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Understanding and conceptualizing how urban green and blue infrastructure affects the food, water, and energy nexus: A synthesis of the literature

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ABSTRACT

The interactive dynamics in the food, water, and energy system as a nexus (FWEN) are critical to the sustainable development of global cities, and they can be mediated by green and blue infrastructure (GBI) in the urban area. Here we provide a comprehensive literature review to examine how GBI affects FWEN in urban centers, an area which is currently understudied. In order to do this, we undertake a systematic review of the literature using a meta-analytic approach and topic modelling. Based on our synthesis, we develop a conceptual framework of the key links between urban GBI and FWEN and the direction and magnitude of the relationship. We found that GBIs can benefit food supply, energy saving, and climate change mitigation but at a price of food safety and water contamination. Well-designed urban construction can help curb the negative effects. Therefore, we need to make deliberate and integrative policy to link GBI with each element in urban FWEN. Moreover, the focus of studies on GBIFWEN links is also heterogeneous across cities: urban agriculture and food security are priorities in cities located in Africa and Asia as well as in lower income and larger cities (but not metropolitan areas), while the cooling effect of green space has been a focus for cities of middle or high income. Finally, current research focuses on isolated analysis, lacking integrated studies needed for decision making supporting tools. While isolated analyses lead to connectivity failures and can result in adverse impacts, integrated analyses can identify interdependencies of environmental resources between parts of a cycle and across different scales, which can increase resource efficiency and minimize environmental degradation. Therefore, our key findings point out the importance of linking the effects of GBI on each component of FWEN in both research and policy making.

1. Background

Sixty per cent of the global population will live in urban areas by 2030, with 90% of this growth in low- and middle-income countries (UN 2019). Almost one billion people currently live in slums and informal settlements. An additional three billion middle-class people will need improved housing over the next 15 years (UN 2019). Other projections show that the global demand for resources will also increase. A recent forecast projected that urban land areas will increase by up to 1.3 million km^2 between 2015 and 2050, an increase of 171% over the global urban footprint in 2015 (Huang et al., 2019). Concomitant with this growth is an expected increase in the demand for food, water, and energy (Simpson and Jewitt, 2019). The increase in the number and size of cities and the ensuing transformation of non-urban landscapes pose significant challenges for reducing the rate of biodiversity loss and related ecosystem functionality and ensuring human welfare (Haase et al., 2014). Hence, urban sustainability practices are essential to reduce resource consumption and its socio-environmental impacts.

Urban areas provide a range of benefits to sustain and improve human livelihood and the quality of life through urban ecosystem

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services (UES), with direct and indirect contributions from ecosystems (i.e. living systems) to human well-being (TEEB 2011; Roeland et al., 2019). These contributions are framed in terms of 'what ecosystems do' for people (Haines-Young and Potschin 2018). Urban ecosystems, that is, urban green and blue infrastructure (GBI) can be characterized by the processes, or functions, that occur within them and the services provided by ecosystems are produced by the functional attributes of ecological communities (Lovell and Taylor 2013; Elmqvist et al., 2015; Richards and Thompson 2019). Working as a network of green spaces and water systems that delivers multiple environmental, social, and, economic values and services to urban communities (Ely and Pitman 2014), GBI includes a diverse set of land uses such as parks and reserves, gardens and backyards, waterways and wetlands, pathways and greenways, farms and orchards, buffers and windbreaks, squares and plazas, roof gardens and living walls (Haase et al., 2014; Andersson et al., 2014; Pitman et al., 2015). Nature-based solutions are essential for providing final UES to urban dwellers. These services are final in that they are the outputs of ecosystems (whether natural, semi-natural or highly modified) that most directly affect the well-being of people. According to the *Common International Classification of Ecosystem Services - CICES* (Haines-Young and Potschin 2018), a fundamental characteristic of final services is that they retain a connection to the underlying ecosystem functions, processes and structures that generate them and can be classified into three main groups i) provisioning (covers all nutritional, non-nutritional material and energetic outputs from living systems); ii) regulation and maintenance (all the ways in which living organisms can mediate or moderate the ambient environment that affects human health, safety or comfort), and iii) cultural (all the non-material, and normally non-rival and non-consumptive, outputs of ecosystems that affect physical and mental states of people).

Indeed, GBI delivers multiple benefits from and to urban areas and the provision of ecosystem services in cities depends on the quality, quantity and connections between urban GBI. By linking plant and water assets or features, urban GBI provides a system of connected spaces and services that create value for both people and the local underpinning ecosystems (Pitman et al., 2015). However, GBI can also produce ecosystem disservices, defined as functions of ecosystems that are perceived as negative for human well-being (Lyytimäki and Sipilä 2009; Gomez-Baggethun et al., 2013). However, these trade-offs need to be understood and evaluated within a local context and with a variety of stakeholders because disservices are highly subjective and variable across different environments (Haase et al. 2014, 2017; Kremer et al., 2016).

Understanding the dynamics of UES is a necessary requirement for adequate planning, management, and governance of urban GBI, with consequent effects on food, water and energy systems. Food, water, and energy (FWE) are interacting resource systems crucial to the survival and socio-economic development particularly in urban areas, as they import most of the FWE. The lack of proper analysis on FWE systems may lead to negative trade-offs impacting policy and technological choices. In fact, conventional sector-specific approaches to urban policy, design, and management miss out on possibilities to more efficiently address human needs, community priorities, and local regional and global resource challenges (GIZ and ICLEI 2014). To overcome this "silo-thinking" the concept of the food-water-energy nexus (FWEN) was proposed in the background paper for the *Bonn2011 Conference*, highlighting the "need to secure local livelihoods and the non-negotiable human rights to water and food" (Hoff 2011). FWEN refers to intersections among food, water, and energy systems that have large impacts on natural resources, on pollution, and on the security of FWE supplies essential to the well-being of the world's population (Gupta 2017; Ramaswami et al., 2017). Thus, the logic behind the FWEN concept is that it shifts attention from a one-sector view to a more integrated one (Al-Saidi and Elagib, 2017). Recognizing the inter-linkages of urban systems represents an important opportunity to provide services to human communities and to optimize cities and metropolitan regions in order to address local, national, and global sustainable development objectives (GIZ and ICLEI 2014; Avellan et al., 2017).

FWE resources are the pivotal fuels for global cities enabling populational and economic growth. Cities are almost entirely dependent on surrounding regions for food, water, and energy to sustain urban population and activities (Zanon et al., 2017). Thus, cities might benefit from a transition towards a circular economy that uses renewable resources and designs cyclical and efficient systems for provisioning water, energy, and food (Ghisellini et al., 2016). Urbanization therefore presents fundamental challenges but also unprecedented opportunities to enhance the resilience and ecological functioning of urban systems (Elmqvist et al., 2015).

In fact, cities are where we must address global and local resource constraints. However, the assessment of the literature on urban nature-based solutions faces two fundamental challenges: first, like in other fields of sustainability research, the body of relevant literature is large, diffuse among disciplines and scales, and fast-growing (Cohen 2017; Liu et al., 2018; Sarabi et al., 2019; Marvuglia et al., 2020). The task of systematically tracking scientific progress is therefore increasingly difficult to manage. Second, despite recent progress, urban FWEN assessments are still in their infancy (GIZ and ICLEI 2014; Simpson and Jewitt 2019; UNESCAP 2019; Zhang et al., 2019; Mitra et al., 2020).

