Environmental Research Letters

TOPICAL REVIEW

A 40-year review of food–energy–water nexus literature and its application to the urban scale

Joshua P Newell, Benjamin Goldstein and Alec Foster

1 School for Environment and Sustainability, University of Michigan, 440 Church Street, Ann Arbor, MI 48109, United States of America
2 Department of Geography, Geology, and the Environment, Illinois State University, Campus Box 4400, Illinois State University Normal, IL 61790–4400, United States of America
3 Authors to whom any correspondence should be addressed.

E-mail: jnnewell@umich.edu, benjgo@umich.edu and alfost2@ilstu.edu

Keywords: food, energy, water, nexus, urban metabolism, literature review

Abstract

Essential for society to function, the production and consumption of food, energy, and water (FEW) are deeply intertwined, leading to calls for a nexus approach to understand and manage the complex tradeoffs and cascading effects. What research exists to date on this FEW nexus? How have scholars conceptualized these interactions at the urban scale? What are some promising approaches? Where are the research gaps? To answer these questions, we conducted a quantitative review of the academic literature on the FEW nexus (1399 publications) over more than four decades (1973–2017), followed by in-depth analysis of the most influential papers using an evaluation matrix that examined four components: 1) modeling approach; 2) scale; 3) nexus ‘trigger’; and 4) governance and policy. Scholars in the fields of environmental science predominated, while social science domains were under-represented. Most papers used quantitative rather than qualitative approaches, especially integrated assessment and systems dynamics modeling although spatial scale was generally recognized, explicit consideration of multi-scalar interactions was limited. Issues of institutional structure, governance, equity, resource access, and behavior were also underdeveloped. Bibliometric analysis of this literature revealed six distinct research communities, including a nascent urban FEW community. We replicated the analysis for this urban group, finding it to be just emerging (80% of papers have been published since 2010) and dominated by scholars in industrial ecology. These scholars focus on quantifying FEW flows of the urban metabolism in isolation rather than as a nexus, largely ignoring the political and socio-economic factors shaping these flows. We propose the urban FEW metabolism as a boundary object to draw in diverse scholarly and practitioner communities. This will advance research on complex FEW systems in four key areas: (1) integration of heterogeneous models and approaches; (2) scalar linkages between urban consumption and trans-boundary resource flows; (3) how actors and institutions shape resource access, distribution and use; and (4) co-production of knowledge with stakeholders.

1. Introduction

Society has a legion of unfortunate examples in which a ‘solution’ to an environmental or development challenge ends up creating new, often unforeseen problems and dilemmas. Let us consider the example of palm oil (figure 1). The oil palm tree originates from Africa but flourishes in any tropical climate and produces higher yields per hectare than any other oilseed crop (Woiciechowski et al 2016). Oil palm, an ingredient in an array of products (e.g. shampoo, cosmetics, cleaning agents, and toothpaste), is becoming the edible oil of choice for much of the world (USDA—Foreign Agricultural Service 2017). Palm biodiesel is also a popular, cost-effective substitute for carbon emitting fossil fuels (Obidzinski et al 2012). However, to plant it, Indonesia has cleared rainforests and carbon-rich peatlands, helping the country become the world’s fifth...
largest emitter of greenhouse gases. Oil palm plantations negatively affect the water quality of freshwater streams, upon which millions of people depend (Carlson et al. 2014). Then there are the impacts on biological diversity, as conversion from tropical forests to plantations has greatly reduced habitat for species such as the endangered Sumatran Orangutan (Fitzherbert et al. 2008, Kubitz et al. 2018).

The palm oil tale is not unique. Rather, it typifies the perils and folly of developing policies and technologies for one sector (e.g. palm as low-carbon energy source or developmental cash crop), without considering the impacts in other realms (Searchinger et al. 2008). It exemplifies the tradeoffs and cascading effects between food (e.g. palm oil), energy (e.g. biodiesel), and water (e.g. water pollution). Unfortunately, these resources have traditionally been managed as independent sectors. Similarly, research streams—food supply and use, water supply and use, energy use, ecosystem health, socio-economic welfare, land use considerations and governance—reflect particular disciplinary silos and topical foci and have often emerged in isolation from each other.

As an antidote, the scholarly and policy communities have called for a ‘nexus’ approach between food, energy, and water (FEW) to better identify unintended impacts and potential synergies within and across these three sectors (Bazilian et al. 2011, World Economic Forum 2011, Bizikova et al. 2013, Mukuve and Fenner 2015). This is admirable and necessary. However, effectively doing so is another matter. FEW systems interact across a dizzying array of spatial and temporal scales; they are frequently both local and global, immediate and delayed (Ericksen 2008). FEW processes are simultaneously ecological, physical, socio-economic, and political. Nexus approaches necessitate successful interdisciplinary and transdisciplinary collaboration, but also a clear understanding of what is included (and excluded) in a particular FEW study—for fear of repeating unintended consequences the nexus approach was designed to avoid. Indeed, these interactions have become interconnected in ways that we have not yet mapped, delineated, or even understood (Howells et al. 2013).

The purpose of this review paper is threefold. First, we take stock of FEW research over the past four decades (1973–2017). How have scholars and researchers studied the interactions of FEW systems? And for how long? What are some promising approaches and how have identified challenges been addressed? In contrast to reviews of FEW nexus scholarship that are largely conceptual (e.g. Leck et al. 2015), our literature review employs a quantitative and evidence-based approach. This approach follows some excellent recent reviews of the FEW nexus, such as the comprehensive evaluation of FEW methods by Albrecht et al. (2018). We use bibliometric analysis to catalog FEW literature and identify important research communities, influential authors, and topical foci. Then, based on this bibliometric review and informed by expert judgment, we analyze 20 influential papers across four categories: (1) Nexus analytic/modeling approach; (2) study scale (geographic and temporal); (3) FEW system ‘trigger’ or catalyst; and (4) governance.

Motivated by the findings in the bibliometric analysis, the second half of the paper focuses on an emerging body of scholarship on FEW systems at the urban scale. Cities are hotbeds for complex FEW system
interactions and they have become the dominant global demand drivers for flows of all types (Grimm et al 2008, Cordell et al 2009, McDonald et al 2014, Kennedy et al 2015, Ramaswami et al 2017). Globalization processes have intertwined urban areas with distant geographies through the exchange of not only FEW, but materials, capital, people, and the like (Seto et al 2012, Yu et al 2013, Hubacek et al 2014). To analyze this subset of FEW systems research, we essentially replicate the methodological approach used for the broader FEW review: (1) bibliometric analysis of the literature; and (2) identification and analysis of influential papers (10 total) using the same four evaluation categories.

