Green Infrastructure: A Theoretical Connection

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Introduction

In urban landscape planning and design Green Infrastructure (GI) has been increasingly considered as a climate change adaptation strategy. The European Union has integrated green infrastructure planning as one of the main strategies to meet the eleventh (Sustainable Cities and Settlements) UN sustainable development goal. In order to optimize GI planning and design and maximize its role in cities adaptive capacity, it is crucial to understand GI's tradeoffs and synergies with relevant interconnected urban systems. Among frameworks that address the role of multiple interconnected urban systems in climate change adaptation is the Food-Energy-Water (FEW) nexus. The framework, however, has remained largely conceptual due to different gaps in data and knowledge (Sperling and Berke 2017).

This paper is a part of an ongoing systematic review of green infrastructure and food-energy-water nexus literature. The broader research provides 1) a framework for classifying existing and possible research areas at the intersections of GI and FEW nexus 2) a critical summary of the most relevant gaps, approaches, methodologies and tools for the identified research areas. This paper provides an overview of the theoretical connection between these two areas of research.

Food-Energy-Water in Green Infrastructure Literature

This section provides a big picture indicating how existing literature in GI is relevant to the FEW nexus. Green Infrastructure literature is growing (Figure 1), however the concept of GI has remained vague. From ecological networks at a national scale to local low impact stormwater management infrastructure in cities, GI has referred to different concepts in different scales and contexts (Hansen and Pauleit 2014). Achieving higher resilience through community self-organization and learning, human well-being, and equitable distribution of resources including ecosystem services are among the emphasized benefits of GI in cities (Colding and Barthel 2013; Krasny et al. 2014; Lovell and Taylor 2013). Despite the studied benefits, green infrastructure programs have been criticized for their limited success in multifunctionality and institutionalization (Lovell and Taylor 2013).

Ecosystem services is defined as the services that biophysical structures or processes provide for humans and they are distinguished in four categories of "provisioning (e.g., food or fresh water), regulating (e.g., local climate regulation), habitat or supporting (e.g., habitats for species), and cultural services (e.g., mental and physical health)"(Hansen and Pauleit 2014). GI ecosystem services related to food, energy and water systems are frequently mentioned in GI literature. However, there is no review that clearly maps the relevance of GI literature to the FEW nexus. In order to understand the relevance and importance of each of these systems to GI research, a series of science mapping analyses on 2,006 search results that had “Green infrastructure” in their topic on a Web of Science database was conducted. The default timeframe is between 1900 to the present. The primary aim of this analys was to address two main research questions: 1) What are the dominant keywords/concepts in green infrastructure literature? 2) What are the main subfields in green infrastructure literature and do they relate to water, energy, and food systems?

In order to answer these research questions, a science mapping R package called “bibliometrix” as well as other R packages for general text mining were used. The results (Figure 1) from the bibliometrix analysis indicates a growing body of GI literature.

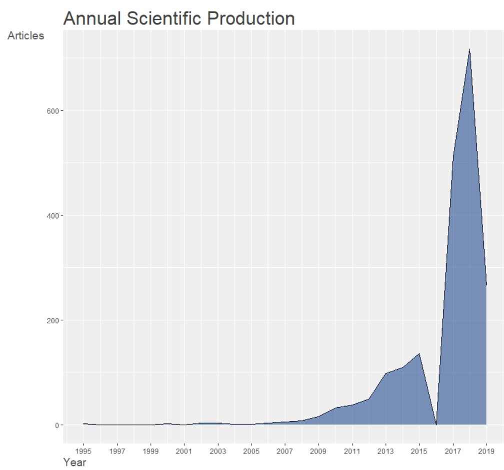


Figure 1: The growing body of GI literature

Table 1 shows a list of the most frequent keywords in all of the literature considered.

