Implementing the urban food–water–energy nexus through urban laboratories: a systematic literature review

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Abstract
The sustainability of complex resource systems, such as the food, water, and energy (FWE) nexus, is increasingly threatened by climate change impacts, expanding populations, urbanization, and economic instability. However, while research on the topic has burgeoned, studies focused on solution development and implementation, especially at the urban level, have lagged behind. Against this background, we review the urban FWE nexus literature. We focus on the operationalization of solutions for implementation, and seek to identify opportunities for participatory approaches. Our results suggest that operationalization would benefit from: (1) more fully integrating urban social complexity; (2) extending our understanding of the nexus to include social responses to the impacts of interventions; and (3) ensuring that projects build knowledge that is not only actionable, but also credible, salient, and legitimate. We then discuss the potential of local, transdisciplinary approaches, in the form of urban laboratories, to shift the focus of FWE nexus research towards operationalization. We conclude with five recommendations: (1) knowledge development should extend to implementation; (2) stakeholders should be engaged, and be able to align solutions with the agency to implement; (3) research should move beyond material flows, and focus on the behaviors, habits, and social patterns that underpin urban complexity; (4) FWE nexus thinking should become part of participatory/laboratory approaches; and (5) policymakers should integrate nexus research into municipal strategies and plans.

Keywords Urban · Participatory methods · Transdisciplinary · Living labs · Knowledge production · Experimentation · Food–water–energy nexus

Introduction

There is an increasingly urgent need for urban sustainability solutions to address complex resource systems, such as the food, water, and energy (FWE) nexus. In our increasingly interconnected world, sectoral silos are no longer acceptable ways to approach sustainability challenges, because solutions based only on one sector or discipline will unavoidably affect others, whether by design or accident. Such interconnections are particularly evident, and critical in FWE sectors, since each is connected to, and often dependent on, the others. In addition, the sustainability and security of the supply and delivery of FWE resources are increasingly uncertain, due to mounting pressures from climate change, urbanization, population growth, and economic instability (Future Earth 2018).

The concept of the FWE nexus emerged in response to the 2007–2008 energy and food crisis (Allouche et al. 2015), and has gained in popularity since 2011, when an international nexus conference was held in Bonn (Hoff 2011), and the World Economic Forum’s 2011 Water Security Report (Waughray 2011) was published. The concept views FWE resources as an integrated and interactive system, and aims to maximize synergies, and minimize trade-offs between resource sectors (Hoff 2011; Bazilian et al. 2011).

To date, research has predominantly been focused on regional and national levels and, in this context, on conceptual issues (e.g. determining what the system consists
of), and descriptive and analytical aspects (e.g. developing a better understanding of its scope and functioning) (Albrecht et al. 2018). More recently, interest has expanded in two directions: globally, in the context of meeting the 2030 Sustainable Development Goals (e.g. Liu et al. 2018; Simpson and Jewitt 2019b), and locally, with respect to its application in urban development and governance (e.g. Artioli et al. 2017; Newell et al. 2019). However, few studies have examined its operationalization for strategic implementation in society (Albrecht et al. 2018; Simpson and Jewitt 2019b). In their review, Leck et al. (2015, p. 452) observed that we do not yet know “how to implement nexus research and deliver real world solutions at multiple scales and in different contexts”. Similarly, Albrecht et al. (2018, p. 20) stated that operationalizing the nexus will require addressing four key features, namely “innovation, social and political context, collaboration, and implementation in policy and practice”.

In spite of and, perhaps, because of current challenges, recent reviews suggest that there is an urgent need for pathways to action, and that socially-engaged multi- and inter-disciplinary approaches are key to transforming FWE science (Scanlon et al. 2017; Simpson and Jewitt 2019a). FWE system change is a reflexive, ongoing process that requires interdisciplinary and transdisciplinary coordination to achieve desirable impacts (Scanlon et al. 2017; Allouche et al. 2018; Pahl-Wostl 2019). Implementing sustainability solutions can, therefore, be a lengthy process that, ultimately, requires the participation of a plurality of non-academic actors (Halbe et al. 2015).

Calls are growing to incorporate these considerations, and foster solutions-oriented implementation at the urban level (Romero-Lankao et al. 2017; Liu et al. 2017; Allouche et al. 2018; Simpson and Jewitt 2019a). Cities are drivers of global environmental change (Grimm et al. 2008), and are increasingly seen as key to understanding and managing the FWE nexus. They are also critical arenas for transitioning to sustainability, as they represent a concentration of policy, resource consumption, economic activity, population growth, innovation, and entrepreneurship (Fuenthschilling et al. 2019). Urban contexts are highly complex arenas in which social, ecological, and technical systems are inextricably entangled (McPhearson et al. 2016). The complexity of social systems is especially central in the context of understanding and intervening in the urban FWE nexus. Current and historic socio-cultural, economic, and political constructs influence access to, and the distribution, delivery, and use of FWE resources (Romero-Lankao et al. 2017; Alberti et al. 2018). Therefore, although it is clear that there are strong connections within the FWE nexus at all levels, the urban nexus may need to integrate layers of complexity that do not play a central role at higher levels of analysis.