Despite (the obvious benefits) of the critical linkages between GBI and FWEN, the available literature still shows fundamental gaps: for example, we still lack studies exploring the effect of GBI on FWEN in cities. The lack of studies calls for in-depth examination on the interaction of these nexus strategic issues to promote the sustainability of the urban environment. To enable a more robust and transparent assessment of the role of urban GBI in the promotion of FWEN approaches, and to advance discussions in urban sustainability, the relevant literature needs to be characterized to answer a few questions: What are the main urban GBI typologies evaluated? What are the main UES provided by the identified GBI typologies? How is the literature organized in terms of geographical location, population size and income level in the available case studies? Finally, what are the core topics in the literature and how are they drawing attention in different parts of the world?

As a step towards addressing these issues, this study aims to gather information on both the direct and indirect effects of different GBI on each FWEN element in cities, in addition to understanding and analyzing how urban GBI can affect the food-water-energy nexus. The main goals of this study are i) to undertake a systematic review of the literature using a meta-analytic approach and topic modelling and ii) based on our synthesis, to develop a conceptual framework of the key links between urban GBI and FWEN and the direction and magnitude of the relationship. We build a reproducible search query based on our understanding of the urban GBI-FWEN literature, focusing on urban ecosystem services related to water, energy, and food systems. We use automated content analysis to gain an overview of the topics and themes in this literature. Finally, we deploy these methods to develop a conceptual integrated framework with the main links between GBI and FWEN in the urban environment.

2. Methodology

To identify papers on urban GBI and their effects on FWEN components, we develop a structured search query (available in the supplementary information) for the Web of Science (WOS) literature database with no timeframe restrictions. Our results are not fully comprehensive, since further databases are available (for example, Google Scholar) and relevant non-English language articles may exist. However, our search results in a fairly restrictive selection of papers, sufficient to provide an overview of the major topics of urban GBI and the FWEN. It has been shown that the overlap between the databases is quite large (Martín-Martín et al., 2018) and our goal is not to be completely comprehensive, but illustrative. Therefore, our aim is to capture the majority of urban GBI-FWEN articles. Thus, by analyzing the WOS database we are capturing the majority of papers in the field and the only papers we are missing are minor ones. We divided the studies into two groups:

i) green infrastructure, which includes studies on urban trees and forests, green spaces, and green belts, etc.
ii) blue infrastructure, which includes studies on water bodies, lakes, rivers, coastal vegetation, urban wetlands, etc.

We identified an initial set of keywords based on the authors' expertise, refining them iteratively through WOS searches. We specified a list of keywords, grouped by each topic area and used the keywords on the WOS platform, identifying more relevant terms, and removing terms that delivered spurious results. We downloaded the titles and abstracts for each topic. We then screened every abstract to decide whether it is relevant. The WOS search query includes specific combinations of keywords for GBI and FWE subjects (e.g. 'temperature control'), as well as more generic strings ('nature-based solutions'). For instance for the food search: TS = ("food" OR "farming" OR "foraging" OR "agriculture" OR "nutrition" OR "nutrition" OR "diet") AND TS = ("urban*" OR "municipal" OR "city" OR "cities" OR "metropolitan" OR "neighborhood") AND TS = ("blue infrastructure" OR "green infrastructure" OR "green space*" OR "green roof*" OR [...] "park") (further details available in the supplementary material). We aim to identify GBI-relevant studies and their effects on one (isolated) or more FWEN components. The screen is completed by *Abstrackr* (Wallace et al., 2012), a web-application collaborative machine learning tool that facilitates screening of abstracts by multiple reviewers in tandem, where abstracts are imported and then screened by reviewers. 871 papers (273 on energy, 383 on food, and 215 for water) are left in the final sample. From this final sample we also extracted the city name, geographical location, population size and, income level for each identified case study.

Aside this subjective tagging, we also introduced an automated latent Dirichlet allocation (LDA) topic modelling which has the benefit of not relying on manual classification. LDA has been applied in multiple literature reviews in summarizing the main topics from a set of texts (Park and Kremer 2017; Cheng et al., 2018). This model summarizes a series of topics, which are composed by specific words based on the context of documents it is fed, assuming that the probability of topics in the documents and the probability of words in topics each follow a Dirichlet distribution. In this way, each document is assigned a topic and each topic enables us to verify if our manual identification captures similar themes. In this research, we include the abstract of all the papers in the final sample for analysis, and conduct the analysis using the "tm" and "topicmodels" packages in R. As this model requires the number of topics as an input, we conduct the analysis multiple times with a range of 3–32 topics. In selecting the optimal number of topics, we manually reviewed and compared the key words constituting each topic and picked 17 topics as additional divisions would only lead to marginal gain in information while fewer topics would oversimplify the subjects covered in the sampled literature. It should be noted that LDA model ideally requires a considerable sample size which can be larger than in this study to demonstrate a good performance, but we still present the results here with its limitation stated in the hope that future research can address this issue with a growing body of literature examining the GBI-FWEN linkage. All 17 topics and detailed information about the topic modelling can be found in supplementary material.

3. Results and discussion

3.1. The effects of GBI on the food-water-energy nexus: a screening of literature

In this section we present the main urban GBI typologies and the related FWE topics (i.e. related UES in most cases) found in the literature review. We found that studies on GBI-FWEN links predominantly focus on food and green infrastructure. A large number of studies on the effects of urban agriculture on food production in cities place food-related topics (or ecosystem services) as receiving the most attention from the literature, followed by energy and water topics as shown in Table 1. Few GBI typologies (i.e. urban agriculture, green roofs, green spaces) can be used for food production, limiting the use of multiple GBIs for this purpose. Meanwhile, energy is the topic that presents the greatest variety of GBI types. It can be understood as a strong motivation on reducing energy consumption in cities and helping urban environments to adapt to changing climates. Studies on energy topics also show more positive effects on their related ecosystem services. Water-related ecosystem services are the least substantial in terms of number of studies but due to the presence of studies on blue infrastructure, they are connected with different types of GBI (i.e. linked to more GBI typologies) (Table 1). Blue infrastructure studies are not as common as their green counterparts. We found that the effects of urban wetlands on water quality & treatment, and stormwater runoff control are the topics most discussed in the literature. Urban wetlands, lakes/ponds, and urban rivers are the only three blue infrastructures analyzed in the literature with connections to at least one topic in each of the FWE systems. In short, results show that GBI stands out in the urban environment for their multifunctionality and connectivity features, offering multiple benefits to local people and FWE systems.

FWE topics identified in this research are related to GBI studies in urban areas, excluding studies on a regional scale or larger. We found that not all topics discussed by researchers are related to the promotion or maintenance of UES. Topics such as formation of urban heat islands or climate change, for example, are climatic phenomena not directly related to UES promoted by different GBI, but which still have effects on human well-being in cities. Similarly, topics such as energy efficiency or energy savings potentially promoted by urban GBI are more related to the socioeconomics of urban life and, therefore, do not fit the *Common International Classification for Ecosystem Services – CICES* (Haines-Young and Potschin 2018). In order to allow researchers to visualize and compare the relationships between the topics found in this literature review and the different classifications available for ecosystem services, we present in the supplementary information an equivalence table between the definitions most used in this field (table SI1).

Table 1
Relationships between different types of green and blue infrastructure and food-water-energy topics, according to GBI-FWEN literature. Values in cells indicate the number of studies that showed positive and/or negative effects (−) in relation to the corresponding topic.