Finally, we consider how these literatures and insights could help craft a coherent, integrative research agenda for urban FEW systems moving forward. We propose using urban metabolism (UM) as an interdisciplinary boundary concept to help integrate complex interactions, disciplines, and stakeholders. Through shared language and empirical focus, boundary objects enable the natural science, social science, and engineering communities to communicate and collaborate more effectively. Each discipline offers particular strengths necessary to understand FEW systems dynamics and interactions.

2. Methods

To understand science and its underlying social and intellectual structure, it is useful to map 'scholarly communities' and their relationships to one another (Small 1997, Zhao and Strotmann 2015). To do so for the academic literature on the FEW nexus, we conducted a quantitative analysis of English-language publications over a 44 year period (1973–2017) using Thomson Reuters’ (2017) Web of Science™ (WOS) citation index. We created two separate literature datasets: one on general FEW nexus research as a whole and one specifically focused on urban FEW research. To generate each, we used a different set of search strings to mine the titles, abstracts, and keywords of all English-language publications in the WOS.

2.1. General FEW nexus literature

The general FEW dataset totaled 1399 publications, based on the WOS search string 'food AND energy AND water AND systems.' The search string was constructed over numerous iterations, developing a broad range of keywords to include as many possible publications on the FEW nexus. For example, 'food AND energy AND water AND nexus' yielded just 193 citations. We excluded articles in the medical and health sciences (e.g. neurosciences, pharmacology, zoology, and nutrition dietetics) that did not discuss relevant dimensions of the FEW nexus. Excluded articles totaled 965 articles for this dataset.

2.1.1. Bibliometric analysis

We then imported the dataset into Bibexcel, free software specifically designed for analyzing bibliometric data (Perrson et al 2009). We used Bibexcel to generate a co-citation network. Co-citation analysis enables one to identify influential publications and relationships within and between a body of publications (Zhao and Strotmann 2015). Co-citation analysis requires a lag time for publications to be cited together (Small 1997, Noyons 2001). We used Gephi, open-source network analysis software, to visualize and analyze the results using a Force Atlas algorithm, which clusters nodes based on the density of links (Bastian et al 2009). To identify FEW research communities in the dataset, we applied the community-detection algorithm (Blondel et al 2008) in Gephi. Generally, high modularity scores indicate the presence of communities within a network (Newman 2006, Shibata et al 2009). Once communities were identified, we labeled their respective research domains by examining the articles within them.

2.1.2. Influential paper analysis

Although relatively comprehensive, the WOS database is primarily limited to English-language publications and it excludes most books and virtually all 'grey' literature publications. WOS also excludes numerous journals, such as Sustainable Production and Consumption, which has published a special issue devoted to FEW systems (Azapagic 2015). Moreover, important FEW systems research to date has been conducted not only by academics but also by governments, nonprofits, and those in the private sector. To capture this important literature, we used the same WOS search strings in Google, limiting our results to the first 100 entries. Unfortunately, it is not possible capture the citations of 'grey' literature publications so they can be included in a bibliometric analysis.

However, this evaluation of the gray literature was instrumental in identifying influential publications on the FEW nexus. Informed by this review, the co-citation analysis, and our own assessment, we selected twenty publications for deeper analysis. Seven were 'conceptual' papers that proposed new ways to model and understand the FEW-nexus generally, and thirteen were case studies.

For the selected papers, we used an evaluation matrix to highlight their respective methodological, topical and conceptual attributes using four criteria: (1) FEW 'trigger'; (2) Nexus modeling approach; (3) Study scale; and (4) Governance. A FEW trigger or catalyst refers to an initial pressure on one FEW sector triggered by demographic evolution, technology shift or other exogenous change that produces ripples and reverberations through the broader FEW network. An example is how growing car ownership in a country could spur biofuel production, affecting the availability of land for food and water for irrigation. Here, energy would be the trigger for shifts in the food and
water systems. **Nexus modeling approach** considers: (a) the general frameworks deployed to conceptualize the nexus; and (b) the specific analytical tools (e.g. Integrated Assessment Modeling) couched within those frameworks or used standalone to investigate the nexus. More precisely, frameworks combine FEW-nexus conceptual models with analytical and decision-making approaches to identify nexus challenges and craft strategies to address these challenges. **Study scale** includes both the geographic scope (i.e. global, regional, national, sub-national or urban) and temporal scale (s) of the FEW study. **Governance and policy** assesses the degree to which the studies considered, for example, the role of formal and informal institutions in shaping FEW systems.

### 2.2. Urban FEW nexus analysis

The citation analysis of the FEWs literature identified an emergent community focused on FEW systems at the urban scale. To analyze, this community in more detail, we essentially replicated the methods (bibliometric analysis and influential paper analysis) used for the broader FEW literature. We generated an Urban FEW’s dataset based on the search string ‘food AND energy AND water AND (city OR cities OR urban).’ This search yielded 213 publications and we conducted the bibliometric analysis using the same steps. To identify influential papers on urban FEWs, we used a more simplified approach. We simply selected the ten most cited papers based on the bibliometric analysis and analyzed them using the same evaluation matrix as for the broader FEW papers.

### 3. Results: meta-analysis of FEW research

Based on our meta-analysis, research on the FEW nexus is a relatively recent area of inquiry. The first publication did not appear until 1988; it documented how changes to precipitation under climate change would affect energy production in Ontario, Canada (Cohen and Allsopp 1988). But as figure 2 illustrates, the FEW research domain has expanded rapidly. In 2016 alone, there were 213 such publications from a range of journals, including *Science* (45 total), *Nature* (18), *Biomass & Bioenergy* (14), *Environmental Science and Technology* (13), and *Proceedings of the Natural Academy of Sciences* (12). Broken down by discipline (WOS-designated) for the entire 1399-publication dataset, the top fields are Environmental Sciences (367 publications), Energy & Fuels (206), Ecology (189), Water Resources (124), and Green & Sustainable Science & Technology (120).

The co-citation analysis of the FEW dataset reveals six distinct scholarly communities or clusters, based on their content coverage (figure 3). Ordered by size, we have labeled these clusters as follows: (1) FEW (136 nodes, *Purple*); (2) Energy–Food (81 nodes, *Green*); (3) Food (60 nodes, *Blue*); (4) Energy–Biofuels (49 nodes, *Yellow*); (5) Ecology (49 nodes, *Orange*); and (6) Urban FEW (42 nodes, *Pink*). These nodes are effectively publications and the supplementary information (available at stacks.iop.org/ERL/14/073003/mmmedia) provides a complete list of them. As indicated, although the WOS search based on keywords yielded these papers, many only tangentially addressed all three (FEW).