Against this background, this article presents a review of the urban FWE nexus literature. The aim is to identify its operationalization, i.e. the process of moving from science or knowledge to practice, and opportunities to apply participatory, solution-oriented approaches, with particular emphasis on urban experimentation. Building on recent reviews of the broader FWE nexus (Endo et al. 2017; Albrecht et al. 2018; Shannak et al. 2018; Liu et al. 2018; Simpson and Jewitt 2019b), and, specifically, the urban FWE nexus (Zhang et al. 2019a; Newell et al. 2019), we analyze the literature, and seek to identify the components found in solutions-oriented sustainability science research (Funtowicz and Ravetz 1993; Gibbons 1994). We discuss the conceptual shifts that could re-orient the urban FWE nexus towards solutions-based, and participatory approaches, such as urban transdisciplinary experimentation. Finally, we conclude with some recommendations with respect to how to engage participatory change processes in the urban FWE nexus.

Methodology

Literature review

The Scopus database was searched, in November 2019, using the following string: “food” and “water” and “energy” and “nexus” and (“city” or “cities” or “urban*” or “metropo*” or “suburb*” or “periurban”). The results were filtered for peer-reviewed articles in English. This resulted in a total of 128 papers. Two criteria were then applied: (1) Does the study have a stated focus on the food, water, and energy nexus, and not another nexus (e.g. energy, water, and air), or a binary (e.g. food-water) construct? Studies on, for example, the climate, land, energy, and water nexus were, thus, excluded to maintain a comparative baseline; and (2) does the article state that the primary relevance or impact is at the urban level? Finally, review papers identified by the search were checked for any additional articles that may not have been captured. These were added to the set, while the review papers were removed to avoid duplicates. Following the application of these criteria, the initial dataset was reduced to 55 papers.

Analysis

The analysis focused on the operationalization of the FWE nexus, and the potential application of participatory, solution-oriented approaches. Thus, the selected papers were examined regarding: (1) their orientation; (2) their conceptual contribution (if any); and (3) participatory methods (if any). Furthermore, we also considered: (4) any proposed future steps, and whether it appeared that non-academic actors had participated.
In this analysis, operationalization can be studied by identifying any gaps in the strategies and approaches used to move from a descriptive–analytical focus, to the implementation of solutions. We understand implementation as direct action in the social arena. It may take the form of a policy, technical, technological, or other intervention with respect to social constructs, arrangements, or institutions.

Following Wiek and Lang (2016), we suggest that there are two intermediate stages in this transition: proposed solutions and tested solutions. Furthermore, we recognize that, as analyses have predominantly focused on regional and national levels, the reconceptualization of the nexus is a critical step in its operationalization in the urban context. Specifically, the FWE concept must be adapted to integrate social–ecological–technical urban complexities.

Orientation

The selected papers were divided into four categories: (1) descriptive–analytical, (2) proposed solution, (3) tested solution, or (4) real-world implementation. These orientations reflect different approaches, and address different aspects of the problem.

Typically, descriptive–analytical studies are model- or tool-based, and aim to develop a definition of the FWE nexus system. They address complex interactions as trade-offs or synergies, within and between resource systems in domains that range from production through consumption to waste. In contrast, solution-oriented studies address issues that have been identified: proposed solution studies assess the potential impacts of a change/innovation within the nexus; tested solution studies often take the form of a pilot implementation in a sheltered, niche context; and real-world implementation studies examine the implementation of a solution in society.

Re-conceptualization

Articles in the dataset were examined regarding their contribution to the reconceptualization of the urban nexus. Operationalization at the urban level requires the incorporation of social complexity, which determines outcomes in cities, into the nexus concept (Foran 2015; Romero-Lankao et al. 2017). Therefore, we were interested in understanding how the nexus concept has been adapted to urban contexts, and for what purpose. Selected studies were examined with respect to the inclusion of non-academic actors, the integration of social complexity, and future steps.

Participatory methods: actors, and implementation processes

Participation was evaluated by identifying the actor configuration of the study, and any engagement with non-academic actors. Non-academic actors play a key role in mobilizing change processes in multi-level, complex systems (Law 1992; Frantzeskaki et al. 2012; Westley et al. 2013; Pahl-Wostl 2019), and the effective integration of nexus research into governance and policy processes (Newell et al. 2019). Cash et al. (2003) suggest, in the domain of sustainable development, that knowledge must be scientifically grounded (credible), relevant and timely (salient), unbiased, and respect the plurality of stakeholder perspectives and beliefs (legitimate). Non-academic actors can help to indicate knowledge inputs and outputs, the salience and credibility of outputs, and the target of the research. Our review adopted a broad interpretation of participation, as the aim was to capture the involvement of non-academic actors at any stage in the research, including interviews.