	FWEN topics / GBI typologies	Food				Water						Energy					
		Food safety	*Food supply*	*Food security*	*Nutritional quality*	*Water quality*	*Water demand, Supply & Savings*	*Stormwater runoff & Flood control*	*Wastewater reuse & Treatment*	*Groundwater quality & Quantity*	*Water management*	*Energy supply & Security*	*Energy efficiency*	*Energy savings*	*Climate change, Carbon footprint & Storage*	*Urban heat island*	*Thermal & Cooling effects*
Green Infrastructure	*Urban forest*		10 (-1)	1		3	3 (-2)	7	1		1	4		8	24	5	21
	Green spaces		14 (-1)	4 (-1)	1	3	1 (-3)	8	2		2	1		4	8	29	56
	Urban/Community gardens		4 (-1)	1	3	1		6								1	1
	Street/Urban trees					4 (-1)	1 (-2)	13 (-1)	1	2 (-1)	1	2		15	15	19	67
	Urban greening/Greenery											1	1	2	1	5	9
	Green belt																1
	Urban agriculture/Farming	3 (-46)	62	124	64	13 (-23)	20 (-5)	19 (-1)	31 (-5)	1	4	2	1 (-1)	27 (-1)	22 (-2)	3	
	Peri-urban agriculture/Forest											1			1		
	Nature-based solutions															1	1
	Sponge city					1		9	1		1				1		
	Green roofs		4	4	1	6 (-1)	1	26	2		2		5	20	7	22	45
	Living/Green walls													3	3	4	8
	Green/Smart buildings												1	2	1		1
	Green infrastructure					4	1	23			2		1		2		-1
Blue Infrastructure	*Water body*		1			-1								2		3	6
	Constructed/Urban wetlands		2			39	1	27	9		3			1	3 (-1)	5	8
	Lakes/Ponds	-2	4	-1		4	1	1	2					1			4
	Urban river	-6	6	1		1 (-3)	1	3			1	1				2 (-1)	5 (-1)
	Creek														1	1	1
	Coastal vegetation		1												1		
	Blue infrastructure																2
	Forested wetlands													1	2		
	Streams					3		3	1		2			1		1	2
	Rain gardens					1		1						1	1		1
	Detention/Stormwater ponds					7		9	2					2	1		2
	Permeable pavements					1	-1	7									
	Bioswales					2		4									
	Urban drainage							1									

Note: Some of the topics identified in the GBI literature can easily be related to urban ecosystem services (and/or disservices). However, other topics are more linked to climatic phenomena or even socioeconomic aspects of city life. If one is interested in identifying UES related to the topics commonly used in the GBI literature, (s)he can check the equivalence table available in the supplementary information of this paper (table SI1). According to the Common International Classification of Ecosystem Services – CICES (Haines-Young and Potschin 2018), UES are defined as the contributions that ecosystems make to human well-being, and distinct from the goods and benefits that people subsequently derive from them. These contributions are framed in terms of "what ecosystems do" for people.

3.1.1. *Core topics in the GBI-FWEN literature*

To validate our classification on the core topics found in the GBI-FWEN literature, we performed a topic modelling analysis. Topic modelling presents similar results as the literature screening, confirming the validity of our manual work. With the 841 abstracts (repetitive literature excluded, i.e. 30) that enter the analysis, we summarize 17 topics (further details in table SI2). Among all identified topics in the GBI-FWEN literature, "*urban agriculture and food security*" and "*cooling effects*" are the most popular topics, followed by "*wetland and nutrient removal*", "*green roof and storm runoff control*", "*regional river and stream restore*", and "*green space and land use change*" (Fig. 1; table SI2). Numerous articles focus on the issue of food security linked with urban agriculture (100 papers). The main focus for the energy-related studies is the cooling effect of green space (98 papers), while the discussion on water is oriented on how the urban wetlands remove nutrients (77 papers) and how green roofs benefits runoff control (76 papers). Overall, the distribution of topics mirrors the pattern observed in Table 1.

The literature also highlights that GBI not only produce ecosystem services, but also ecosystem disservices and, therefore, the same GBI can have either positive or negative effect on, for example, food (Table 1). On one hand, planting their own food, cities ensure the food supply, particularly for the urban poor in developing countries. On the other hand, food safety turns out to be a significant concern due to the environmental pollution (Huang et al., 2006; Morales et al., 2016). For instance, heavy metal becomes the top issue sourced from atmospheric deposition (Russo et al., 2017; Ng et al., 2018). In addition, sewage reuse in the urban agriculture (UA), while enhancing the efficiency of the urban water system, adds to concerns about food safety with pathogens transferring from wastewater to food (Miller-Robbie et al., 2017). Urban agriculture itself also may contribute to water contamination with fertilizer and pesticides similar to any other farming system (Thuong et al., 2013; Wielemaker et al., 2018). In addition, UA is studied by 67% of papers highlighting impacts on water demand (Heusinger et al., 2018). Therefore, unintended negative impacts of each GBI must be taken into account, as this can offset the objectives that motivate the expansion of GBI in cities. According to the literature, UA may have negative impacts on food safety (66% of total negative impacts of UA), water quality & treatment (18%) and water demand/savings (16%) in urban areas. However, its presence as green space also helps control runoff to reduce the risk of flooding.

When it comes to blue infrastructure and their effects on the environment, water bodies have positive impacts related to local temperature reduction, creation of micro-climates and reduction of heat islands formation in cities (Table 1). For instance, 8% of urban wetlands studies focus on thermal & cooling effects, another 5% on urban heat island (UHI) reduction and only 1.5% on climate change issues. Preserving green areas and water resources as a means to