Table 1: Most frequent keywords in GI studies

	Tab	Freq
1	GREEN INFRASTRUCTURE	699
2	ECOSYSTEM SERVICES	196
3	INFRASTRUCTURE	167
4	GREEN	150
5	URBAN	109
6	URBAN PLANNING	108
7	CLIMATE CHANGE	90
8	SUSTAINABILITY	86
9	**STORMWATER**	**83**
10	**STORMWATER MANAGEMENT**	**64**
11	URBANIZATION	59
12	BIODIVERSITY	54
13	MANAGEMENT	49
14	RESILIENCE	48
15	URBAN GREEN INFRASTRUCTURE	44
16	LOW IMPACT DEVELOPMENT	42

17	PLANNING	42
18	SUSTAINABLE DEVELOPMENT	37
19	NATURE-BASED SOLUTIONS	36
20	**URBAN AGRICULTURE**	**34**
21	**URBAN HEAT ISLAND**	**34**
22	URBAN ECOLOGY	30
23	GREEN SPACE	29
24	CLIMATE CHANGE ADAPTATION	28
25	DEVELOPMENT	27
26	ECOSYSTEM	26
27	GREEN ROOF	26
28	LANDSCAPE	26
29	**RUNOFF**	**26**

As can be seen, the top keywords are related to general topics such as ecosystem services, urban planning, climate change and sustainability. Keywords related to water (blue) energy (orange) or food (green) are highlighted. It is evident form the table above that there are far more articles with water related keywords than energy and food related systems.

For further analysis of the keywords, a co-occurrence function in the bibliometrix package was used. The results (Figure 2) show the water and energy subfields as highly recognizable, while the food cluster is barely recognizable, close to the ecosystem services focused studies.

