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

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TOPICAL REVIEW

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

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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

Figure 1. Oil palm mill and plantation in Sumatra, Indonesia. Oil palm production–consumption exemplifies tradeoffs between food, energy, and water. Source: Paul Hilton, National Audubon Society.

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, Kubitza *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 FEWs 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 'gray' 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 'gray' 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

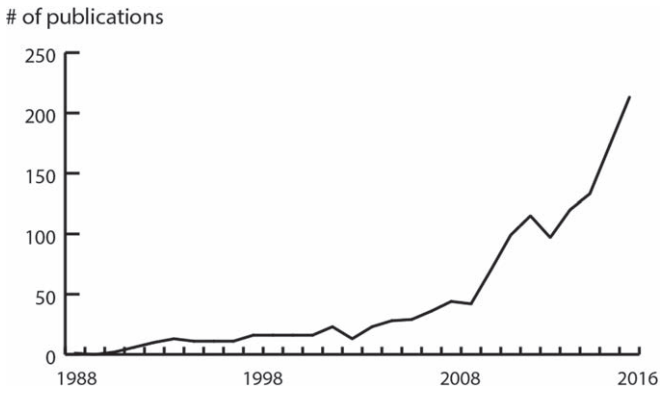

Figure 2. Academic publications on the food–energy–water nexus, 1988–2016.

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 FEWs 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/mmedia) 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