Participation was also analyzed in relation to planned implementation processes. Future steps were categorized in terms of, for example, whether more research was recommended, or a pilot study. The analysis also extended to whether the inclusion of other disciplines was recommended.

Results

Our analysis confirmed the lack of approaches that seek to operationalize sustainability solutions in the urban FWE nexus. Only two (4%) studies presented a real world implementation of a nexus solution.

Technical solutions were, by far, the most prevalent. Of the 40% of studies that described potential solutions, they comprised 73%. They were almost equally divided between those that sought to improve resource use efficiency, and those that sought to increase the production of FWE resources (through, for example, urban agriculture, or rooftop solar panels).

Only 7% of studies could be categorized as participatory. We examine these results in more detail in the following sections, based on data included in Supplementary Material 1.

Orientation

Our review revealed that the current literature is largely descriptive–analytical, and focused either on quantifying or conceptualizing the urban nexus. Although many studies considered the potential impact of changes in the nexus, few addressed the testing and implementation of sustainability solutions.

Descriptive–analytical

Descriptive–analytical studies comprised 60% of the dataset (33 papers). Of these, 70% (23) used or developed models or tools to quantify the urban nexus (see Fig. 1).
Models and tools

Studies that quantified the urban FWE nexus used various models and tools (Table 1) to understand resource flows. Unsurprisingly, urban metabolism was well-represented, as were input–output and footprint studies (Albrecht et al. 2018; Newell et al. 2019). This group of studies spans multiple levels. For example, Hussien et al. (2017) studied FWE flows at the household level; Chini et al. (2017) and Feng et al. (2019) concentrated on the city level; Zhang, Zhang, Hao et al. (2019a, b) focused on the regional level; and Ramaswami et al. (2017) tested a trans-boundary urban FWE nexus framework.

Conceptual

Of the descriptive–analytical studies, 27% (9) were conceptual, and proposed a diversity of ways in which to integrate urban social complexity into the nexus.

A clear theme was the need to integrate power, politics, and inequalities. Unequal power dynamics (Covarrubias et al. 2019) are shown to have impacts on justice and resilience (Schlör et al. 2018), access to resources (Martínez-Guido et al. 2019), and health (Giatti et al. 2019). Consequently, Dalla Fontana and Boas (2019) suggested integrating urban political ecology into models. This idea is, in part, exemplified in a model developed by Daher et al. (2019).

Other studies focused on cross-scale or multi-level dynamics. Covarrubias (2019) advocated the need for further analysis to determine pathways that couple material and social flows, while Chirisa and Bandauko (2015) argued that African cities should be considered as a network, to connect the urban nexus with national and regional sustainability strategies and agendas. Schulerbrandt Gragg et al. (2018) used causal loop diagrams to identify cross-scale, multi-level interactions and drivers from local to global levels.

Proposed solutions

Proposed solutions comprised 27% (15) studies, and could be divided into two types: urban agriculture (UA) methods, or quantitative models. Both types explore the potential impacts of innovative techniques or technologies. Exceptions examined the potential of decentralized governance (Lahmouri et al. 2019), household investment strategies (Topi et al. 2016), or urban planning (Gondhalekar and Ramsauer 2017). Nearly all studies recommended more research before implementation, often citing the need for a better understanding of how the suggested change would interact with society.

Many solutions are production or efficiency-based, and explore the potential impact of technical innovations on FWE resources. Quantitative models are used in several studies to assess the potential of technological innovations or to understand FWE systems for decision-making or interventions. Examples include efficiencies in London’s FWE metabolism (Villarroel Walker et al. 2014, 2017), strategies to adapt to seasonal variation in resource use and availability (Hussien et al. 2018), or ways to support decision-making focused on clean energy (Bieber et al. 2018). UA is well-represented. It is often cited as a potential, small-scale solution that shifts the focus from resource use to production. Studies noted multiple benefits, including rainwater capture for local agriculture (Amos et al. 2018), managed algae production to capture nitrogen and phosphorous run off (Dal Bo Zanon et al. 2017), and the reuse of wastewater in local agriculture (Miller-Robbie et al. 2017).

Two participatory studies fell into this category; both were centered on engaging stakeholders in problem–solution discussions, or scenarios. One tested a role-playing game focused on reducing household greenhouse gas emissions (Agusdinata and Lukosch 2019), while Treemore-Spears et al. (2016) used a stakeholder workshop to address complex, socio-historical FWE nexus inequalities.