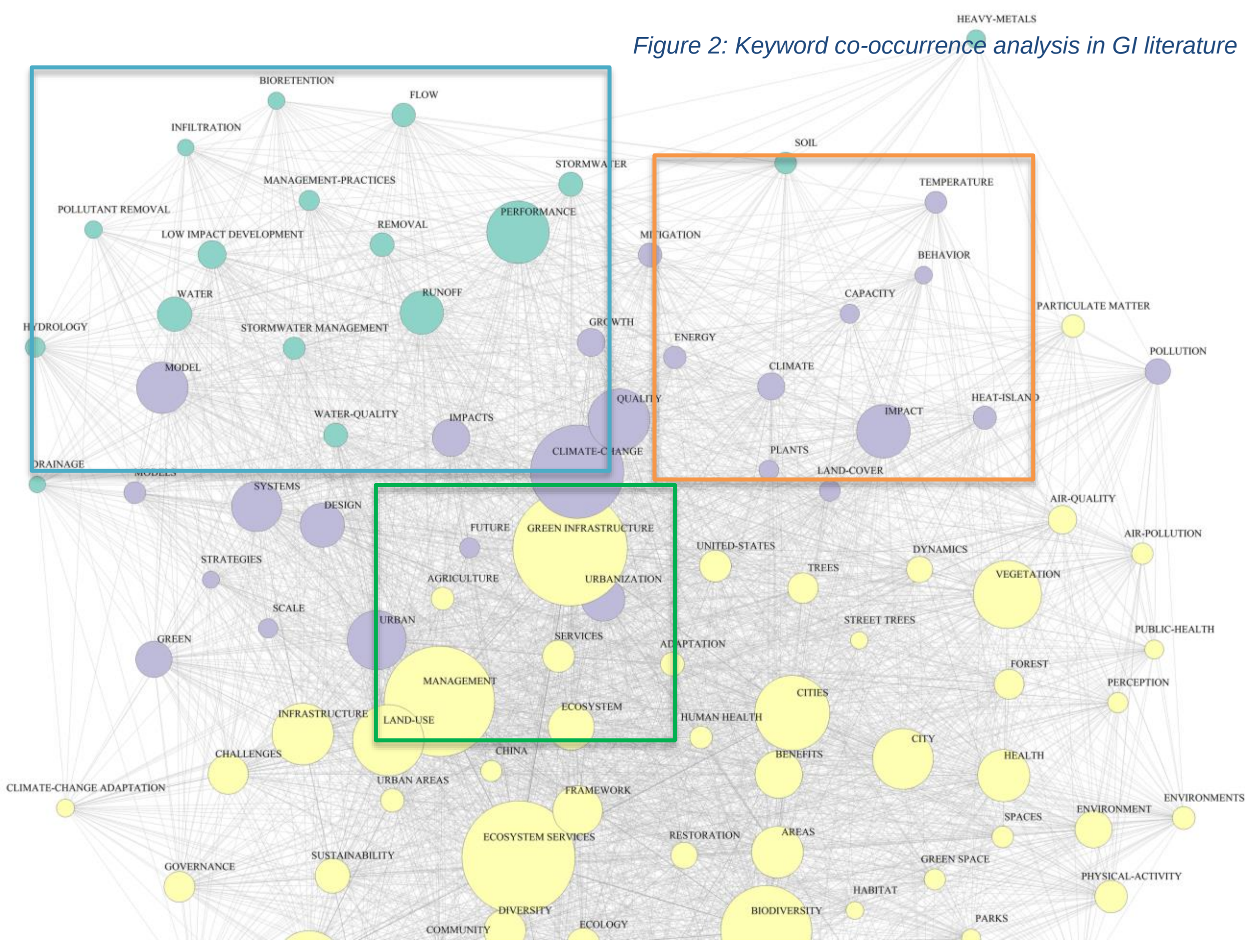


Figure 2: Keyword co-occurrence analysis in GI literature

In addition to using the bibliometrix package, in order to find the clusters of the subfields in the GI literature, a Latent Dirichlet Allocation algorithm (LDA) was run on the articles' keywords and abstracts. Only the word stems were used in the process of tokenization of the keywords and abstracts in order to avoid repetition. LDA algorithms at k=3, 5, 10 were tried. Looking at the relevance of the results, k=5 was selected as optimum. The results for the keywords and abstracts are below.

Figure 3: Clustering of the keywords in GI literature

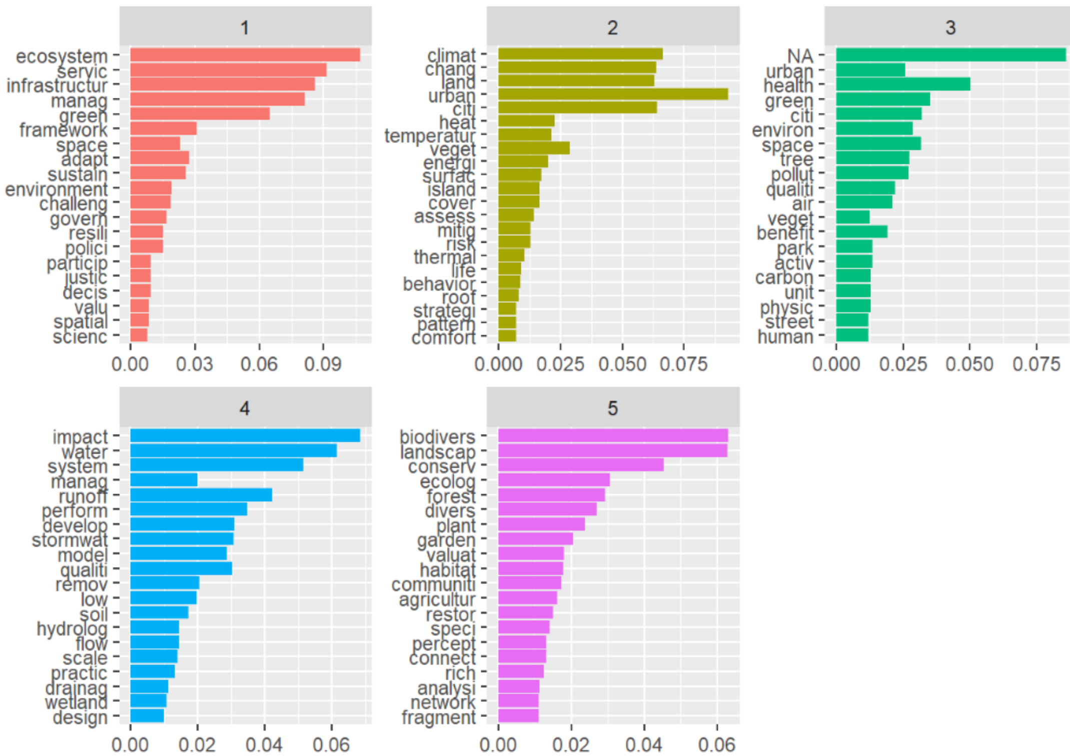


Table 2: The most frequent keywords in each of the clusters of the article's keywords