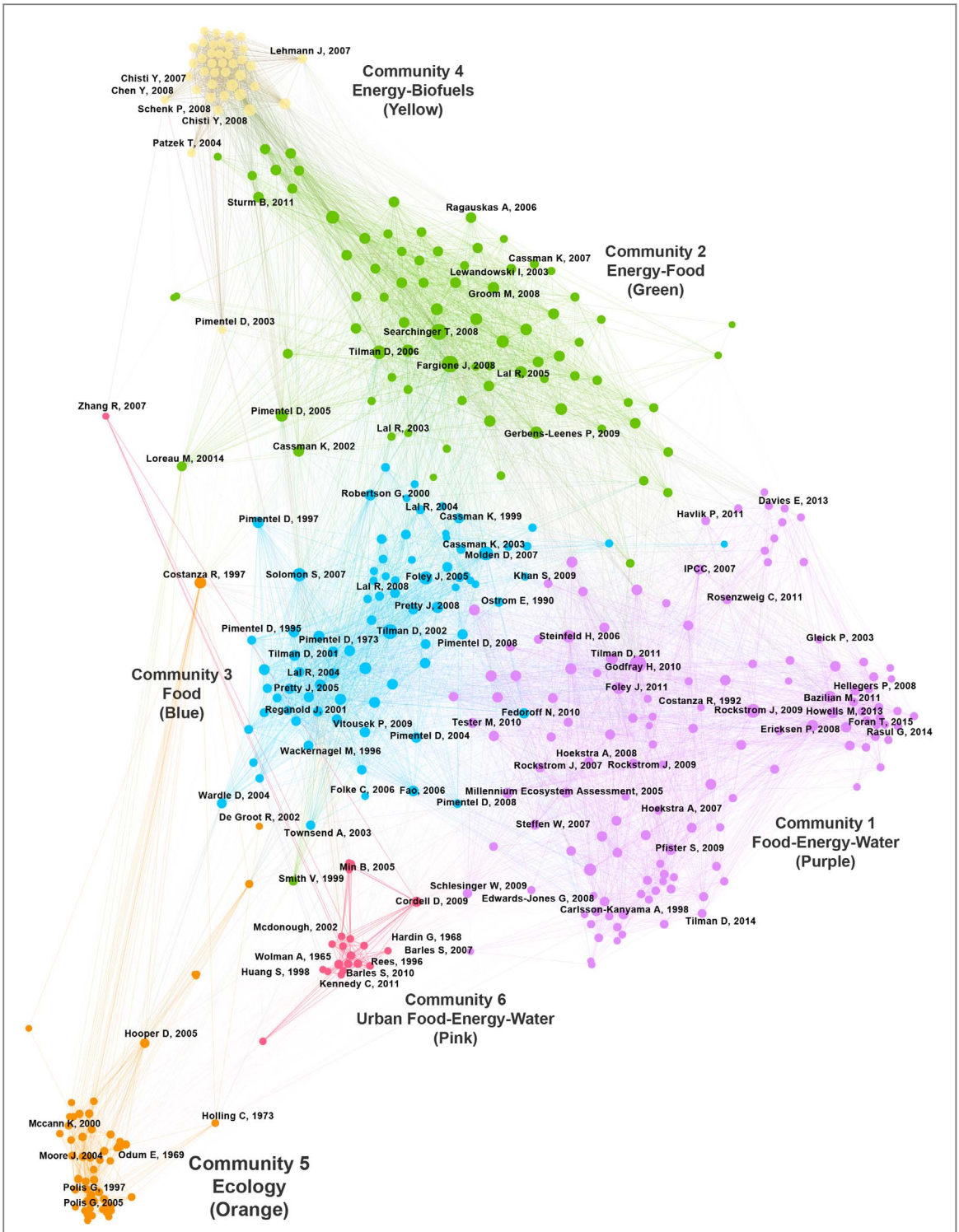

Figure 3. Six scholarly communities of food–energy–water research, 1973–2017. This co-citation network illustrates influential nodes (papers) and their edges (links to other papers). Each node represents a publication that has been cited together with another publication in the dataset. The links ('edges') illustrate the connections between nodes that are cited together. Nodes connected by edges also attract each other, so that the more nodes in a community are connected, the denser it becomes. Similarly, the distance between communities is determined by the number and size of connections between them. These scholarly communities are often highly disciplinary.

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 (Bazilian *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 (Bazilian *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) (Bazilian *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 (Bazilian *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 (Bazilian *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. Bazilian *et al* 2011). All studies focused on how formal institutions shape the FEW nexus, except Foran

(2015) who emphasized the potential for informal institutions to sustainably manage FEW resources.

3.2. FEW case studies

We evaluated 13 influential FEW case studies (table 1) across a range of disciplines: Environmental Sciences (4 studies), Environmental Studies (4 studies), Water Resources (3 studies), Green & Sustainable Science & Technology (1 study) and Agricultural Economic Policy (1 study).

3.2.1. Nexus modeling approach

Six case studies utilized frameworks designed or adapted specifically to FEW systems (shaded blue in table 1). As with the conceptual studies, complexity ranged from meta-frameworks, such as CLEW (Howells *et al* 2013, Karlberg *et al* 2015) and the Multi-scale Integrated Assessment of Society and Ecosystem Metabolism (MuSIASEM) (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.

	Nexus modeling approach			Study scale		
Author, year	Framework	Analytical tool(s)	FEW Trigger	Geographic	Temporal	Governance and policy
Siegfried *et al* (2010)	—	Regression model with supervised learning	W → F	Sub-national	1970–2005	No
Davies and Simonovic (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: F → W F → E, W E → W, F	National and sub-national	—	Yes
Howells *et al* (2013)	CLEW	Conjoined IAMs	E → W, F	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
Mukuve 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.