The largest cluster (FEW (Pink)) also best represents an integrated nexus-based approach. Prominent nodes are publications by Bazilian *et al* (2011) and Howells *et al* (2013), both of which are included in our 20 influential publications analysis. In total, seven such publications come from this cluster. Notable journals include *Science, Ecology and Society, and Energy Policy*.

The Energy–Food cluster (Green) largely focuses on links between food production, land use change, and GHG emissions. The two most prominent nodes are Fargione *et al* (2008) and Searchinger *et al* (2008). Both papers address the GHGs implications of clearing land for biofuels. Prominent journals in this cluster include *Biomass & Bioenergy, Science, and Agriculture, Ecosystems & Environment*. The Food Cluster (blue) is similar but more broadly focused on the environmental and energy impacts of agriculture. The two most prominent nodes are the Tilman *et al* (2002) paper on agricultural sustainability and the Foley *et al* (2005) paper on global land use. Notable non-journal publications include the IPCC.
Working Group 1 report and an edited volume on water–food by the International Water Management Institute (2007). Prominent journals include Science, Philosophical Transactions of the Royal Society B, and Agriculture, Ecosystems & Environment.

Energy-Biofuels (Gray), the fourth largest community, focuses in particular on energy from micro-algae and related biofuels (e.g. Chisti 2007, 2008, Schenk et al 2008). The community was the tightest in the sense that almost all of the nodes were connected to each other (i.e. almost all of the papers were cited together). Influential nodes include papers by Chisti (2007, 2008) and Chen et al (2008). Prominent journals include Bioresource Technology,
Biotechnology Advances, and Applied Energy. The Ecology (Orange) cluster is more tenuously connected to FEWs, with emphases on ecosystem services (Costanza et al. 1997), biodiversity (Loreau et al. 2001, Hooper et al. 2005), and food web dynamics (Polis et al. 1997). This lack of connection is reflected by the comparatively few links with other communities (figure 3). Papers by Polis and McCann are influential nodes, as are seminal ecology papers by Odum (1969) and Holling (1973). Prominent journals include Ecology, Nature, and Science.

The smallest of the six clusters focused on Urban Food–Energy–Water (Pink). Prominent journals include Science, Energy Policy, and The Proceedings of the National Academy of Sciences. Many of the prominent authors in this community overlap with those from the analysis of the Urban FEWs literature dataset, which is discussed in section 4.

3.1. FEW conceptual papers
We analyzed seven influential papers that conceptualized and proposed analytical frameworks to characterize, understand, and model the FEW nexus. Six came from the academic literature in the WOS-defined disciplines of Environmental Sciences (Miara et al. 2014, Kraucunas et al. 2015), Environmental Studies (Bizikova et al. 2013, Foran 2015), Water Resources (Hoff 2011), and Economics (Biziliani et al. 2011). Of these six, four appear in the FEW cluster of the co-citation analysis, and two were added based upon our assessment of their importance to the academic FEW literature. One came from the ‘gray’ literature (Vogt et al. 2014). In theory, all the reviews placed interdisciplinarity at the core of the FEW research agenda based on the rationale that the breadth of challenges was beyond the requisite knowledge of a single researcher or discipline (Biziliani et al. 2011). In practice, social science was under-represented and there was a preference for quantitative (rather than qualitative) methods. This mirrors the findings of the FEW review by Albrecht et al. (2018) which found that nearly three-quarters of the studies relied on quantitative approaches.

3.1.1. Nexus modeling approach
Each paper proposed an approach to model nexus interactions. As the nexus consists of individual components interacting in unforeseen ways, systems thinking dominated the modeling approaches. For instance, Integrated Assessment Models (IAM) use data-heavy mathematical representations to capture the interplay of agriculture, energy, hydrology, and climate systems at large scales (e.g. nation, region, or global). The Climate–Land–Energy–Water (CLEW) (Biziliani et al. 2011) and Platform for Regional Integrated Modeling and Analysis (PRIMA) (Kraucunas et al. 2015) frameworks exemplify the application of IAM to the FEW nexus. Related to IAM is system dynamics (SD), a simpler method to mathematically model sub-system interactions and emergent system-level behavior. Foran (2015) suggested using SD to model nexus behavior, and then combining this with critical social science theories to explain the drivers (e.g. demographic shifts, development agendas, etc) and power dynamics that shape the nexus. Simpler than SD is the water footprint method, which accounts for the water needed to provide goods or services. Hoff (2011) proposed applying this method to energy and food production as a means to capture the water–food and water–energy interactions.

Systems thinking can also take qualitative forms. To illustrate the nexus, Miara et al. (2014) and Bizikova et al. (2013) used discussions of the subsystems and their interactions supported by numerical evidence from the literature. The ‘Urban Nexus Approach’ (Vogt et al. 2014) is also primarily qualitative, though fused with a participatory design agenda (to alleviate nexus stress) and management science tools (to monitor progress towards goals).

3.1.2. FEW trigger
The FEW trigger precipitates change throughout the nexus. For instance, Miara et al. (2014) showed how scaling-up production of algal biofuel requires land, water, fertilizer and energy inputs and, in the process, triggers changes to a region’s food production capacity, and energy and water demands. The provision of water (Bizikova et al. 2013), energy (Biziliani et al. 2011, Wagner and Breil 2013, Miara et al. 2014), and food (Hoff 2011) all served as FEW triggers of system-wide change. Often there are multiple triggers: simultaneous growth in demand for FEW. Thus, identifying a single trigger is usually a modeling or conceptual simplification (Hoff 2011).

3.1.3. Study scale
FEW systems operate across multiple scales. For instance, river systems can sprawl across multiple administrative scales and climatic regions. Although most conceptual papers acknowledged the importance of a multi-scalar perspective, when actualized, this was underdeveloped. Many of the papers prioritized a single scale, ranging from project site (Bizikova et al. 2013) to administrative (e.g. city, nation) (Vogt et al. 2014) to ecological (river basin, watershed) (Foran 2015, Kraucunas et al. 2015).

3.1.4. Governance and policy
Governance (i.e. how institutions shape or manage FEW systems) was a key theme in five of the conceptual papers (Biziliani et al. 2011, Hoff 2011, Bizikova et al. 2013, Vogt et al. 2014, Foran 2015). But precisely how this would be tackled in predominantly quantitative frameworks was not clear, even to some review authors (e.g. Biziliani et al. 2011). All studies focused on how formal institutions shape the FEW nexus, except Foran
including their physical inputs and outputs, spatial interlinked production processes that produce goods, studies were mainly quantitative, with two exceptions. We evaluated 13 in institutions to sustainably manage FEW resources. (Sharma 2016 thinking informed an evaluation matrix that identified across a range of disciplines: Environmental Sciences and the identification and enables comparisons of competing technologies and environmental burdens of production systems supply chains (Giampietro et al 2013), to simpler frameworks using one or two specific tools (Davies and Simonovic 2011, Mohtar and Daher 2014, Villamayor-Tomas et al 2015).