Tested solutions

Tested solutions only comprised 9% (5) papers, and the majority focused on UA. Sanjuan-Delmás et al. (2018) assessed the feasibility and impact of rooftop greenhouse gardening for food production. A four-step, Roof Mosaic approach was developed by Toboso-Chavero et al. (2019) as a way to integrate food and energy production, and rainwater harvesting in cities. Salvador et al. (2019) employed the Roof Mosaic approach to test the potential of a university technology park to be self-sustainable with respect to its FWE needs. Holt et al. (2017) redesigned plasticulture beds to optimize food production while increasing crop density, with pilot studies in the United States.
Table 1  Summary of results within orientation categories

| Orientation                      | Definition                                                                 | Focus of study | Explanation                                                                                           | Examples                                                                 | References                                                                 |
|---------------------------------|---------------------------------------------------------------------------|----------------|------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|----------------------------------------------------------------------------|
| Descriptive-analytical          | Studies aimed at providing more knowledge and information on defining the FWE nexus system and the complex interactions within and between resource systems from production to consumption to waste | Quantitative   | Models and tools generally data heavy analytical methods to identify and understand FWE nexus interactions | Integrated assessment modeling, urban metabolism assessment, material and energy flow analysis, input–output assessment, footprint assessment, network analysis, urban transboundary assessment | Hussien et al. (2017), Liang et al. (2019), Currie et al. (2017), Hu et al. (2018), Chini et al. (2020), Chini and Stillwell (2019), Feng et al. (2019), Zhang et al. (2019a, b), Ramaswami et al. (2017) and Zimmerman et al. (2018) |
| Qualitative                     | Conceptual                                                                | Qualitative    | Studies for developing the FWE nexus concept through understanding complex interlinkages              | Influence of power relations, structures, and functions in FWE nexus management and networks; integrating justice and resilience; access to, and exclusion from FWE resources for disenfranchised communities; urban political ecology; health impacts | Artioli et al. (2017), Covarrubias et al. (2019), Schlör et al. (2018), Martínez-Guido et al. (2019), Dalla Fontana and Boas (2019), Giatti et al. (2019) |
| Proposed solutions              | Studies which suggest potential ways, often innovations, to address urban FWE nexus issues or problems | Impact assessment | Technological innovation innovation techniques or technologies, generally for efficient resource use, are assessed using quantitative models | Inter alia: urine separation, sewage pyrolysis, algae production, clean energy, wastewater treatment and reuse, water reclamation | Villarroel Walker et al. (2014), Hussien et al. (2017) and Bieber et al. (2018) |
| Urban agriculture               | The potential of urban agriculture methods explored for FWE nexus synergies in local resource production | Innovation     | Technology Urban agriculture The potential of urban agriculture methods explored for FWE nexus synergies in local resource production | Inter alia: rooftop rainwater harvesting, upscaling current urban agriculture, floating algae production, aquaponics, wastewater reuse | Amos et al. (2018), Mohareb et al. (2017), Dal Bo Zanon et al. (2017), Wu et al. (2019) and Miller-Robbie et al. (2017) |
| Tested solutions                | Studies in which small scale implementation of solutions are conducted     | Innovations    | Technologies The feasibility and impact of potential solutions are tested in a sheltered, niche context | Vertical rooftop greenhouse, rooftop garden with rainwater harvest and solar panels | Sanjuan-Delmás et al. (2018), Toboso-Chavero et al. (2019), Salvador et al. (2019) and Holt et al. (2017) |
| Real world implementation       | Studies in which solutions are implemented at their intended level         | Solution       | Implementation The enactment of a policy, regulation or other municipally backed program                | Subsidy program to encourage paddy rice farming to replenish urban groundwater supplies | Taniguchi et al. (2019) |
| Methodological approach         | Urban Nexus—a transdisciplinary, multi-innovation, ‘living lab’           |                |                                                                                                       | The ‘movable nexus’ for integrating urban living labs for learning and management of urban FWE nexus issues | Yan and Roggema (2019) |
The final paper in this category tested a method developed by Vogt et al. (2014a, b) in the context of a United Nation’s ESCAP, GIZ, and ICLEI project called the Urban Nexus. The authors described three case studies (in India, the Philippines, and Indonesia) that employed the Living Lab construct (Lehmann 2018). Each was influenced by ideas from the circular economy, and targeted FWE resource security, sustainability, and local agency and capacity development, linked with inexpensive, low-tech innovation.

Real-world implementation

Only two studies fell into this category. Taniguchi et al. (2019) examined the outcome of a program in Kumamoto, Japan, when the city determined that a fall in the water table was due to decreased upstream rice paddy farming. Subsidies were introduced to incentivize farmers to irrigate their rice fields. The study found that the initiative both stimulated economic growth, and replenished groundwater levels. However, the authors noted that should the subsidy lapse, these benefits were likely to disappear. In the second study, Yan and Roggema (2019) described the development and deployment of a design-led method. Named the ‘moveable nexus’, it was developed in an urban living lab, and integrated with existing labs in an effort to engage urban resources, technology and knowledge, and improve FWE nexus management.