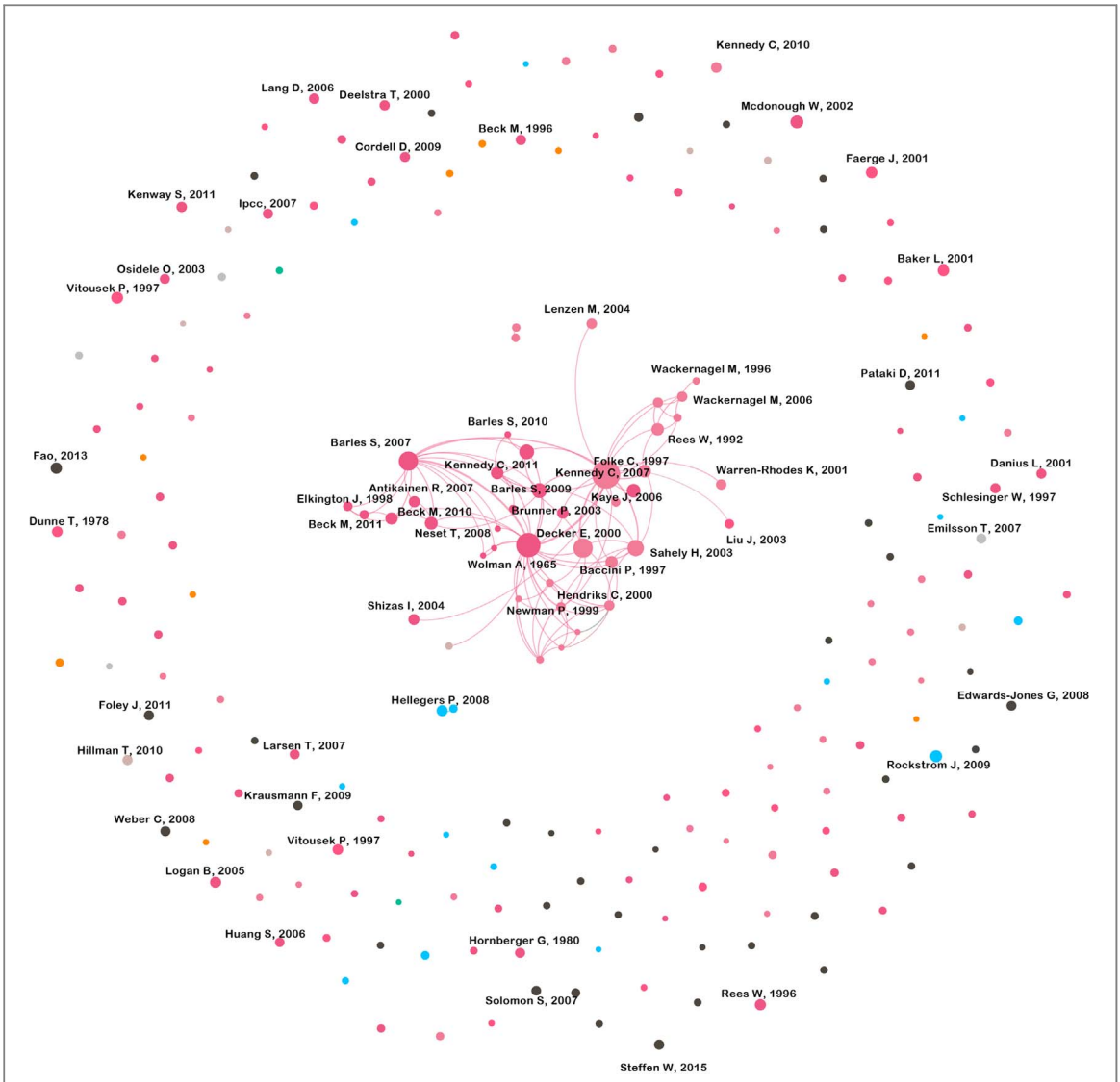

Figure 4. The scholarly community of urban food–energy–water research, 1988–2017. Note how just one cluster has formed in this co-citation network of the literature. It is dominated by industrial ecologists, with some work by those in applied ecology and planning.