Some case studies used modeling approaches proposed in the conceptual papers, including the variants of IAM (Giampietro et al 2013, Howells et al 2013, King 2014, Guillaume et al 2015, Karlberg et al 2015) and SD (Davies and Simonovic 2011). General systems thinking informed an evaluation matrix that identified drivers of change in one nexus component and spillover effects on other components (Rasul and Sharma 2016). Mohtar and Daher (2014), Villarroel Walker et al (2014), and Al-Ansari et al (2015) utilized life cycle assessment (LCA). LCA accounts for the resource use and environmental burdens of production systems and enables comparisons of competing technologies and the identification of environmental ‘hotspots’ in supply chains (Hellweg and Milà i Canals 2014). Villarroel Walker et al (2014) coupled LCA with multi-sectoral systems analysis (MSA) to understand the cross-sectoral and nexus ramifications of technologies and policies on five sectors (i.e. energy, water, food, forestry and waste). Embedded within MSA is the method of material flow analysis (MFA), which tracks the stocks, flows and interactions of materials in sociotechnical or socio-natural systems (Baccini and Brunner 2001). Mukuve and Fenner (2015) also employed MFA, standalone, to the nexus. Other approaches included statistical regression (Siegfried et al 2010) and value chain analysis (VCA) (Villamayor-Tomas et al 2015). VCA describes the interlinked production processes that produce goods, including their physical inputs and outputs, spatial configuration, and governance structures. The case studies were mainly quantitative, with two exceptions. Rasul and Sharma (2016) opted to qualitatively assess each nexus component and its influence on nexus system performance. Villamayor-Tomas et al (2015) combined VCA with the networks of action situations approach (NAS). NAS grapples with decisions surrounding resource use and the social contexts in which those decisions are made. Combining VCA with NAS, thus, describes how and why resources came to be allocated to certain production practices, providing insights into how the nexus might be better managed.

Four cases explicitly quantified FEW-related environmental pressures, such as the greenhouse gas emissions associated with a FEW system (shaded gray, table 1). The remaining studies used water, energy or food indicators to benchmark nexus performance (e.g. calories of food consumed).

3.2.2. FEW trigger
Some authors considered initial shocks to FEW systems in tandem (Al-Ansari et al 2015, Rasul and Sharma 2016), as both state and control variables. Although comprehensive, it is challenging to disentangle cause and effect from such models. Most cases focused on a single nexus trigger: energy (Giampietro et al 2013, Howells et al 2013, Karlberg et al 2015), food (Giampietro et al 2013, Mohtar and Daher 2014, Guillaume et al 2015, Mukuve and Fenner 2015) or water (King 2014, Villamayor-Tomas et al 2015). Others considered a simplified water–food nexus (Siegfried et al 2010, Davies and Simonovic 2011, Giampietro et al 2013). Land was sometimes modeled instead of food (Howells et al 2013, Karlberg et al 2015, Mukuve and Fenner 2015), allowing linkages to a study area’s production capacity, but at the cost of abstracting from final land use (e.g. land for biofuels versus food).

3.2.3. Study scale
Only two of the evaluated studies modeled multiple scales (Mukuve and Fenner 2015, Villamayor-Tomas et al 2015), although the MuSIASEM framework was demonstrated on two scales, but using different cases (Giampietro et al 2013). Researchers prioritized nations (Giampietro et al 2013, Howells et al 2013, Mohtar and Daher 2014, Al-Ansari et al 2015, Mukuve and Fenner 2015) or sub-national administrative regions (Siegfried et al 2010, Giampietro et al 2013, King 2014, Mukuve and Fenner 2015, Villamayor-Tomas et al 2015). Regional (Guillaume et al 2015, Karlberg et al 2015, Rasul and Sharma 2016), urban (Villarroel Walker et al 2014, Villamayor-Tomas et al 2015) and global (Davies and Simonovic 2011) scales saw less attention.

With respect to temporal scale, historical, forecasting and atemporal cases were equally common (5, 4 and 4 studies, respectively). However, the popularity of IAM and SD methods, which are geared towards scenario analysis, suggests that future work may orient towards FEW forecasting. As with spatial scale, temporal scalar mismatch is a concern given that climate
### Table 1. Results of evaluation matrix applied to food–energy–water case studies.

| Author, year | Framework | Nexus modeling approach | Analytical tool(s) | FEW Trigger | Study scale | Governance and policy |
|--------------|-----------|-------------------------|--------------------|-------------|-------------|-----------------------|
| Siegfried et al (2010) | — | Regression model with supervised learning | W → F | Sub-national | 1970–2005 | No |
| Davies and Simonic (2011) | ANEMI | System dynamics | W → F | Global | 1960–2000 | No |
| Giampietro et al (2013) | Multi-scale Integrated Assessment of Society and Ecosystem Metabolism (MuSIASEM) | Integrated Assessment Model (IAM) | 3 cases: | National and sub-national | — | Yes |
| Howells et al (2013) | CLEW | Conjoined IAMs | | National | 2005–2030 | No |
| Villarroel Walker et al (2014) | — | Material Flow Analysis (MFA), Life Cycle Assessment (LCA) | | Urban | 2010 | No |
| Mohtar and Daher (2014) | WEF Nexus Tool 2.0 | LCA | F → E, W | National | 2030 | Yes |
| King (2014) | — | IAM | W → E, F | Sub-national | — | No |
| Al-Ansari et al (2015) | — | LCA | | National | — | No |
| Karlberg et al (2015) | Climate–Land–Energy–Water | Conjoined IAMs | E → W, F | Regional | 2011–2030 | Yes |
| Mukwe and Fenner (2015) | — | Sankey Diagrams (akin to MFA): Resource flow mapping | F → E, W | National, sub-national and local | 2012 and 2015 | No |
| Guillaume et al (2015) | Water Global Assessment and Prognosis (WaterGAP) 2.2 | Hydrology model (akin to IAM) | F → E, W | Regional | 1900–2000 | Yes |
| Villamayor-Tomas et al (2015) | Institutional Analysis and Development Framework | Networks of Action Situations, Value Chain Analysis | W → E, F | Urban and sub-national | — | Yes |
| Rasul and Sharma (2016) | — | Qualitative systems thinking | | Regional | — | No |

Note. Gray shading denotes studies that covered environmental emissions (e.g. greenhouse gases). Blue shading denotes FEW specific frameworks.
and hydrological patterns are often only observable over decades or longer (Cash et al. 2006). For instance, some studies only considered one (Mohtar and Daher 2014, Villarroel Walker et al. 2014) or two years (Mukuve and Fenner 2015). These short time periods are not able to capture slow-changing or decadal climate dynamics, handicapping decisions that may emerge based on these models. Most of the other studies avoided this pitfall by modeling multiple decades (Siegfried et al. 2010, Davies and Simonovic 2011, Howells et al. 2013, Guillaume et al. 2015, Karlberg et al. 2015).