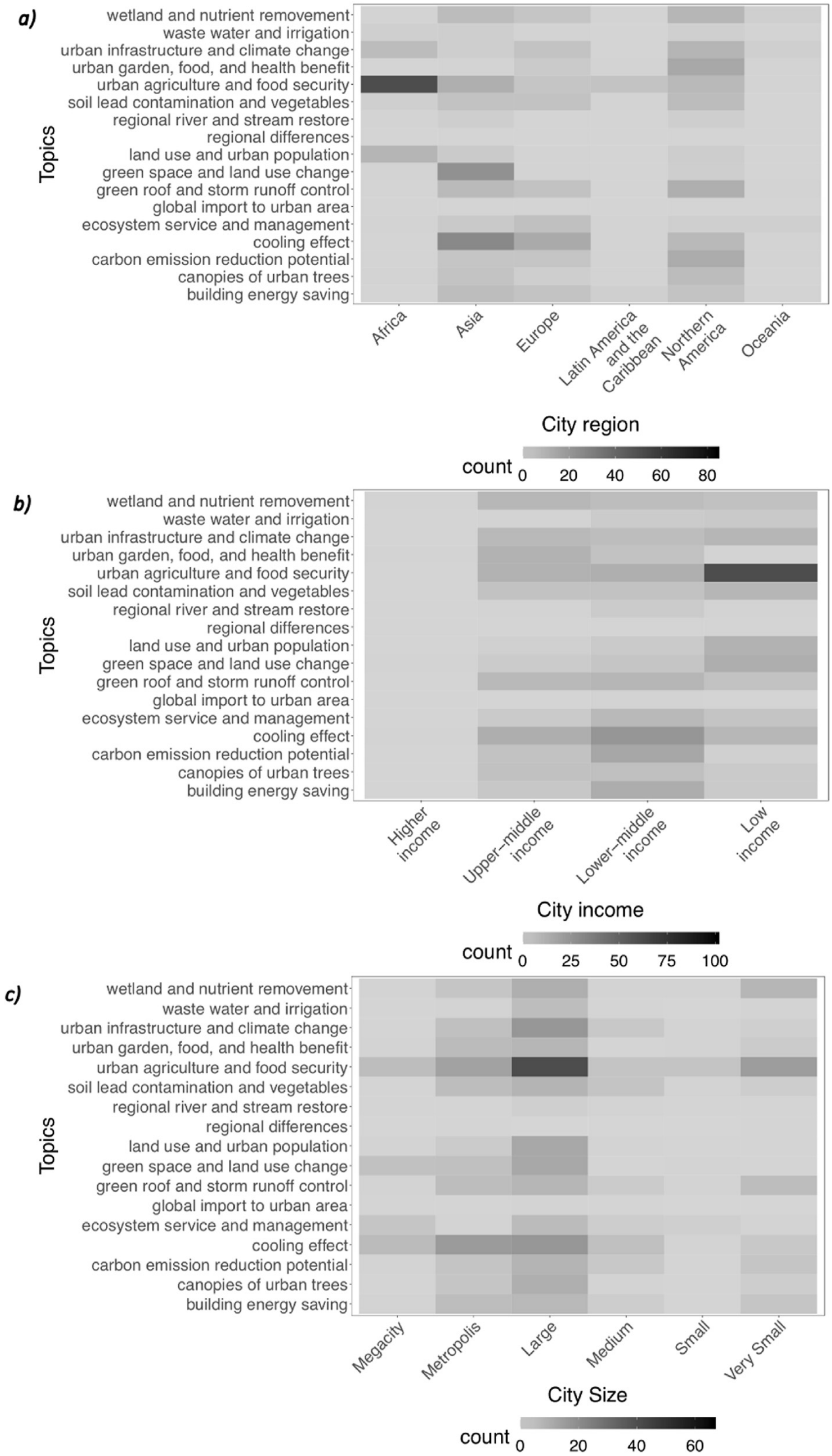

Fig. 1. Heatmap visualization of hot research topics by *a)* city region, *b)* city size, and *c)* city income level.
Note: Urban population data are from the "United Nations Urbanization Prospects Population Data" for 2015 for cities over 300,000 inhabitants. Multiple data sources were used to determine the population for cities with less than 300,000 inhabitants (data sources include the UN, country censuses, Wikipedia census counts and population-specific websites – Population. city, City Population, CEIC, World Population Review). Cities were grouped into six different population sizes, according to the UN classification (UN 2018): Very Small (<0.3 Million), Small (0.3–0.5 M), Medium (0.5 – 1 M), Large (1 – 5 M), Metropolis (5–10 M), Megacity (>10.0 M). For more details on city size ranges please refer to: https://population.un.org/wup/Publications/Files/WUP2018-Methodology.pdf.
GDP per capita for each city was used to rank cities by income level, with data from DRYAD (Kummu et al., 2019), a nonprofit membership organization recognized as a 501(c)3 organization by the U.S. Internal Revenue Service (available at: https://datadryad.org/resource/doi:10.5061/dryad.dk1j0). Four quartiles (i.e. at each USD$ 14,350.96) were defined, according to the lowest and highest GDP analyzed, as follows: Low-income (USD$ 979.42–15,330.39), Lower-middle income (USD$ 15,330.39–29,681.35), Upper-middle income (USD$ 29,681.35–44,032.31) and Higher-income (USD$ 44,032.31–58,383.27).

counteract the effects of heat islands, promote greater biodiversity and flood protection in urban centers is just one way to promote ecosystem services that can be enhanced through efficient management of water and green adjacent areas, contributing to greater livability of cities. However, interesting trade-offs may take place. Water bodies mentioned above can also act as heat retention systems, contrary to the expected process of local temperature reduction (Moyer and Hawkins 2017). Therefore, positive or negative effects from (in this case) water bodies on human well-being must be analyzed from the overall socioecological context of particular urban areas (Haase et al., 2014). For example, water bodies have positive impacts related to local temperature reduction in temperate low humidity climates. In cities with hot humid climates, water increases humidity, has little effects on temperature but reduces overall human thermal comfort. Other unintended negative effects may also arise, for example, from the use of wastewater as a source of irrigation for urban gardens (Lydecker and Drechsel 2011; Egwu and Agbenin 2013), as well as from the increase of mosquito borne diseases that can be exacerbated by GBI (Lõhmus and Balbus 2015). In addition, promoting the expansion of urban green spaces can increase the demand for irrigation as well as compete for land with food production in cities (Lowry et al., 2011; Johnson et al., 2015; Thomas and Gill 2017).

Green infrastructure, street trees, green spaces, green roofs, urban forests and other vegetation such as urban agriculture can help reduce local temperature (Table 1). These effects on temperature are due to shading of urban surfaces and evapotranspiration mechanisms (Livesley et al., 2016; Endreny et al., 2017; Amani-Beni et al., 2018; Sangkakool et al., 2018). These green infrastructures, when located near or over buildings, have an even greater impact on local micro-climate, and reduce the need for artificial cooling and indirectly contribute to energy savings (Santamouris 2014; Morales et al., 2016; dos Santos et al., 2019; Xiao et al., 2018). Urban forests and trees are also highlighted by the literature for their potential to store carbon (McGovern and Pasher 2016; Woldegerima et al., 2017; Park et al., 2018), as well as to improve urban runoff and flood control (Thiagarajan et al., 2018). Urban agriculture advocates argue that some energy can be saved from the avoided food mileage, as well as from avoided packaging and cooling activities. Some authors, however, suggest that UA in temperate climates has the potential to be a more environmentally damaging food source than conventional agriculture, mostly due to energy-related impacts linked to greenhouses operation (Goldstein et al., 2016). Nonetheless, gains in energy efficiency could be realized through the co-location of UA operations with waste streams (Mohareb et al., 2017). Different conclusions on the same subject have motivated researchers to seek an integrated framework that takes all the trade-offs and indirect effects of each GBI into account.

3.2. Heterogeneity of GBI-FWEN links in global cities

In this section we present the core topics found in the GBI-FWEN literature. Based on the results of topic modelling, we summarized the frequency of different topics by cities with different size (population) and income level (per capita GDP) located in the global regions. The detailed descriptive data are presented in supplementary information file (figure SI1). Overall, food-related studies account for 46% of all GBI literature, followed by energy- (31%), and water-related studies (23%). As expected, GBI-FWEN links vary among cities with different characteristics, as below.

3.2.1. A topic map of GBI-FWEN case studies

In an analysis by region, about 55% (519/951) of all urban case studies identified in the literature (with no distinction between GBI types) focused on North America (28%) and Asia (27%) (figure SI1). African and European case studies account for 18% each, while significantly fewer case studies were found in Latin America (5%) and Oceania (5%).