Note: *the keywords are stemmed to avoid repetition (the gray additions provide examples of the actual words)*

Energy	**Water**	**Food**
urban	impact	biodivers(ity)
climat(e)	**water**	landscap(e)
citi(es)	system	conserv(e)
chang(e)	**runoff**	ecolog(y)
land	perform	forest
veget	develop	divers(ity)
heat	**stormwat**(er)	plant
temperatur(e)	**qualiti**(es)	**garden**
energy	model	valuat(ation)
surfac(e)	remov(e)	habitat
cover	manag(e)	communiti(es)
island	low	**agricultur**(e)

assess	soil	restor(e)
mitig(ate)	**flow**	speci(es)
risk	**hydrolog**(y)	connect
thermal	scale	percept(ation)
life	practic(e)	rich
behavior	**drainag**(e)	analysi(s)
roof	**wetland**	fragment(ed)
comfort	design	network
pattern		
strategi(es)		

In the keywords clustering results (Figure 3 and Table 2), cluster 2 has keywords related to relationship of GI with Energy system including heat, energy, temperature, thermal and comfort. Cluster 4 represents GI studies that connect with water system and has keywords such as water, runoff, stormwater, hydrology, drainage and wetland. Consistent with bibliometrix keyword co-occurrence analysis, research on food and GI does not show up as a clear cluster/subfield but it is recognizable in the cluster with keywords such as biodiversity, community gardens and urban agriculture (cluster 5).

In the abstracts clustering results (Figure 4 and Table 3), cluster 5 has the keywords related to relationship of GI with Energy system including heat and temperature. Cluster 3 represents GI studies that connect with water systems and has keywords such as water, stormwater, runoff, flood and hydrology. Studies on food and GI does not show up as a clear cluster/subfield in abstracts clustering. The other clusters are too general to be associated with the food system.