Participatory methods: actors and future steps

Our analysis highlighted that participatory approaches are rarely used. Only 7% (4) studies included participatory methods, and all of these involved solutions: two described proposed solutions, one presented tested solutions, and one concerned a real world implementation. At the same time, 45% (23) papers directly or indirectly implied the current or future involvement of non-academic actors. Only two (4%) suggested future stakeholder participation in the development of solutions. Sixteen papers (29%) proposed policy implications, which we understand to indicate the potential future use of findings by non-academic actors. Interviews featured in six papers (11%). Although interviews are not strictly participatory, they can indicate the integration of non-academic knowledge systems. However, only in one study were resident stakeholders interviewed, while the remainder gathered information from experts and practitioners (Fig. 2).

Participatory methods

Three of the four participatory studies were described as transdisciplinary. Two of these used urban living labs (Lehmann 2018; Yan and Roggema 2019), and the third deployed a game-based scenario (Agusdinata and Lukosch 2019). The fourth took the form of a stakeholder workshop (Treemore-Spears et al. 2016). Each proposes a different way forward: a return to descriptive-analytical approaches (Lehmann 2018), the diffusion of methods (Yan and Roggema 2019), building on the current study (Agusdinata and Lukosch 2019), and moving toward the implementation of solutions (Treemore-Spears et al. 2016).

Potential future stakeholder integration

Daher et al. (2019) and Schulerbrandt Gragg et al. (2018) were the only two, non-participatory papers that suggested the future, direct participation of stakeholders. Daher et al. (2019) developed a holistic tool, and suggested using its outputs to facilitate stakeholder dialogue, and develop strategic policies. Similarly, Schulerbrandt Gragg et al. (2018) developed a tool, aiming to run field tests that would raise the profile of social issues in urban food systems.

Villarroel Walker et al. (2017) conveyed a need for stakeholder engagement when they suggested that progress “now rests on developing an approach that works more closely with the linguistic, qualitative ways of articulating community hopes and fears, while preserving the networks of causal logic enabling privileged, non-foreclosing policy and technology interventions to be identified” (p. 16).

Although nine papers (16%) proposed technology adoption or diffusion of methods as next steps, none provide details of potential methods or strategies. For example, Hussien et al. (2018) proposed an effective household water saving strategy in Duhok, Iraq, but did not indicate who would use this information, or how. Similarly, UA studies do not indicate pathways for the implementation of innovative solutions, such as floating production for coastal cities (Dal Bo Zanon et al. 2017), rooftop production (Sanjuan-Delmás et al. 2018; Toboso-Chavero et al. 2019; Salvador et al. 2019), or urban aquaponics (Wu et al. 2019).
Policy relevance

A main application of the FWE nexus is in the management of resource systems. Therefore, it is not surprising that 29% of the studies in the dataset claimed to be policy relevant. However, none appeared to be directly connected to an ongoing or forthcoming policy process. Several studies addressed not what policies are needed, but rather how policies are made. For example, in the United States, Feng et al. (2019) advocated taking a holistic view of urban FWE in Detroit, Michigan. In Beijing, China, Li et al. (2019a, b) identified a hierarchy of critical FWE systems and subsystems, and Elagib et al. (2019) advocated integrated decision-making with respect to hazard management and the FWE nexus in Khartoum, Sudan. Finally, Lahnouri et al. (2019) showed the benefits of the decentralized management of FWE resources, emphasizing the need for decision-making among local people who are best-informed about the situation.

Future research into societal actors

Three papers suggested that further research should target societal actors. For instance, Artioli et al. (2017) suggested that research should identify actors who have the authority and capacity to drive integrated management, while Covarrubias and Boas (2019) and Covarrubias et al. (2019) advocated that there is a need for better coordination and skill-building among policy actors and governance networks.

Discussion

Our review reveals a clear disconnect between studies that describe the FWE nexus, those that propose and test solutions, and research into the implementation of these solutions. We identified three main gaps in operationalization, and opportunities to apply participatory, solution-oriented approaches. First, current approaches do not adequately take into account complex urban dynamics that must be integrated when localizing the concept, and its application. Second, the dominant technical solutions do not indicate how to integrate societal actors and their needs. Third, participatory methods remain nascent, and they seem to be a clear window of opportunity for solutions-focused approaches.

In this section, we discuss three broad shifts that can address these gaps and help change the focus from descriptive–analytical to solutions-based. The first is a conceptual shift that seeks to integrate urban complexity. The second aims to foster bottom-up interactions and impacts, and the third requires adapting solutions-based approaches to ensure that new knowledge production is credible, salient, and legitimate.