Ninety percent of all GBI studies developed in Africa focused on food-related issues, which leads the region to account for a third of all food-related studies across the globe (figure SI1), with a strong focus on urban agriculture (Fig. 1a). "*Urban agriculture and food security*" has been the main topic studied among the different types of GBI. Therefore, it is intuitive that "*urban agriculture and food security*" is also the most prominent topic among all food-related topics in GBI-FWEN literature. In addition to be the most popular topic in Africa, it has also attracted the attention from Northern American and Asian cities (Fig. 1a). Urban agriculture, as a means to contribute to food security, has become a key urban survival strategy in the rapidly growing but food-insecure cities of the Global South and in Africa (Smart et al., 2015). Particularly in some eastern and central African cities, nearly half of all vegetables and maize consumed by city dwellers are from urban agriculture (Smart et al., 2015). Urban agriculture can also play an important social role in developing countries, since in addition to producing food for consumption, it can be a source of income for the poorest populations and may represent a significant portion of the income of these families (Smith 2001; Smart et al., 2015; Kanosvamhira 2019).

Many topics with different characteristics are distributed mainly in North American and Asian cities (Fig. 1a). It is important to highlight that the different socio-ecological context of cities must be taken into account when promoting nature-based solutions for improvements in FWE systems, especially water and energy systems. About half of all GBI studies developed in Asian cities are energy related. This makes Asia account for 45% among all energy-related studies across the globe, followed by North America (23%) and Europe (22%) (figure SI1). Among all the energy-related topics, "*cooling effects*" has attracted the most attention from researchers, especially in Asia. In the context of rapid urbanization, the temperature of cities continues to increase because of the heat island phenomenon caused by land cover changes from natural and semi-natural land cover types into sealed impervious surface as well as changes in the land surface temperature (Zhou et al., 2017; Marando et al., 2019). In 2015 the Chinese rate of urbanization (i.e. the increase in the proportion of urban population over time) was 56%, and the urban population is expected to increase by 70% in 2030 (Sun et al., 2016). This caused China (116 studies) to become the focus of "*cooling effect*" research in Asian cities (260). In addition, urban green spaces have been proven to significantly decrease ambient air temperature and mitigate heat islands created by urbanization; thus, its cooling effect indirectly contribute to energy savings and emissions reduction (Zhang et al., 2014). Besides, planting trees can alleviate urban heat island effects for their shading and cooling effects, especially in regions with a long and hot summer, such as Taipei (Akbari et al., 1997; Lin and Lin 2010). Technologies aiming to increase the albedo of cities and the use of vegetative-green roofs appear to be very promising, presenting a relatively high heat island mitigation potential, which can also have significant benefits on the energy performance of buildings, providing passive cooling to the built environment (Zinzi and Agnoli 2012; Sisco et al., 2017). Therefore, as it has a high rate of urbanization and is home to large populations, the topics "*cooling effect*", "*green space and land use change*", "*canopies of urban trees*" and "*building energy saving*" are the main topics related to resolving the heat island issue and have been increasingly popular in Asia.

Despite being a drought-stricken territory, studies on the effects of different GBI on water systems have been rare in Africa (<5%). Again, taking into account the local socioeconomic and socio-ecological context (lack of financial resources, basic living conditions and low level of development of cities), it can be inferred that both the low pluviosity and reduced impervious surfaces mean that the region does not suffer from problems such as stormwater runoff and flash flooding. On the other hand, green roofs could be further explored to collect rainwater for irrigating urban agriculture (Sisco et al., 2017), once the latter seems to be a well-developed option in African cities (Kutiwa et al., 2010; Kanosvamhira 2019; Olivier, 2019). Similarly, developing countries often suffer from a lack of wastewater treatment and pollution of water bodies, and therefore some GBI (e.g. urban wetlands) could be used for water treatment (Land et al., 2016; Avellan et al., 2017).

North American cities account for 41% of all water-related studies found in the GBI-FWEN literature, followed by Asia (27%) and Europe (18%). "*Wetland and nutrient removal*" and "*green roof and storm runoff control*" are the most popular topics in these regions (Fig. 1a). Urbanization also has significant impacts on water systems. Rapid urbanization has resulted in decreasing proportions of permeable underlying surface in urban areas and increasing severity of urban stormwater runoff pollution. Indeed, humans have strongly impacted almost every aquatic ecosystem in the world (Baron et al., 2002). Nutrient pollution has become a greater disturbance in these systems as urban development intensifies. Constructed wetlands have been increasingly used for tertiary treatment of domestic wastewater (Table 1) which can then be used for irrigation, cleaning, or to supply water to natural areas as well as to treat agricultural runoff and urban stormwater runoff before the water returns to the environment (Land et al., 2016; Avellan et al., 2017). Additionally, the impervious surfaces such as roads, buildings and roofs are increased in the process of urbanization. This significantly affects the natural hydrologic cycle by increasing stormwater runoff rates and volume. Green roofs as a nature-based solution could reduce urban stormwater runoff, retain a large amount of rainwater for a longer time and delay the peak discharge (Shafique et al., 2018). That could explain why the topic "*green roof and runoff control*" are the most popular in the highly urbanized areas in Northern America, Asia and Europe. It is interesting to note that urban forests and riparian vegetation with pervious soils are highlighted for their potential to improve urban runoff and flood control and in fact, they have a much larger overall area and storage capacity than green roofs (Thiagarajan et al., 2018). However, urban forests are less discussed than green roofs in GBI literature and possible explanations for this may lie in the fact that urban GBI studies commonly disregard forests that extend beyond city limits (regional planning). In addition, green roofs are initiatives that appear as a feasible small-scale option for city residents and can be adapted to different urban conditions such as the increasingly scarcity of areas for the implementation of larger green infrastructures (Zhang et al., 2014; Shafique et al., 2018; dos Santos et al., 2019). Finally, the management of green roofs is centered on individuals, bringing citizens the feeling of being part of a change that can be observed on a small scale.

3.2.2. Case studies bias towards large cities and the Global South

The GBI-FWEN literature shows a heterogeneous distribution according to different population sizes. Most studies focus on cities with a population between 1 and 5 million people, i.e. large cities (37% = 351/951) (figure SI1). The occurrence of studies in cities with opposite sizes such as metropolises (18%) and very small cities (17%) suggests that the benefits of GBI have been explored in different contexts in GBI-FWEN literature. In a division into FWE systems, large cities account for about a half of all food-related studies and about 30% of all each energy- and water-related literature. Studies in metropolises are more concentrated on energy-related issues (22% of all energy studies), followed by food (19% of all food) and water (12% of water), while very small cities are more concerned about water issues (20%).

In an analysis by GBI-FWEN topics, "*urban agriculture and food security*" is a popular discussion in large cities (Fig. 1b). Other topics identified in the literature and related to energy and water systems, such as "*cooling effect*" and "*wetland and nutrient removal*" are also explored in cities with this size. Among all studies on food-related issues in large cities, 46% were conducted in African cities, such as Accra, GHA (11 studies), Kampala, UGA (7), Harare, ZIM (7), Cape Town, SAF (7) and Dakar, SEN (6), all experiencing the rapid urbanization. A possible explanation for the interest of these cities in urban agriculture and food security can be the context of rapid urbanization large cities are experiencing, where urban agriculture is being advocated as a means to mitigate the growing food insecurity of the urban poor. On the other hand, very small cities are also starting to pay attention to urban agriculture and food security, especially those located in Africa.