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	Modeling approach	FEW trigger	Study scale		Governance
				Geographic (location(s))	Temporal	
Wolman (1965)	Public, Environmental and Occupational Health	MFA	EW, FW	Urban (hypothetical US city)	Single year	Yes
Newman (1999)	Environmental Studies	MFA, social science methods	—	Urban (no specific city)	Single year	Yes
Hendriks *et al* (2000)	Public Administration	MFA	—	Urban (Vienna, Austria)	—	Yes
Decker *et al* (2000)	Energy and Fuels	MFA	—	Urban (multiple cities)	—	No
Baccini and Brunner (2001)	Environmental Sciences	SFA/MFA	—	Urban (Vienna), Regional (Vienna Metro Region)	Single year	Yes
Sahely *et al* (2003)	Environmental Sciences	MFA	—	Urban (Toronto, Canada)	1987, 1999	No
Kennedy *et al* (2007)	Environmental Sciences	MFA	—	Urban (multiple cities)	Single year	No
Barles (2007)	Environmental Sciences	SFA	FE	Urban (Paris, France)	1817, 1869, 1913	No
Barles (2009)	Environmental Sciences	MFA	—	Urban (Paris, France), Metropolitan (Metro Paris), Regional (Paris Region)	2003	Yes
Kennedy *et al* (2011)	Environmental Sciences	MFA, carbon footprint	—	Urban (no specific city)	—	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 how 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 predominately 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 nexus 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 stakeholder 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