Shifting the urban FWE nexus to solutions

Integrating urban complexity

Urban nexus framing can help to integrate social complexity, and improve our understanding of a local nexus. Our review confirms that, as Romero-Lankao et al. (2017) suggest, this has already begun. Various issues have been shown to be relevant at the urban level: policies, inequalities, power, historical developments and cultural patterns, politics, and economics (Foran 2015; Kairnns et al. 2016; Artioli et al. 2017; Covarrubias 2019; Dalla Fontana and Boas 2019). However, the preponderance of studies that propose or test technical or technological solutions, but do not address their implementation, confirms that little attention has been paid to developing specific solutions (e.g. Guan et al. 2020; Heard et al. 2017). Furthermore, the express integration of social complexities reflects the need for bottom-up projects, to understand multi-level, multi-sector synergies, and trade-offs (Ramaswami et al. 2017). We recognize that integrating social dynamics into quantitative models is difficult, and that nexus researchers are often already overburdened by data. Therefore, we suggest that researchers accept the uncertainty that is inherent in local, context-specific dynamics, and develop pathways that link social and technical projects with higher-level nexus and sustainability goals and agendas.

From top-down flows to bottom-up interventions

Most of the tested solutions included in this review focus on the resource efficiency impacts of technological solutions. However, such solutions require significant upscaling, and buy-in from the public to have an impact. In this context, we found little evidence of a discussion about the trade-offs and opportunity costs of investing in, and implementing these solutions at the city level (Gondhalekar and Ramsauer 2017; Villarroel Walker et al. 2017).

Impacts from sustainability interventions in the nexus can appear at any level, due to the multi-scalar, multi-level interactions inherent in the nexus. Therefore, the second conceptual shift requires understanding urban FWE nexus interactions not only as incoming flows, but also as outgoing impacts. It is important to understand how the nexus system may respond to an intervention, to avoid unintentional, undesirable consequences (Chapin et al. 2010). This thinking reverses the directionality of flow—from a top-down model, where resources flow from source to use (Bijl et al. 2018)—to a bottom-up model, where the focus is on synergies and trade-offs from use to source. This conceptualization can also help to set boundaries regarding the depth and breadth of the social context (Sect. 4.1.1) associated with an identified FWE nexus sustainability problem (Garcia and You 2016).
Knowledge production

The studies included in this review show that the knowledge necessary for developing and implementing solutions in the nexus is diverse and varied (e.g., Treemore-Spears et al. 2016; Lehmann 2018; Daher et al. 2019; Taniguchi et al. 2019; Agusdinata and Lukosch 2019). They also suggest that, at the implementation stage, certain types of knowledge are more important than others. Therefore, along with shifts in conceptualization, we suggest that the transition to a solutions-orientation requires a parallel shift in the credibility, salience, and legitimacy of academic knowledge. Making research actionable and acceptable is key: if this does not happen, sustainability solutions can become political, cultural, and economic footballs.

It is critical that researchers take into account the local political and socio-cultural context, and to understand how their study may disrupt that context, either now or in the future. Are appropriate municipal policy structures (e.g. integrated resource management pathways) in place? Have municipal departments asked for help? Is the study aligned with current or future planning, and strategies? Who are the actors that have the agency to turn knowledge into action, and what knowledge do they need to enable that action? Who are the potential winners and losers? What can be done to share benefits, and minimize inequalities? We argue that participatory approaches, which address these and other questions, can provide the credibility, salience, and legitimacy for solution-focused research.

Sustainability and participatory approaches

Nexus research requires a plurality of perspectives, interests, knowledge bases, and expertise (Howarth and Monasterolo 2016; Cairns and Krzywoszynska 2016; Kurian 2017; Allouche et al., 2018; Bergendahl et al. 2018; Shannak et al. 2018; Hoolohan et al. 2018). As Scanlon et al. (2017) state, “integrating multiple disciplines in science and academia, industry, and government holds great promise for transforming FEW science for societal benefit” (p. 3554). Yet, our review, like others, demonstrates that transdisciplinary approaches remain rare (Albrecht et al. 2018; Simpson and Jewitt 2019b; Newell et al. 2019). Nevertheless, our work reveals an opportunity to integrate participatory methods from sustainability science, and benefit from inter-and transdisciplinary learning and experience regarding local-level sustainability innovation, strategy implementation, and the governance of change processes (Halbe et al. 2015).

Sustainability science has emerged over the past 20 years, and seeks to address today’s most pressing sustainability challenges (Kates 2001). Sustainability science research can be described as both descriptive–analytical and solutions-oriented (Lang et al. 2012). It aims to determine pathways to sustainability, through interventions that are often based on participatory processes. The latter propose and test actions that can result in societal change (Spangenberg 2011; Lang et al. 2012; Polk 2014). Participation assumes a level of co-production with stakeholders and can, therefore, increase trust, confidence, and applicability to local contexts (Norström et al. 2020). Even short-term participatory approaches, such as the stakeholder workshop conducted by Treemore-Spears et al. (2016), can be seen to support actions that lead to a more just and sustainable society (Culwick et al. 2019). They, therefore, play a key role in the conceptual shifts that are discussed above, as they create a foundation for credible, salient, and legitimate knowledge (Cash et al. 2003).