Forty-two percent of all energy-related studies in large cities were conducted in Asia (39/92), in cities such as Changchun (7), Fuzhou (4), Taipei (3). For metropolises, about half of energy studies are located in China, in cities such as Harbin, Suzhou, and Nanjing. All the studies in these typical Asian cities assess the cooling effect of green space (including forests) at city scale, as shown in Fig. 1a and b. Thus, the energy-related topic "*cooling effect*" has been especially popular in metropolises and large cities. One reason for this may be that larger cities are where heat islands occur more frequently (Zhou et al., 2017) and, depending on the level of local income, may reflect in greater use of air conditioners (Zhang and Lahr 2018). Thus, more GBI initiatives aimed at space cooling could lead to an indirect reduction in the use of energy for this purpose (Sisco et al., 2017; Xiyan et al., 2019). According to IEA (2018), the electricity for space cooling is growing faster than for any other end use in buildings and this demand is expected to triple by 2050. And this is not only because temperatures are rising, but also because people's incomes are growing, especially in hottest countries (most affected by climate change). Projections are that China, India and Indonesia will account for half of all the growth in energy consumption for cooling over the next 30 years (IEA 2018). However, in the case of cities with a lower income level, where the use of air conditioners differs from cities with higher income, the implementation of green roofs (among other GBIs) would be more related to human thermal comfort and well-being provided by these GBI. Even so, some indirect impact on the energy system (depending on the scale of reduction in local temperature), could happen by reducing the use of fans and the energy needed to cool perishables or frozen foods in residential and commercial buildings.

Large cities account for one-third of all water-related studies, while small cities represent 20% of these. Small and medium cities have been attracting less attention in GBI studies that analyze the effects on water. About 45% of studies on water issues in large cities are located in North America (29/69), such as Cleveland (3), Salt Lake City (3), Vancouver (2), St. Paul (2), Portland (2). North America is also the main foci of studies in very small cities, accounting for about 60% of all water-related studies for this city size. Most of the remaining literature on water have been developed in Europe (33%). The effects or benefits of urban green infrastructures such as urban forest, green roofs, rain garden, permeable pavements and wetland detention ponds are evaluated mainly in very small cities of Europe and North America. From a topic analysis, "*wetland and nutrient removal*" and "*green roof and storm runoff control*" are the main water-related topics discussed in both large and very small cities (Fig. 1b). Whether a city is very small or large, located in a low rainfall, hot, arid landscape or in a high rainfall, flood risk climate, the links between different GBI mentioned above and their water-related ecosystem service will not be valued for the same final services in all cities, as each urban center presents its own topographical, climatic, cultural, and industrial context (Livesley at al 2016).

3.2.3. Income level shapes interests in different GBI-FWE links

Overall, studies on GBI-FWEN are divided almost evenly between cities with low- (37% = 352/951), lower-middle (34%) and upper-middle income levels (28%) (Fig. 1c). Probably due to a higher level of development, with better urban infrastructure and reduced local environmental impacts on FWE systems, higher-income cities have not been the main focus of GBI studies (1% of all GBI studies), with 80% of which carried out in Washington, US (4 papers) and Singapore, SIN (4) for the effects of green roofs on UHI reduction (Li et al., 2014; Sangkakool et al., 2018).

Low-income cities focus mainly on food-related issues, accounting for half of all studies on food for all the income levels assessed. Middle income cities respond for the other half (figure SI1). Overall, "*urban agriculture and food security*" is the most popular topic in low-income cities located in Africa (56%) and South-Central Asia (25%). These regions are undergoing the fastest rates of urban population growth (WB 2014). Food access remains a major challenge to food security particularly in the poorest regions of the world (sub-Saharan Africa and parts of Southern Asia) (FAO et al., 2014). The urban poor in low-income cities are especially vulnerable to food security. Unlike the rural poor, urban dwellers do not have access to food safety nets like agriculture, and the high costs of shelter, transport, and healthcare further undermine the affordability of sufficient food (Cohen and Garrett 2010). In addition, urban agriculture is a key source of household income in low-income cities though actual returns are low. Meanwhile, urban agriculture can facilitate women's contribution to household food availability amid other household responsibilities and provide distinct benefits such as economic and social advancement (Poulsen et al., 2015). Future threats to food security such as population growth, global climate change, biodiversity loss, and resource depletion present significant challenges to addressing food insecurity in low-income cities (Godfray et al., 2010).

Energy is the most discussed topic in middle income cities, accounting for 75% of all energy studies (50% in lower- and 25% in upper-middle). This group of cities is more concerned on energy-related topics such as "*cooling effect*", "*carbon emission reduction potential*" and "*building energy saving*" (Fig. 1c), represented by Beijing, Seoul and London in lower-middle group and Hong Kong, Phoenix and New York in upper-middle group. Overall, urbanization boosts household consumption as urban households tend to be wealthier. In addition, with rapid urbanization, an increasing number of rural residents have been migrating to urban areas (WB 2014). In doing so, they gradually adopt local urban lifestyles with high ownership of electric appliances. Thus, urbanization is likely to continue to be an important determinant of the growth in energy use in cities such as Beijing, with well-known impacts on the living conditions and human well-being in urban centers (Zhang and Lahr 2018). GBI initiatives can be a means of not only contributing for regulating microclimates, reducing UHI formation and improving human thermal comfort at building scale (through shading and humidifying effects, among others) but also for mitigating carbon emissions from reduced energy demands. In addition to emissions, middle income cities such as London and Beijing have been increasingly concerned about improving buildings energy (and thermal) efficiency and local distributed generation to make cities more resilient to future energy price shocks or interruptions to supply (ACE 2016; Zhang et al., 2014, Antonopoulus and Shandas, 2019). Therefore, investing in GBIs associated with the energy performance of buildings (green roofs and solar panels in smart buildings, for example) can help cities to meet their energy and socio-environmental goals, maintaining their economic competitiveness.

Middle income cities also account for three-quarters of all water studies (36% lower- and 38% upper-middle). About half of all water case studies were carried out in the U.S., mainly in New York and Los Angeles (23% and 10% of U.S cities, respectively). The remaining 25% of water-related studies has been developed mainly in low-income cities of Asia (China and India) and Europe (England and Italy). From the topic analysis, "*wetland and nutrient removal*" and "*green roof and storm runoff control*" are concerns in lower-middle cities, represented by Beijing, Melbourne and Hamilton. It indicates that developed cities in North American, Asia and Europe that are experiencing rapid urbanization have been the focus of water-related topics.

This systematic review highlights the strategic role of each GBI and its effects on FWEN in different city groups in order to advance the understanding of urban sustainability. It also helps to identify gaps in knowledge and can be useful for decision-making aimed at promoting both GBI and FWEN in cities. We found that GBI can have positive and negative effects on urban FWEN. The negative effects can and should be addressed by policymaking. Finally, in cities with different sizes, different income levels and those located in different regions, GBI can have heterogeneous effect on FWEN and should be adapted to specific local policy targets.