### 3.2.4. Governance and policy

Six papers considered governance issues primarily through discussions of current FEW management practices. Some research addressed multiple scales (Guillaume et al. 2015, Karlberg et al. 2015). For instance, independent management of water resources by each state in the Lake Tana Region of Ethiopia could negatively affect food and energy production across the region as a whole (Karlberg et al. 2015). Others focused on national or regional policies (Siegfried et al. 2010, Mohtar and Daher 2014). Topical foci were water usage and treatment (Siegfried et al. 2010, Villarroel Walker et al. 2014), food security (Al-Ansari et al. 2015), institutions (Villamayor-Tomas et al. 2015), social, economic, and land use issues (Karlberg et al. 2015, Mukuve and Fenner 2015), carbon emissions (Mohtar and Daher 2014), and biofuels (King 2014). Some studies chose to address specific policies to manage a nexus component and how that might shape nexus behavior overall. An example is Karlberg et al. (2015) who found that the Ethiopian federal government’s plans for agricultural intensification would have negative tradeoffs in terms of water use.

### 4. Results: meta-analysis of Urban FEW research

The urban FEW dataset reveals the formation of just one community (figure 4). Although partially...
attributable to its smaller size (213 publications), a more significant factor is its adolescence, with 80% of studies published after 2010. In terms of WOS categories, they closely resemble the larger dataset and include: Environmental Sciences (103 publications); Green & Sustainable Science & Technology (37 publications); Environmental Engineering (37 publications); Environmental Studies (29 publications); and Water Resources (26 publications).

As figure 4 illustrates, the major nodes and edges are tightly clustered and dominated by scholars from industrial ecology (IE) and cognate fields, with some notable exceptions. These include seminal papers by Rees (1992) (trained in ecological economics and regional planning) on the ecological footprint, by ecologist Folke and colleagues (Folke et al 1997) on ecosystem appropriation by cities, and by biologist Decker and colleagues (Decker et al 2000) on energy and material flow through the urban ecosystem.

To analyze the urban FEW literature more deeply, we evaluate the top 10 cited papers in this cluster, the majority of which are from the field of IE (shaded gray in table 2). The most highly cited paper is by Abel Wolman (1965), who famously introduced the concept of a city’s ‘metabolism’.

4.1. Nexus modeling approach

Although no study proposed or applied formal urban FEW frameworks (a la Vogt et al 2014), ‘UM’ modeling was ubiquitous. In IE and engineering circles, UM is defined as, ‘the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste’ (Kennedy et al 2007, p 44). UM encapsulates the phenomenon of urban material and energy demands, which these scholars then try to quantify by various methodological approaches.

All of the UM studies used some form of flow analysis (material or substance) to quantify fuels, electricity, water, food, construction materials and other key ‘metabolic drivers’ at varying complexity. As shown in table 2, this could be either MFA, the study of a general class of materials (e.g. wood, food), or substance flow analysis (SFA), the application of flow modeling to a chemical element or compound (e.g. carbon, nitrogen, etc). Importantly, the modeling focus was limited to anthropogenic sources, with only a few authors discussing the influence of natural processes (e.g. hydrological systems) (Decker et al 2000, Baccini and Brunner 2001, Kennedy et al 2011).

IE UM research has a long history of accounting for FEW flows, but these have been modeled in a stratified manner that have ignored inter-flow relationships, leaving the nexus largely unacknowledged. One exception is the study of London’s metabolism by Villarroel Walker et al (2014) which combined MFA and MSA to capture urban-scale FEW interactions. Moreover, as with the general FEW work, social science approaches were largely lacking, with the exception of Newman (1999) who proposed extending the UM concept to consider measures of livability (e.g. health, income, urban design quality) and socio-economic and cultural dynamics.

4.2. FEW trigger

Only two simplified FEW triggers appeared: energy (Wolman 1965, Barles 2007) and food (Wolman 1965). Analysis of impacts on system-level behavior was limited to general discussions of the dependence on other nexus components as production factors (e.g. agricultural production as a driver of water use for irrigation). Generally, a ‘black-box’ modeling approach predominated, with underlying drivers (be they socio-economic, demographic, geographic, or due to the urban form itself) of FEW and other consumables downplayed, and flows considered in isolation from each other.

4.3. Study scale

In the ten papers, city (core or metropolitan) was the privileged geographic scale. Although all conceptualized cities as open systems linked to distal production regions through ‘trans-boundary’ material and energy flows, only Barles (2009) and Baccini and Brunner (2001) specifically illustrated the embeddedness of the urban FEW system within a broader nexus by showing how multi-scalar modeling affects both the results and the recommendations. Notwithstanding, the studies were largely aspatial with respect to grounding the origins of water, food, energy and other resources in specific geographies (e.g. palm oil from Indonesia), ascribing trans-boundary flows to a distant ‘hinterland’.

Temporally, assessments of a single year dominated, with occasional longitudinal benchmarking (Sahely et al 2003, Kennedy et al 2007) or historical reconstruction (Barles 2007). Single year, static UM snapshots are prone to temporal scalar mismatch and have limited design or policy relevance (Kennedy et al 2011).

4.4. Governance and policy

Numerous studies suggested that UM accounting could aid in developing and monitoring urban environmental policy (Wolman 1965, Newman 1999, Hendriks et al 2000, Baccini and Brunner 2001, Kennedy et al 2011). Only three studies used UM models to assess specific policies and these were limited to water (Wolman 1965) and waste management (Hendriks et al 2000, Barles 2009). No studies seriously explored the social processes and interactions governing UM, with only Hendriks et al (2000) alluding to workshops with key stakeholders as a means to form management policies.
Table 2. Influential papers on the urban food–energy–water nexus.