Figure 4: Clustering of the abstracts in GI literature

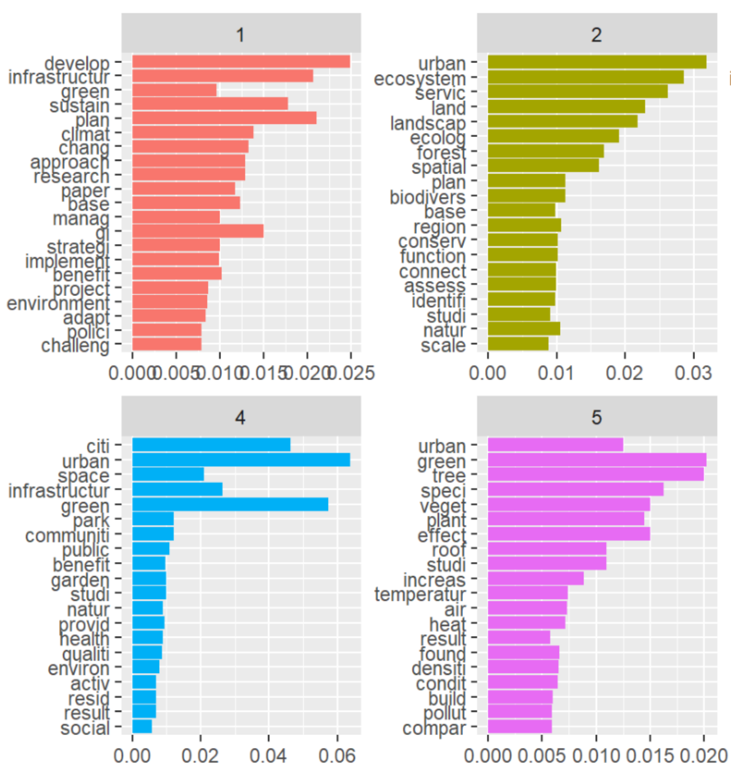


Table 3: The most frequent keywords in each of the clusters of the abstracts

***Note:** the keywords are stemmed to avoid repetition (the gray additions provide examples of the actual words)*

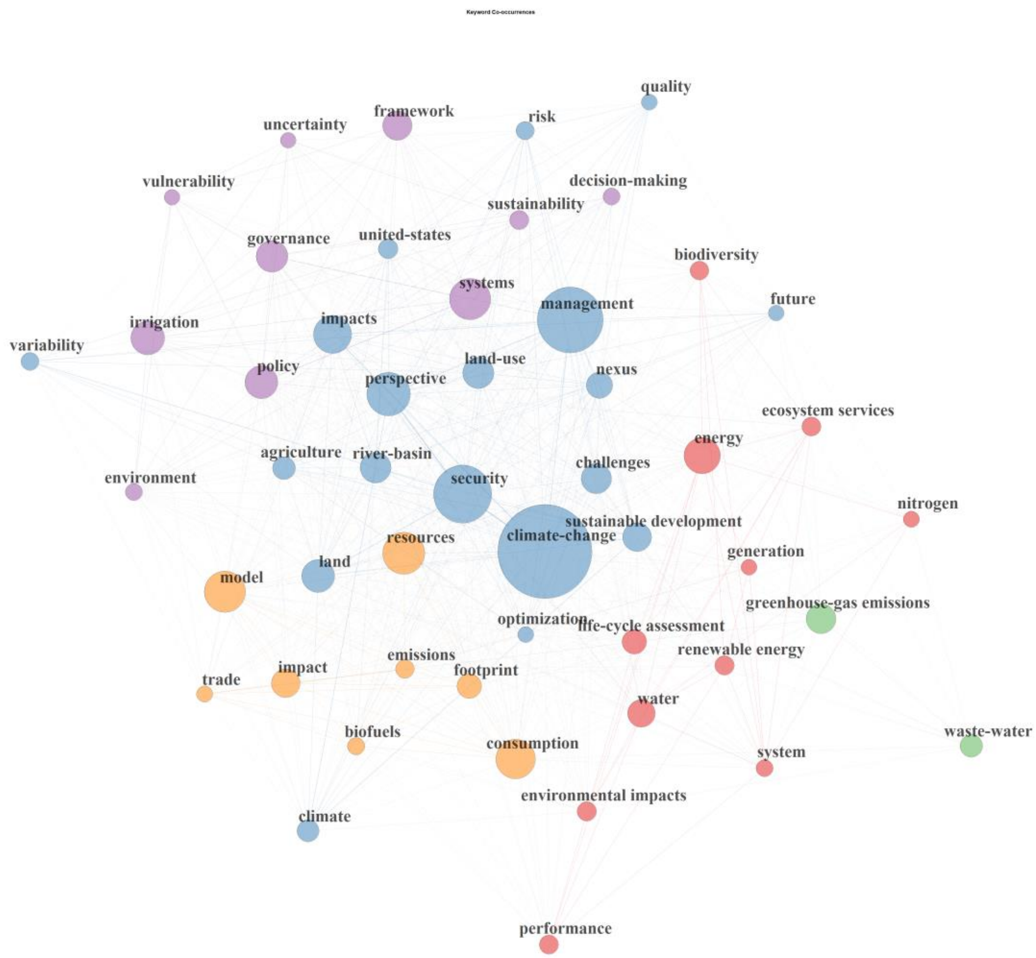
Energy	Water	Food
green	**water**	Other clusters are too general
tree	**stormwat(er)**	
speci(es)	system	
veget(ation)	model	
effect	**runoff**	
plant	design	
urban	manag(e)	
studi(es)	soil	
roof	impact	
increas(e)	reduc(tion)	
temperatur(e)	perform	
air	effect	
heat	**flood**	
found(ation)	**hydrolog(y)**	
densiti(	surface(e)	
condit(tion)	increas(e)	
build	infrastructur(e)	
compar(e)	result	
pollut(ant)	cost	
result	gi	