3.3. A conceptual integrated GBI-FWEN framework

Isolated effects of various types of GBI on food, water, and energy resources in cities are well documented in the literature. In contrast, both the integrated and indirect effects of GBI on urban FWEN have been the focus of a small portion of research on FWE systems. The complex relationship between these systems is stressed throughout this study; however, urban demands for food, water, and energy have effects that go beyond the city boundaries (Zhang et al., 2019). Recognizing that few cities can provision all FWE requirements within their own boundary is the first step to the understanding and delineation of second-order or trans-boundary effects of FWE systems (Ramaswami et al. 2012, 2017; Hubacek et al., 2014). Trans-boundary effects are, therefore, influences of process outcomes at one location on possible process outcomes at nearby locations (e.g. supply of municipal energy demand). Large cities may be creating geospatial demands for FWE production that are poorly known and, therefore, the understanding of FWE production-demand linkages can provide insights on where/how environmental conditions can restrict FWE supplies to cities (Hubacek et al., 2014; Ramaswami et al., 2017; Zhang et al., 2019). On the other hand, each city has numerous FWE interactions occurring within its boundaries and GBI can play a key role in alleviating pressures on FWE systems (UNESCAP 2019). Therefore, understanding the relationships between GBI, their effects on the urban FWEN and how these effects will be translated into trans-boundary demands makes it possible to compare, for example, the socio-environmental and economic impacts generated by urban and conventional agriculture. The interdependence between GBI and the FWEN coupled with life cycle analyses of each production system provides an overview of the impacts that solutions adopted in cities can cause when analyzed on a broader scale (Al-Ansari et al., 2015; Villamayor-Tomas et al., 2015; Mannan et al., 2018; Zhang et al., 2019). However, cities often lack detailed relevant data on water, (and especially on) energy, and food systems, which makes both in- and trans-boundary analysis very difficult, posing significant challenges to the practical implementation of the FWEN (UNESCAP 2019; Simpson and Jewitt 2019).

Besides the complexity of the FWEN interrelationships, the lack of a generalizable framework to assess the nexus in cities (and its trans-boundary impacts) is also related to the systems limits

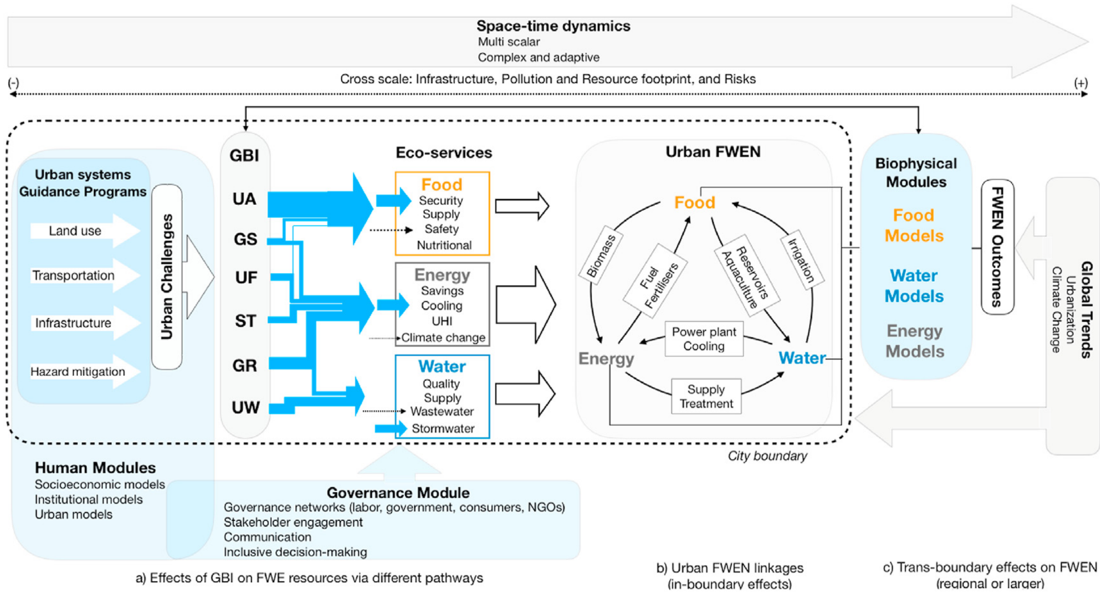

Fig. 2. Conceptual framework for the effects of GBI on the FWE nexus in cities, depicting the importance of further understanding of the sociotechnical system (development of governance, human, urban, and biophysical modules.
Note: UF: Urban forest; GS: Green space; ST: street trees; UA: Urban agriculture; GR: Green roofs; UW: Urban wetlands.
a) Effects of GBI on individual FWE resources and their respective ecosystem services, according to the literature: The thickness of blue arrows represents the number of articles in a given topic (relevance of the pathway). The most discussed eco-service for each food, water, and energy resource is highlighted (small blue arrows). Black dashed arrows represent the main negative effects of GBI on FWE ecosystem services. White arrows represent the connections each FWE box have to different GBIs. The thickness of white arrows represents a highest or lowest connectivity to different types of GBI (relevance for a nexus approach).
b) The FWEN diagram and how it can be affected by different GBI in cities (indirect and in-boundary effects), according to the literature.
c) Indirect effects of GBI on regional FWEN (trans-boundary effects). External factors influencing urban GBI and the FWEN are also highlighted (socioeconomic, biophysical and socioecological components, in light blue boxes).
Source: Adapted from Hoff (2011), Bazilian et al., (2011), Ramaswami et al. (2017), Newell et al., (2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(geographical and analytical) (Zhang et al., 2019). In addition, the different approaches used to evaluate the FWEN makes the search for a conceptual model even more complex (Endo et al., 2015; Albrecht et al., 2018; Newell et al., 2019; Simpson and Jewitt 2019). Despite the lack of more specific technical approaches aiming to reduce the inherent uncertainties of the theme, most of the FWEN studies are technical and lack both institutional and governance analyses to guide stakeholders on how to promote the urban FWE nexus (Bazilian et al., 2011; Frantzeskaki and Kabisch 2015; Biggs et al., 2015; Weitz et al., 2017).

Given the nature of current isolated analysis on urban GBI-FWEN, we provide an integrated framework, based on the findings of our literature review. The integrated framework intends to relate GBI types, FWE topics (or ecosystem services) and FWE systems in an illustrative form as outlined in Fig. 2, which illustrates the overall structure and characteristics guiding the establishment of possible causal relationships. First, specific links are identified through their reiterated occurrence in the empirical results of the studies assessed in the literature review. The links between the main GBI typologies and the food-, water-, and energy-related topics are highlighted (Fig. 2a). Most of these topics can be understood as urban ecosystem services, as they ultimately result in benefits to human well-being (as shown in table SI1). Then, we coupled the well-known nexus framework (Hoff 2011; FAO 2014) to the final services provided by each GBI type.

Overall, the production of energy requires water, while the supply of water requires energy, and the production of food requires both water and energy – these processes are known and are universally applicable (Hoff 2011; Bazilian et al., 2011; Howells et al., 2013). Within city boundaries, the cross-sectoral FWE interactions (shown in Fig. 2b) are also expected to occur in all cities, although the magnitude of contributions will vary by case to case (Haase et al., 2017; SEI 2018; Newell et al., 2019). Beyond city boundaries, we have trans-boundary effects that should be addressed by regional policies (Fig. 2c). Urban FWEN studies are in an early stage (Zhang et al., 2019; Newell et al., 2019; UNESCAP 2019; Mitra et al., 2020) and, therefore, urban GBI links to FWE systems still need to be better understood (SEI 2018; Simpson and Jewitt 2019; Almenar et al., 2021). In addition, given the rapid rate of urbanization worldwide (Seto and Ramankutty 2016), cities can play a key role in adopting the FWEN approach (Artioli et al., 2017). Although conceptual and not exhaustive, this framework allows an initial visualization of what can be done by individuals, companies and political institutions at different scales.