Our review only identified two longer term participatory approaches (Lehmann 2018; Yan and Roggema 2019). Both studies developed, tested, and partially implemented local FWE nexus solutions, indicating the potential for such approaches. Transdisciplinary research seeks to bring together actors who can co-develop credible, salient, and legitimate knowledge, and implement solutions to sustainability problems within a specific context (Pohl and Hirsch Hadorn 2008; Hansson and Polk 2018). Learning is a key output; actors and stakeholders can become transformative change agents, who are able to apply diverse knowledge systems and perspectives to issues within and beyond the context (Gibbons 1994; Moser 2016). Transdisciplinarity has been used in the urban nexus context to obtain a more holistic understanding of the system (Bergendahl et al. 2018), notably its power dynamics (Bréthaut et al. 2019), and as a way to understand potential solution pathways (Agusdinata and Lukosch 2019). We argue that transdisciplinary processes should be used in multi-sector description–analysis studies that are linked with the development of interventions.

All of the tested solutions included in this review involved experimentation. Most addressed technical and technological solutions, but did not look at how they could be integrated and disseminated in society. In the context of sustainability science, experimentation is a way to test potential solutions to complex, local problems, and trigger a sustainability transition (Sengers et al. 2019). Lehmann (2018) illustrates a transdisciplinary, experimental process, which is often framed as an urban laboratory (UL). The method can bridge the technical and social divide, and help to identify relevant solution pathways.

There are several types of ULs; examples include Transition Labs, Urban Living Labs, City Labs, and Real World Labs (Bulkeley et al. 2016; Schäpke et al. 2018; Culwick et al. 2019). Many have emerged from the tradition of transition experiments (Nevens et al. 2013). According to Sengers, Wieczorek, and Raven (2019, p. 154), “society is itself a laboratory and a variety of real-world actors commit to the messy experimental processes tied up with the introduction of alternative technologies and practices to purposively
re-shape social and material realities.” Thus, ULs can embody the community integration and innovation called for by Villarroel Walker et al. (2017), and provide structure for the stakeholder dialogue proposed by Daher et al. (2019).

Both Lehmann (2018), and Yan and Roggema (2019) employed the Urban Living Lab approach. These two studies highlight the diversity and flexibility of such approaches. Lehmann (2018) show how local FWE land use, production, and delivery issues can be addressed through technological and system innovation, while Yan and Roggema (2019) develop an innovative design and collaboration process for local FWE projects.

Conclusions and recommendations

The concept of the FWE nexus is a significant step forward in understanding the complexity of human–environment interactions. It has the potential to integrate and, in some ways, operationalize the United Nation’s Sustainable Development Goals (Liu et al. 2018; Vanham et al. 2019). However, gaps remain in ways to implement change processes that have desirable sustainability outcomes at multiple levels. Our study builds on the existing literature combining sustainability science and the FWE nexus. For example, Halbe et al. (2015) propose a framework for sustainability transition governance in the broader FWE nexus, and identify key aspects such as experimentation and stakeholder participation. Albrecht et al. (2018) note that innovation and collaboration are essential in moving the nexus agenda ahead; similarly, we argue that a focus on transdisciplinary experimentation is a promising way forward.

Our results lead us to propose the following recommendations. These recommendations are aimed at decision-makers who can facilitate the integration of UL approaches, and operationalize solutions on the ground. They are: (1) carry knowledge development through to the implementation of change strategies; (2) engage relevant stakeholders at all stages in the solutions process to align potential solutions with actors who have the agency to implement them; (3) move beyond flows and metabolism, and engage the behaviors, habits, and social patterns that underpin urban complexity; (4) include nexus thinking in participatory/laboratory approaches, and (5) purposefully integrate research into municipal strategies and plans. Taken together, these five can align the goals of ULs and FWE initiatives. They can ensure that UL outcomes are directly relevant to a broader sustainability strategy, while creating pathways for a sustainability transition in the urban FWE nexus.

Carry knowledge development through to the implementation of change strategies. The FWE nexus literature provides a wealth of tools and models to help us understand how resource systems are entangled at multiple scales (Albrecht et al. 2018); however, this knowledge is rarely operationalized. Our review only identified three research teams that drew upon their previous work to advance toward implementation (Villarroel Walker et al. 2014, 2017; Chini et al. 2017; Hussien et al. 2017, 2018; Chini and Stillwell 2019). Linking context-specific descriptive–analytical research with solution–innovation approaches can optimize overall efforts, exploit synergies, and minimize trade-offs in time, energy, and funding. Coordinating research in this way would enable purposes and objectives that are co-defined with stakeholders on the ground to be aligned with learning and new knowledge that can be efficiently integrated into models and tools. Aligning top-down with bottom-up purposes also addresses the problem of ULs that are run in similar contexts, but which are often unconnected and uncoordinated (Hodson et al. in Marvin et al. 2018).