Green Infrastructure in Food-Energy-Water Literature

The food-energy-water nexus has been defined as a function of the interaction among the three sectors in order to identify “the critical dependencies, synergies, and feedback loops between systems” (Sperling and Berke 2017). The recent attention to hazard mitigation and climate change adaptation has been the building block and the driving force of the literature on FEW. The FEW Nexus notion gained attention after releasing the World Economic Forum report in 2011 and Bonn Conference in 2012 (Wichelns 2017). The notion has resulted in many meaningful studies. However, the body of research has been criticized for different gaps including 1) remaining highly conceptual with lack of narrowly defined research studies (Sperling and Berke 2017) 2) over emphasizing on large scale agriculture and policymaking and lack of integration of multiple scales (Wichelns 2017) 3) lack of its connections to the issues that are comprehendible for stakeholders in urban areas including urban communities.

Since literature on FEW is relatively young and green infrastructure is not yet a well-established subfield in the FEW nexus, the topic modeling method that we used for GI literature is not meaningful here. However, a keyword co-occurrence analysis (Figure 5) highlights some common general areas of research such as ecosystem services, biodiversity and sustainability.

Figure 5: co-occurrence keyword analysis of 469 studies that have Water-Energy-Food Nexus keyword in their topic from Web of Science (WoS) database.



Beyond these general associations, green infrastructure has been mentioned in Food-Energy-Water nexus literature in different contexts. There are direct calls for including natural infrastructure in the nexus (Ozment, DiFrancesco, and Gartner 2015). Ozment et al. (2015) argue that, given the massive investment in food, energy and water infrastructure in cities and the future uncertainty due to climate change, natural infrastructure should be integrated to the FEW nexus because of its role in increasing adaptive capacity and cost reduction in urban infrastructure planning. This role is realized through providing several benefits for management of FEW, GI's regulating ecosystem services such as flood and drought mitigation and GI's contribution to increasing the resilience and lifespan of gray infrastructure (Ozment, DiFrancesco, and Gartner 2015).

The Theoretical Connection; Frameworks for the integration of FEW

The result of the cluster analyses and the review of FEW nexus literature show existing but not integrated pieces of FEW nexus in Green infrastructure literature. This section explores this connection further by asking: How GI focused FEW nexus studies can address some of the current gaps in FEW nexus literature?

As it was apparent in the keyword analysis of GI literature, the most relevant field to GI is urban planning and design. While the Food-Energy-Water nexus is not an urban design theory, the literature in FEW Nexus marginally has touched large scale urban planning approaches. GI focused FEW research can be used as an experimental space to contextualize FEW thinking in urban design and planning. In doing so, they can be beneficial to FEW research gaps in two main aspects; they can be used as 1) a way to downscale large scale FEW dynamics to a site/neighborhood scale 2) a strategy to communicate FEW nexus to urban communities and utilize community-engaged processes to manage urban food, energy and water (FEW). There have been recent attempts to contextualize FEW thinking in urban planning and design, highlighting participatory design at multiple scales as an important strategy for this contextualization (Sperling and Berke 2017; Yan and Roggema 2019).

Sperling and Berke (2017) propose an *Urban Nexus Science* framework. The framework aims to integrate FEW nexus research to urban planning and design to improve infrastructure, land use, and hazard mitigation planning and decision-making. It calls for participatory modeling and stakeholder engagement for evaluating the solutions related to urban FEW and a new focus on decentralized, closed-loop models of spatial planning. They identify different urban problems that can be used to practice the framework, such as urban agriculture, water treatment technologies or energy solutions. The framework is among the first attempts to bridge urban planning and design to FEW nexus research. However, it remains very conceptual and does not provide a practical guide for identifying the possible research areas at the intersection urban planning and design and FEW.