| Author, year | WoS category | Geographic (location(s)) | Modeling approach | FEW trigger | Study scale | Temporal | Governance |
|-------------|--------------|--------------------------|-------------------|-------------|------------|----------|------------|
| Wolman (1965) | Public, Environmental and Occupational Health | Urban (hypothetical US city) | | | | Single year | Yes |
| Newman (1999) | Environmental Studies, social science methods | Urban (no speciﬁc city) | | | | Single year | Yes |
| Hendriks et al. (2000) | Public Administration | Vienna, Austria | | | Yes | Single year | Yes |
| Decker et al. (2000) | Energy and Fuels | Multiple cities | | | No | | |
| Baccini and Brunner (2001) | Environmental Sciences, SFA/MFA | Vienna, Regional (Metro Vienna), Regional (Metro Paris), Metropolitan (Metro Paris) | | | | | |
| Sahely et al. (2003) | Environmental Sciences | Toronto, Canada | Yes | | | | |
| Kennedy et al. (2007) | Environmental Sciences | Multiple cities | No | | | | |
| Barles (2007) | Environmental Sciences | Paris, France, Metropolitan (Metro Paris), Regional (Paris Region) | No | Yes | | | |
| Barles (2009) | Environmental Sciences | Paris, France | Yes | | | | |

Note: Publications by industrial ecologists are shaded gray.
5. Discussion

Scholarship on the FEW nexus is relatively young (first publication appeared in 1988), with environmental scientists especially prominent. Our bibliometric analysis identified six distinct research communities working in the realm of the FEW nexus, but only one focused on all three (i.e. FEW). Review of 20 influential papers reveal methodological approaches that are largely quantitative and either combine existing modeling tools or customize a particular one. Although the research generally recognizes the importance of spatial scale, explicit consideration of multi-scalar interactions is limited.

One of the clearest and most persistent gaps in the broader FEW literature is the lack of sufficient focus on issues of institutional structure, governance, equity, resource access, and behavior. Although the case studies and conceptual papers reviewed did consider the role of formal institutions, only Foran (2015) considered how informal networks of actors might manage FEW resources. Studies skirted issues of equity in resource use or access by concentrating on aggregate availability within a study system (Mohtar and Daher 2014, Karlberg et al. 2015), rather than FEW distribution amongst actors. FEW components, however, are unevenly shared. For instance, the US produces ample calories per capita (USDA 2018), yet over 15 million households remain ‘food insecure’ (Coleman-Jensen et al. 2017).

Shifting to the urban FEW literature, one finds similar tendencies. This research is even younger (80% of papers published since 2010) and dominated by scholars in the field of IE who deploy UM modeling to quantify material and energy stocks and flows. Although IE UM has significantly advanced knowledge in the area of urban environmental burdens (Kennedy et al. 2007), these approaches have been largely static, insensitive to multi-sectoral interactions and weak on socio-economic and political analyses (Swyngedouw 2006, Newell and Cousins 2015). Some of these ‘metabolists’ are themselves skeptical that simply reporting UM parameters had salience for policy (Kennedy et al. 2011), since underlying demand-drivers and related governance levers are indeed black-boxed.

Both this urban research and the broader FEW literature, therefore, indicate the need for techniques, approaches, and frameworks that can help integrate researchers, policy makers, and actors. FEW nexus challenges necessitate a complex systems perspective to capture component interactions (Bazilian et al. 2011). One means to do this is through ‘boundary objects’. Useful devices to leverage respective disciplinary expertise (Newell and Cousins 2015), boundary objects are malleable concepts that enable communication across disciplines through use of shared terminology, even though a term may be conceptualized will vary by discipline (Brand and Jax 2007). Boundary objects, therefore, provide a mechanism through which to draw in the manifold group of researchers (e.g. ecologists, economists, engineers, geographers, political scientists) and practitioners (e.g. policy makers and planners) necessary to capture interactions and scales in complex systems.

Urban metabolism (UM) is one such boundary object that numerous scholars have identified as particularly appropriate for interdisciplinary collaboration because the concept travels across engineering and the natural and social sciences (Kennedy et al. 2011; Kennedy and Hoornweg 2012; Broto et al. 2012; Pincetl et al. 2012; Ramaswami et al. 2012). But this UM research has evolved into a series of relatively distinct research frameworks amongst various disciplines, with varying definitions, theories, models, and emphases. In fact, bibliometric analysis (1965–2014) reveals that three distinct scholarly islands of UM have emerged: (1) IE; (2) political ecology; and (3) urban ecology (Newell and Cousins 2015). Political ecologists focus on social dynamics and governance of the UM and the methods are predominantly qualitative. Urban ecologists, meanwhile, consider analysis of complex sub-system interactions as the key to understanding emergent urban metabolic behavior (Golubiewski 2012), disavowing what they consider to be ‘black-box’ modeling of IE.

The remainder of this paper, therefore, considers how the urban FEW metabolism might function as a boundary object, bringing together these three ecologies as well as those who have worked in FEW systems more broadly. In terms of the latter, we focus on the infusion of IAM and SD modeling approaches in UM research. In particular, we briefly focus on four key research needs identified in the urban FEW review: (1) integration of modeling from social sciences; (2) spatializing the flows to understand their multi-scalar dimensions; (3) focus on governance and equity; and (4) co-creating useful knowledge with stakeholders and policy communities. These gaps are apparent in broader FEW literature as well. This integration will advance understanding of Urban FEW systems and nexus challenges.

5.1. Integrative nexus framing and modeling

Figure 5 provides a conceptual schematic of a ‘UM’ system that combines the respective expertise of political ecology, urban ecology, and cognate disciplines with that of industrial ecology. Essentially, in this schematic, the UM is composed of four subsystems—governance networks; networked material and energy flows; infrastructure and form; and socio-economic dynamics. These subsystems are themselves, multi-scalar, networked, and often strongly coupled. This interdisciplinary UM framework would then provide the basis for integrated urban FEW nexus modeling that extends beyond the static and segmented flow modeling on environmental burdens that predominates in IE UM research. Interestingly, the communities that interact with these systems all share
a focus on ‘flows.’ The difference being that social science is often focused on flows of information, capital, and influence rather than, for example, mass, energy, and water. In IE UM modeling, the primary analytical tools are MFA, SFA, and LCA.

This urban FEW research could incorporate approaches prevalent in the broader FEW research, especially IAM and SD modeling. The latter would couple particularly well with the mass-balance stock-flow based models. Only a handful of scholars have incorporated SD in UM modeling, focusing on water (Zhang et al. 2008, Qi and Chang 2011) and energy (Feng et al. 2013). IAM could help capture dynamic urban FEW flows and situate them within larger agricultural, hydrologic, and climatic systems. The broad scope of IAM makes it well suited for ‘big n’ studies of coordinated action across cities (e.g. energy, water or food policies across cities in a particular country). Another promising modeling approach, which builds on substance flow analysis, is MSA. Villarroel Walker et al. (2014) used MSA to better understand London’s waste treatment metabolism (see section 3.2).