Engage relevant stakeholders at all stages of the solutions process to align potential solutions with actors who have the agency to implement them. Although participation takes various forms, it is essential to have a core set of key actors and stakeholders who are in a committed partnership with academic institutions to co-define and co-develop a UL. The composition of the project team is critical in establishing the credibility, salience, and legitimacy of outcomes, but it is important to consider this as an open, inclusive, and reflexive process.

The UL often exists across multiple contexts (e.g. social, cultural, political, organizational, and institutional), all of which may have different criteria regarding credibility, salience, and legitimacy (Hansson and Polk 2018). Therefore, it is important to involve and coordinate stakeholders (Covarrubias et al. 2019) who have the agency and capacity to deploy resources in a timely manner (Seyfang et al. 2010; Brown and Westaway 2011; Frantzeskaki et al. 2014; Covarrubias and Boas 2019). Cultivating key public and private sector connections may require a sustained effort to establish trust and buy-in, as short- and long-term planning, coordination, and redundancy are essential for projects to unfold smoothly. Moreover, as the UL evolves, actors or actor groups will shift from the center to the periphery, and back again. Who is ‘sitting at the table’, at what time during the process, can influence the boundaries of the negotiation between what should be done, and what can be done in the UL.

Move beyond flows and metabolism, and engage the behaviors, habits, and social patterns that underpin urban complexity. Broadening the descriptive analysis to include patterns of resource use can be key to nexus sustainability, as these patterns are supported by systems and habits that are held in place by culture, society, and individual preference. FWE resource access, affordability, knowledge, and options are not equally distributed through city communities and populations. Therefore, neither problems nor solutions
may lie within the resource system, but in the underlying societal structures that guide development (Allouche et al. 2015; Foran 2015). The underlying causal elements/interactions, and their enabling conditions may be determined by understanding the complexity surrounding resource use (Halbe et al. 2015). This, in turn, can open up a dialogue about where to focus efforts to obtain the desired impact. Following on from this, strategies for change can be developed, which may require coordinated efforts across scales, sectors, and levels (King and Carbajales-Dale 2016).

*Include nexus thinking in participatory/laboratory approaches.* The outcomes of UL processes, “have the potential to be scaled up across systems of provision to achieve sustainability transitions at a large scale” (Marvin et al. 2018, p. 1)—but only if they are incorporated into higher level strategies and agendas, such as the FWE nexus. Identifying cross-level synergies in FWE resource systems can open up a new perspective that moves learning to multi-level networks, and municipal agencies/authorities. For example, Engström et al. (2018) found a mismatch between local, sustainable energy choices (biofuels), and unsustainable water resource outcomes in biofuel production regions. Understanding such cross-scale and cross-sector trade-offs is key to sustainability in the FWE nexus (D’Odorico et al. 2018). However, ULs often focus too closely on local issues, and neglect unsustainable, unintended consequences elsewhere. At the same time, ULs are well-suited to uncovering, and taking advantage of synergies between social and material flows (Covarrubias 2019). Identifying and understanding the dynamics of interconnections between these flows can have a significant influence on the innovative, experimental solution options in the UL, and their potential impact (Luederitz et al. 2017; Forrest et al. 2019).

*Purposefully integrate research into municipal strategies and plans.* The implementation of the nexus agenda will require multi-level coordination of policies and policy fields (Pahl-Wostl 2019); it must transcend sectoral divisions, and transform approaches to resource use and management. Municipal authorities often have regulatory power over the flow and trade of FWE resources, notably infrastructure investment (or the lack of), which is highly relevant to issues of resource access, affordability, and delivery (Artioli et al. 2017). ULs benefit from institutional level support that can link outcomes to broader sustainability transitions (Evans and Karvonen 2014; Bulkeley et al. 2018). The judicious selection of actors can ensure that high-level agendas are integrated into UL priorities, and that knowledge production is aimed at critical issues, such as the Sustainable Development Goals (Liu et al. 2018; Simpson and Jewitt 2019b). However, this is not without challenges. Hodson et al. (in Marvin et al. 2018) note that coordination requires knowledge, skills, and time. Moreover, the municipality must be onboard, and be able to make personnel available to participate in a variety of labs that might be running at any given time (Yan and Roggema 2019). Staff must have the capacity to aggregate the learning and knowledge that is developed, and have the agency to translate it into policy or other actions (Covarrubias and Boas 2019).

Given the multi-scale complexities of the FWE nexus and the ever-growing importance of cities in global environmental sustainability, we anticipate an expansion of solution-focused approaches. The latter must be contextually relevant, and implementable to meet sustainability and security goals. Our recommendations take into account the potential to integrate transdisciplinary experimentation research at urban and local levels with policy strategies. Moreover, including policymakers in the process would heighten the relevance and urgency of FWE nexus project outcomes. Given the recent surge in interest in the FWE nexus, we hope that the focus turns toward developing solution pathways that link levels and agendas to implement change in policy and practice.

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