To exemplify how the effects of a given GBI on local and regional FWEN is currently analyzed by the literature, let us take the case of urban agriculture. Studies on UA are more related to food security issues, while its energy and water aspects are less explored (Fig. 2a). Negative effects from UA (and from other types of GBI) are also currently underexplored. Because of the large number of studies linking UA and food issues, food-related topics have been more prominent in the literature (larger blue arrow in Fig. 2a), when compared to water and energy. Since most studies on GBI-FWEN focus on urban agriculture and food-related issues, it is noted that the potential direct and indirect effects that UA can cause on the water-energy nexus are underestimated. Interestingly, these findings differ a little from some reviews of GBI and ecosystem services literature, which have focused primarily on the supply of urban regulating and cultural ecosystem services (Andersson et al., 2014; Haase et al., 2014; Keeler et al., 2019). This difference may be due to the fact that many studies on GBI carried out on a regional scale have not been included in our urban GBI review, which may also contribute to a greater number of studies on a site-specific scale, mostly urban agriculture or green roofs with food production. In addition, the body of evidence firmly establishes the many and diverse socioenvironmental benefits of UA, including more extensive urban food production (Pitman et al., 2015; Russo et al., 2017). In fact, UA has ecological benefits by reducing the city waste, improving urban biodiversity and air quality (among others), and overall reducing the environmental impact related to both food transport and storage (Orsini et al., 2013). Depending on the scale, changes in local food demands caused by UA activities affect the urban FWEN through the food entry point. These changes in the food component will affect the trans-boundary food supply (Fig. 2c), indirectly affecting the urban FWEN, also in terms of water and energy requirements (Fig. 2b). Finally, UA demands themselves will directly affect UA supply and be indirectly affected by both local and regional demands for food.

We found that energy-related topics (or ecosystem services) are linked to a wider variety of GBI typologies (white arrows in Fig. 2a). This indicates that the links between these types of GBI and their energy eco-services are key parts in understanding the local FWEN, and should be further explored by future studies. Part of this interest from the GBI-FWEN literature on energy-related eco-services can be explained by a relevant number of studies developed in large medium-income cities, mostly concerned with their increasing energy consumption and emissions, as well as with the formation of UHIs and energy efficiency of buildings. Overall, this framework can help to unravel a broad set of relationships between GBI-FWE systems, which in turn, could inform urban policies, strategies and interventions.

4. Concluding remarks

4.1. Implications for future research on GBI-FWEN in cities

To date, the majority of FWEN studies have focused mainly on global macro-scale resource security, making it difficult to apply the nexus approach at city scale. Since there is not only a single FWEN model that fits all different analyses or objectives, nexus approaches and frameworks must be scaled or modified for different spatial (e.g., cities, countries, and regions). However, although there is no methodological consensus, FWEN flows can be estimated from different existing frameworks and methods, using qualitative or quantitative approaches. This can be viewed as a weakness, as some findings and specific technical and policy solutions proposed in the reviewed studies are often difficult to synthesize. Another concern identified in the literature is that livelihoods and the environment are often omitted from FWEN assessments. Especially from the perspective of implementing or expanding GBI in urban centers, these issues must be further analyzed by future research, as well as being the focus of policies for food, water, and energy resources.

Our systematic review not only provides evidence of the key effects different urban GBI have on the FWEN, but it also contributes to the identification of gaps and emerging areas of research. Systematic reviews with meta-analyses have become increasingly common due to ever-increasing amounts of data and associated publications, as well as thanks to the use of novel computational data-collection methods (e.g. big data, computational linguistics, and cutting-edge machine-learning techniques). These literature syntheses embodied systematic methods to reliably extract factual and qualitative information from the literature and help researchers deal with large collections of scientific text. However, alternative reviewing approaches that include documents metadata (such as information on authors, citations, year written, or words shared between articles, etc.) should be further employed to map the growing GBI-FWEN literature and make the production of assessments more tractable. Examples of these types of approaches are systematic mapping, bibliometrics, and research weaving (i.e. a combination of bibliometrics and systematic mapping) (Nakagawa et al., 2018). Thus, by providing a better understanding of a topic in terms of both research content and people involved, this information can contribute to researchers forming new collaborations, increasing the effectiveness and capacity of research, as well as driving innovation.

4.2. Policy development for urban GBI-FWEN

Our findings can provide input to public policies and the socio-environmental planning of urban centers. Stakeholders should clearly comprehend how GBI and FWE systems are interconnected in urban areas, aiming to promote cities' sustainability. Despite being ultimately related to human well-being, urban GBI is unlikely to help drive change if their positive effects are not well communicated to stakeholders (i.e. by better connecting with decision-makers, emphasizing participatory approaches, and contributing to capacity building). By developing a conceptual framework with the main links between the urban GBI and FWEN, this paper intends to assist the decision-making process by presenting the impact of main causal relationships on the urban FWEN that result from the implementation of different types of GBI in cities, highlighting potential conflicts or win—win situations. In developing this conceptual framework, the overall message of this article is intended to be useful to different stakeholders, including decision-makers, politicians, technicians, researchers, community leaders, among others.

Policymaking should also integrate different elements (e.g. plans, guidelines, strategies, frameworks) in the FWEN when trying to develop nature-based solutions toward sustainable urban development, since links between research and urban planning are quite limited. This could help avoid unintended consequences, e.g. water contamination as a side product of urban agriculture or increased water and energy demands for green space or food production. Meanwhile, there can be co-benefits as well, e.g., green roofs that control for storm runoff and also bring about cooling effects; urban wetlands that help clean wastewater and reduce urban heat island formation. In addition to their contribution to the quality of life, urban GBI can promote greater resilience in urban areas, thus altering their capacity to deal with growing environmental and socioeconomic issues. Thus, the management of urban GBI must be connected to the socioecological dynamics of each location or region, with their cultural, economic, and political specificities jointly guiding the development of a goal-based GBI-FWEN framework. In this way, policy goal setting should take into consideration the possible synergies and trade-offs associating to a variety of pathways in the GBI-FWEN links, while the effective evaluation of certain GBI development should take into account their impact on multiple elements jointly. These recommendations follow the mainstream of urban GBI, ecosystem services, and FWEN literatures (Haase et al., 2014; Elmqvist et al., 2015; Cohen 2017; Albrecht et al., 2018; Richards and Thompson 2019; Albert et al., 2019; Sarabi et al., 2019; UNESCAP 2019; Simpson and Jewitt 2019; Newell et al., 2019; Seddon et al., 2020; Almenar et al., 2021). As the integrative framework is yet to be developed as a policymaking supporting tool (and will not be exhaustive, since there is no one-size-fits-all model), we hope this review can serve as a starting point for stakeholders to improve understanding of how GBI can affect food, water, and energy systems simultaneously and interactively in urban areas.

Greater integration between local governments and societies with regional and national governments can promote the positive effects of urban GBI on the planning of food, water, and energy systems developed beyond city limits. The advancement of the desired sustainability in the use of scarce resources should not necessarily depend on national policies and initiatives. Smaller and more achievable goals that are closer to citizens can be better accepted by the community, bringing the feeling of being part of a change that can be observed on a small scale. Nature-based solutions are a consequence and cause of changing attitudes towards sustainability in cities, and their development shows that urban planning, political will, and social participation must always be intertwined to make the world a better place.

CRediT authorship contribution statement

Rodrigo A. Bellezoni: Conceptualization, Methodology, Investigation, Data curation, Supervision, Writing - original draft, Writing - review & editing. **Fanxin Meng:** Conceptualization, Methodology, Investigation, Data curation, Writing - original draft. **Pan He:** Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Karen C. Seto:** Conceptualization, Investigation, Supervision, Writing - review & editing, Funding acquisition.

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.

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Appendix A. Supplementary data

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