Then there is network analysis, which is used to infer the causality between the structure and functionality of a complex system (Watts and Strogatz 1998; Barabási and Albert 1999; Strogatz 2001; Newman 2003; Newman 2010). Ecological network analysis (ENA) applies network thinking to resources and environmental challenges (Chen and Chen 2012). Urban systems and FEW systems lend themselves to ENA by virtue of their complex nature, typified by numerous actors and processes interacting in unseen ways. ENA has been applied to urban contexts (Chen et al. 2011, Zhang et al. 2013, Lu et al. 2015) and FEW nexus challenges at urban...
Chen (2015) and other scales (Spiegelberg et al. 2017, Wang et al. 2017), but as with SD, the diffusion of ENA into IE metabolism thinking has been limited (see Zhang et al. 2013, Lu et al. 2015).

The integration of these primarily quantitative approaches with qualitative ones needs further development. Cousins and Newell (2015) integrated a geographic information system, LCA, interviews, and historical analysis to delineate the water supply metabolism of Los Angeles and there are other isolated examples. Foran (2015) proposes blending systems dynamics modeling with governance theory and Miara et al. (2014) fuse energy accounting and qualitative analysis (see section 3.1).

5.2. Multi-scalar perspectives

As noted, IE UM research is largely aspatial with respect to the origins of food, water, energy, and other resources. An initial advancement would be to map trans-boundary material and energy flows to empirically demonstrate how urban areas induce change to FEW systems in distal, scattered locations (Hubacek et al. 2014), illustrating how these are nested and multi-scalar. This would involve coupling urban spatial data with other novel datasets (e.g. trade data, forestry data, geospatial water scarcity data) to track these flows (Flach et al. 2016, White et al. 2018).

The multi-scalar dimension of urban systems, therefore, requires managing, storing, and integrating massive, diverse, and heterogeneous datasets (Townsend 2014). These data come in varying formats, resolutions, monitoring frequencies, identifiers and geo-references (Kitchin 2014). Spatial data have incongruent boundaries, temporal scales, demographic cohorts, and so on. National and state agencies may regularly collect standardized data, but most urban governments do not (Horta and Keirstead 2017). Political units of analysis do not always capture important FEW dimensions, such as natural systems (e.g. trans-boundary river flows). As Cash et al. (2006) identify, these ‘scalar mismatches’ frequently cause failures in natural resource management.

One example are the very aqueducts praised by Wolman (1965) that bring water to the arid cities of the Southwest US. Although they alleviated water shortages for these cities, these aqueducts also supported a population boom that has necessitated import of yet more water from ecosystems and watersheds suffering climate change-induced drought (MacDonald 2010). In essence, mid-century planners solved immediate problems within these cities, but degraded environments outside the city and built a system that may be unable to adequately supply water in the future. Fortunately, emerging data integration and management tools can be used to capture the multi-scalar dimensions of the urban FEW systems. For example, scholars at the University of Illinois-Chicago have used an UM framework to integrate, visualize, and analyze heterogeneous geospatial and temporal data (Cruz et al. 2013).

5.3. Governance and policy

UM studies in IE have been anemic in terms of equity, governance, and behavioral dimensions of material and energy flows. With respect to policy, these studies often end with lackluster prescriptions and recommendations for how to manage urban resource flows more efficiently. As Foran (2015, p 656) has concluded, the ‘social dimensions of resource linkages remain thinly described and undertheorized,’ necessitating a ‘critical social science of the nexus.’ A foundation for this exists. Political ecologists, for example, have published research on the UM of cities in the US, Europe, and beyond (Gandy 2002, Keil and Boudreau 2006, Heynen et al. 2006, Demaria and Schindler 2016). A key research focus has been unveiling power relationships shaping urban space with the normative goal of fostering more sustainable and democratic forms of urban environmental governance and policy-making (Swyngedouw and Heynen 2003, Desfor and Keil 2004, Swyngedouw 2004).

Social scientists are also developing innovative approaches to the co-production of knowledge and action with stakeholder and policy communities (Frantzeshaki and Kabisch 2015, Muñoz-Erickson et al. 2017). Management and assessment models may be scientifically sound, but publicly unacceptable if developed ‘behind closed doors.’ In these instances, the motivation behind them, how they are constructed, and their utility appears obscure to stakeholders (Driessen and Glasbergen 2002). Open and participatory model development builds familiarity, confidence and acceptance in the models and enables a more diverse group of participants to engage (van den Belt 2004). Albrecht et al. (2018) highlighted these ‘digital sharing platforms’ (e.g. Wolfe et al. 2016) as promising means of communicating nexus complexity to diverse stakeholders. Decision support systems (DSS) provide a portal by which the expert or participant structures model input to simulate future desired conditions (Serat-Capdevila et al. 2011). A DSS also enables presentation and visualization of model results. There are cooperative modeling exercises supported with an accompanying DSS targeted at the shared needs of FEW producers, resource managers, regulators, and decision makers (Renger et al. 2008).

Through this co-production, stakeholders feel a sense of common, shared ownership and confidence in the resulting models (Cockeill et al. 2007, Tidwell et al. 2008). This confidence is then conveyed to policy makers and the public in ensuing management decisions. For these reasons, in their Urban NEXUS framework, Vogt et al. (2014) made participatory design integral to the development of urban FEW management policies. Another example of this co-production is the Network of Action Situations approach used by Villamayor-Tomas et al. (2015) in their FEW case work.
5.4. Other FEW systems as boundary objects

Framing the urban FEW metabolism as a boundary object can attract a diverse group of scholars and practitioners to more fully capture the scale, complexity, and interactions of a particular system. We have briefly noted how this could enable the infusion of modeling approaches (e.g. SD), data management and visualization strategies, consideration of governance dynamics, and the development of decision-support and collaborative planning tools. Other FEW systems (e.g. food supply chains, bioenergy production, waste water treatment) could similarly serve as empirical boundary objects to collaboratively develop integrative approaches and responses to sustainability and resilience challenges.

6. Conclusion

Past failures in managing FEW resources underscore the importance of considering interconnections between food, energy, and water. As a response to these failures, scholars, planners, and policy makers have proposed a nexus approach to understand tradeoffs, spillover effects, and synergies. FEW-nexus scholarship first appeared in 1988 and through bibliometric analysis we identified six distinct communities in this rapidly expanding area of research. Broadly speaking, these communities theorize the FEW nexus as a system of systems that requires analyses of interdependencies. Like other reviews, we found a deficit in terms of theorizing and analyzing the socio-economic dimensions of the nexus (Albrecht et al 2018, Boyer and Ramaswami 2017), particularly the actors and institutions that shape access, distribution, and use of FEW.