Yan and Roggema (2019) provide a more detailed framework that integrates FEW thinking to urban planning and design. *Moveable Nexus* is a very recent methodology in understanding the FEW implications of urban agriculture. The framework is a design-led approach and consists of design methods, evaluation tools and participation mechanisms. The framework calls for downscaling the FEW research for urban areas, residents and planners while looking at the FEW problems and solutions at multiple urban scales. It also emphasizes the importance of having a participatory/community-engaged/interdisciplinary approach to problem solving in the context of urban FEW management. The authors summarize the guiding principles of nexus science in urban planning and design based on Hoff (2011) as to 1) Invest in ecosystem systems to secure FEW provisions; 2) Create more with fewer environmental costs; 3. Ensure accessibility to food, water and energy to all residents. The principles guide urban design and planning practices to be collective, circular and decentralized at multiple urban scales. While they acknowledge different urban initiatives that make use of FEW linkages, such as small hydropower generation or local production for local consumption, they see “urban agriculture as a key facilitator of nexus thinking, needing water and energy to be productive”

While both frameworks identify urban agriculture as one of the most relevant planning and design contexts to facilities nexus thinking, considering other types of urban green infrastructure and their different ecosystem services can help to define more opportunities for research at the intersection of FEW, urban design, planning and GI. This further helps to identify relevant gaps in tools, methodologies and advancing FEW research.

Based on this initial review, a second question is posed to be further explored in the next step of this research: “How can we leverage the similarities in GI and FEW research problems and methodologies for creating a framework for the research at the intersection of the two?”

Next Steps

The next step of this review draws a holistic overview of research at the intersection of FEW and GI, utilizing the similarities in GI and FEW research problems and methodologies. The two main similarities are 1) Both GI and FEW nexus are framed as allocation/optimization problems. 2) Both GI and FEW nexus use ecosystem services as a main system level quantification methodology (this is evident in keyword co-occurrence in both topics).

Based on these similarities, a framework for classifying existing and possible research areas at the intersections of GI and FEW nexus and a critical summary of the most relevant gaps, approaches, methodologies and tools for the identified research areas will be proposed.

Acknowledgment

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Bibliography

Colding, Johan, and Stephan Barthel. 2013. “The Potential of ‘Urban Green Commons’ in the Resilience Building of Cities.” *Ecological Economics* 86 (February): 156–66. https://doi.org/10.1016/j.ecolecon.2012.10.016.

Hansen, Rieke, and Stephan Pauleit. 2014. “From Multifunctionality to Multiple Ecosystem Services? A Conceptual Framework for Multifunctionality in Green Infrastructure Planning for Urban Areas.” *AMBIO* 43 (4): 516–29. https://doi.org/10.1007/s13280-014-0510-2.

Krasny, Marianne E., Alex Russ, Keith G. Tidball, and Thomas Elmqvist. 2014. “Civic Ecology Practices: Participatory Approaches to Generating and Measuring Ecosystem Services in Cities.” *Ecosystem Services* 7 (March): 177–86. https://doi.org/10.1016/j.ecoser.2013.11.002.

Lovell, Sarah Taylor, and John R. Taylor. 2013. “Supplying Urban Ecosystem Services through Multifunctional Green Infrastructure in the United States.” *Landscape Ecology* 28 (8): 1447–63. https://doi.org/10.1007/s10980-013-9912-y.

Ozment, Suzanne, Kara DiFrancesco, and Todd Gartner. 2015. *Natural Infrastructure in the Nexus*. International Union for Conservation of Nature and Natural Resources. https://doi.org/10.2305/IUCN.CH.2015.NEX.4.en.

Sperling, Joshua B., and Philip R. Berke. 2017. “Urban Nexus Science for Future Cities: Focus on the Energy-Water-Food-X Nexus.” *Current Sustainable/Renewable Energy Reports* 4 (3): 173–79. https://doi.org/10.1007/s40518-017-0085-1.

Wichelns, Dennis. 2017. “The Water-Energy-Food Nexus: Is the Increasing Attention Warranted, from Either a Research or Policy Perspective?” *Environmental Science & Policy* 69 (March): 113–23. https://doi.org/10.1016/j.envsci.2016.12.018.

Yan, Wanglin, and Rob Roggema. 2019. “Developing a Design-Led Approach for the Food-Energy-Water Nexus in Cities.” *URBAN PLANNING* 4 (1): 123–38. https://doi.org/10.17645/up.v4i1.1739.