One of the six FEW communities is a nascent cluster on urban FEW systems; this is salient given that cities drive global FEW use through their consumption (direct and indirect). These scholars are predominantly industrial ecologists who model the material and energy flows of the UM and have historically treated each nexus component in isolation, even when modeling the stocks and flows of all three. We can augment this approach by deploying the urban FEW metabolism as an empirical boundary object to attract the diverse researchers and stakeholders necessary to collectively diagnose and address ecological, material, and socio-economic challenges. The paper identifies specific modeling tools (e.g. SD, IAM, and ENA), qualitative approaches, and co-production strategies to move beyond black-box aggregate measures of a city’s metabolism, to capture relationships between nexus components, and to understand the multi-scalar processes that drive direct and indirect city-scale use of food, energy, and water. By incorporating these approaches, collaborative urban-FEW nexus research can produce scholarship that helps cities move towards a sustainable FEW-nexus, both within and beyond their administrative boundaries.

Acknowledgments

The authors would like to thank the US National Science Foundation (NSF) for sponsoring this research. These including the following NSF grants: FEW Workshop: Scaling-up Urban Agriculture (#1541838); Sustainability Research Network (SRN, #1444745); and UNS: U.S.–China: Integrated Systems Modeling of Food–Energy–Water (FEW) Nexus for Urban Sustainability (#1605202).

ORCID iDs

Joshua P Newell @ https://orcid.org/0000-0002-1440-8715
Benjamin Goldstein @ https://orcid.org/0000-0003-0055-1323

References

Al-Ansari T, Korre A, Nie Z and Shah N 2015 Development of a life cycle assessment tool for the assessment of food production systems within the energy, water and food nexus. Sustain. Prod. Consum. 2 52–66
Albrecht T, Crootof A and Scott C A 2018 The water–energy–food nexus: a comprehensive review of nexus-specific methods Environ. Res. Lett. 13 043002
Azapagic A 2015 Special issue: sustainability issues in the food–energy–water nexus Sustain. Prod. Consum. 2 1–2
Baccini P and Brunner P H 2001 Metabolism of the Anthroposphere (Cambridge, MA: MIT Press)
Barabási A-L and Albert R 1999 Emergence of scaling in random networks Science 286 509–12
Barles S 2007 Feeding the city: food consumption and flow of nitrogen, Paris, 1801–1914 Sci. Total Environ. 375 48–58
Barles S 2009 Urban metabolism of Paris and its region J. Ind. Ecol. 13 898–913
Bastian M, Heymann S and Jacomy M 2009 Gephi: an open source software for exploring and manipulating networks 3rd Int. AAAI Conf. Weblogs Soc. Media pp 361–2
Bazilian M et al 2011 Considering the energy, water and food nexus towards an integrated modelling approach Energy Policy 39 7896–906
van den Belt M 2004 Mediated Modeling: A System Dynamics Approach to Environmental Consensus Building (Washington, DC: Island Press)
Bizzozero L, Roy D and Swanson D 2013 The water–energy–food security nexus: towards a practical planning and decision-support framework for landscape investment and risk management IISD Report (Winnipeg, International Institute for Sustainable Development)
Blondel V D, Guillaume J-L, Lambiotte R and Lefebvre E 2008 Fast unfolding of communities in large networks J. Stat. Mech. Theory Exp. 10008 6
Boyer D and Ramaswami A 2017 What is the contribution of city-scale actions to the overall food system’s environmental impacts? Assessing water, greenhouse gas, and land impacts of future urban food scenarios Environ. Sci. Technol. 51 12035–45
Brand F S and Jax K 2007 Focusing the meaning(s) of resilience: resilience as a descriptive concept and a boundary object Ecol. Soc. 12
Broto V C, Allen A and Rapoport E 2012 Interdisciplinary perspectives on urban metabolism J. Ind. Ecol. 16 851–61
Carlson K M, Curran L M, Ponette–González A G, Ratnasari D, Ruspita, Lisnawati N, Purwanto Y, Brauman K A and Raymond P A 2014 Influence of watershed–climate interactions on stream temperature, sediment yield, and
Available at https://www.ers.usda.gov/data-products/food-availability-per-capita-data-system/interactive-charts-and-highlights/ (Accessed: 22 February 2019)

USDA—Foreign Agricultural Service 2017 Oilseeds: World Markets and Trade (December 2017) (United States Department of Agriculture)

Villamayor-Tomas S, Epstein G, Evans T and Kimmich C 2015 The water–energy–food security nexus through the lenses of the value chain and the institutional analysis and development frameworks Water Altern. 8 735–55

Villarroel Walker R, Beck M B, Hall J W, Dawson R J and Heidrich O 2014 The energy-water-food nexus: strategic analysis of technologies for transforming the urban metabolism J. Environ. Manage. 141 104–15

Vogt C, Zimmerman M and Brekke K 2014 Operationalizing the Urban NEXUS Report (Bonn: Deutsche Gesellschaft für Internationale Zusammenarbeit)

Wagner I and Breil P 2013 The role of ecohydrology in creating more resilient cities Ecol. Hydrobiol. 13 113–34

Wang S, Cao T and Chen B 2017 Urban energy–water nexus based on modified input–output analysis Appl. Energy 196 208–17

Watts D J and Strogatz S H 1998 Collective dynamics of ‘small-world’ networks Nature 393 440–2

White D J, Hubacek K, Feng K, Sun L and Meng B 2018 The water-energy-food nexus in east Asia: a tele-connected value chain analysis using inter-regional input–output analysis Appl. Energy 210 550–67

Woiciechowski A L, Bianchi A, Medeiros P, Rodrigues C, Porto L and Vandenbergh D S 2016 Feedstocks for biofuels Green Fuels Technology (Biofuels) ed C R Soccol et al (Cham: Springer) pp 15–39

Wolfe M L, Ting K C, Scott N, Sharpely A, Jones J W and Verma L 2016 Engineering solutions for food–energy–water systems: it is more than engineering J. Environ. Stud. Sci. 6 172–82

Wolman A 1965 The metabolism of cities Sci. Am. 213 178–90

World Economic Forum 2011 Introduction Water Security: The Water–Food–Energy–Climate Nexus (Washington, DC: Island Press) pp 1–16

Yu Y, Feng K and Hubacek K 2013 Tele-connecting local consumption to global land use Glob. Environ. Change 23 1178–86

Zhang X H, Zhang H W, Chen B, Chen G Q and Zhao X H 2008 Water resources planning based on complex system dynamics: a case study of Tianjin city Commun. Nonlinear Sci. Numer. Simul. 13 2328–36

Zhang Y, Liu H and Chen B 2013 Comprehensive evaluation of the structural characteristics of an urban metabolic system: model development and a case study of Beijing Ecol. Modell. 252 106–13

Zhao D and Strotmann A 2015 Analysis and Visualization of Citation Networks (San Rafael: Morgan and Claypool)