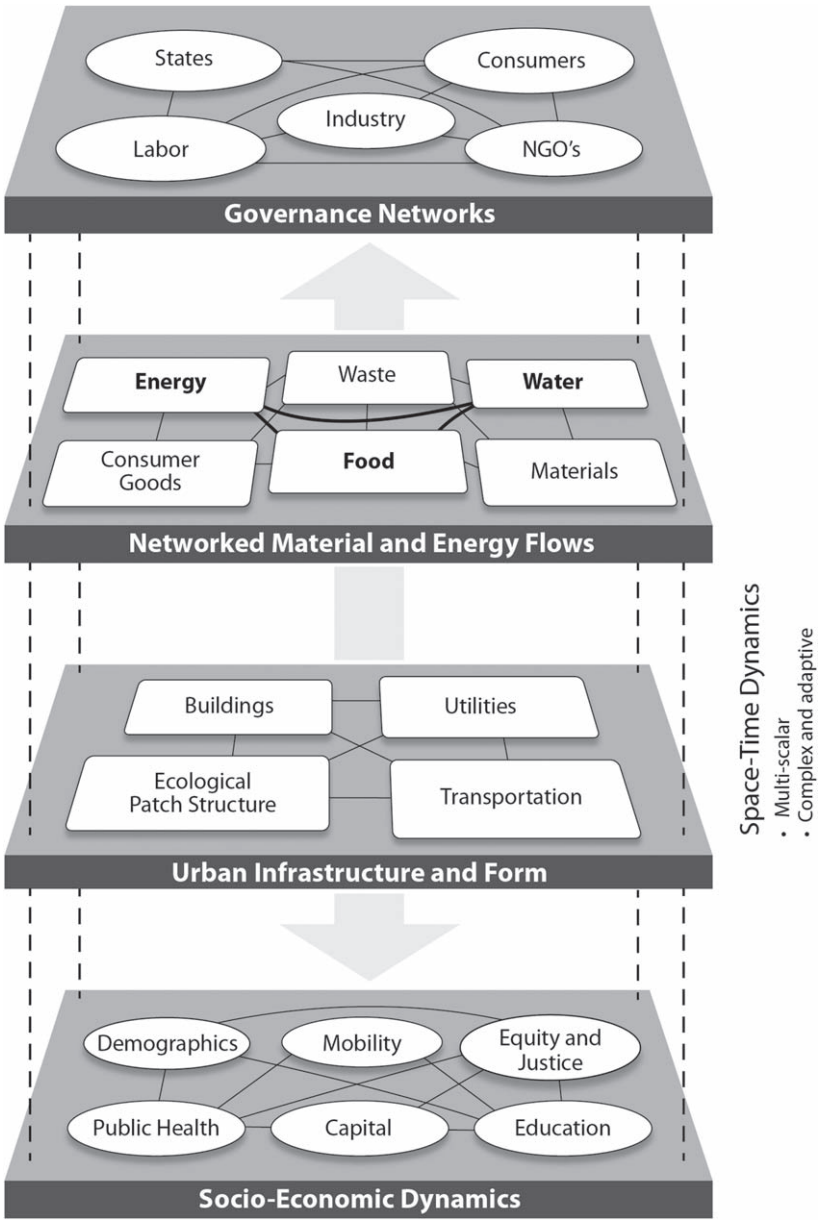

Figure 5. Conceptual schematic of the material, socio-economic, and ecological components in the metabolism of a city. Source: (adapted from Meerow *et al* 2016)

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 and

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), illuminating 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 (Frantzeskaki 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 (Cockerill *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.

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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 Anthrophosphere* (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)
Bizikova 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

metabolism along a land use intensity gradient in Indonesian Borneo *J. Geophys. Res. Biogeosci.* **119** 1110–28
Cash D W, Adger W N, Berkes F, Garden P, Lebel L, Olsson P, Pritchard L and Young O 2006 Scale and cross-scale dynamics: governance and information in a multilevel world *Ecol. Soc.* **11** art8
Chen S and Chen B 2015 Urban energy consumption: different insights from energy flow analysis, input-output analysis and ecological network analysis *Appl. Energy* **138** 99–107
Chen S, Fath B D and Chen B 2011 Information-based network environ analysis: a system perspective for ecological risk assessment *Ecol. Indicators* **11** 1664–72
Chen S Q and Chen B 2012 Network environ perspective for urban metabolism and carbon emissions: a case study of Vienna, Austria *Environ. Sci. Technol.* **46** 4498–506
Chen Y, Cheng J J and Creamer K S 2008 Inhibition of anaerobic digestion process: a review *Bioresour. Technol.* **99** 4044–64
Chisti Y 2007 Biodiesel from microalgae *Biotechnol. Adv.* **25** 294–306
Chisti Y 2008 Biodiesel from microalgae beats bioethanol *Trends Biotechnol.* **26** 126–31
Cockerill K, Tidwell V C, Passell H D and Malczynski L A 2007 Cooperative modeling lessons for environmental management *Environ. Pract.* **9** 28–41
Cohen S J and Allsopp T R 1988 The potential impacts of a scenario of $C0_2$-induced climatic change on Ontafio, Canada *J. Clim.* **1** 669–81
Coleman-Jensen A, Rabbitt M, Gregory C and Singh A 2017 Household Food Security in the United States in 2016 United States Department of Agriculture—Economic Research Services
Cordell D, Drangert J O and White S 2009 The story of phosphorus: global food security and food for thought *Glob. Environ. Change* **19** 292–305
Costanza R *et al* 1997 The value of the world's ecosystem services and natural capital *Nature* **387** 253–60
Cousins J J and Newell J P 2015 A political–industrial ecology of water supply infrastructure for Los Angeles *Geoforum* **58** 38–50
Cruz I F, Ganesh V R and Mirrezaei S I 2013 Semantic extraction of geographic data from web tables for big data integration *Proc. 7th Work. Geogr. Inf. Retr.—GIR '13* pp 19–26
Davies E G R and Simonovic S P 2011 Global water resources modeling with an integrated model of the social-economic-environmental system *Adv. Water Resour.* **34** 684–700
Decker E H, Elliott S, Smith F A, Blake D R and Rowland F S 2000 Energy and material flow through the urban ecosystem *Annu. Rev. Energy Environ.* **25** 685–740
Demaria F and Schindler S 2016 Contesting urban metabolism: struggles over waste-to-energy in Delhi, India *Antipode* **48** 293–313
Desfor G and Keil R 2004 *Nature and the City: Making Environmental Policy in Toronto and Los Angeles* (Tucson, AZ: The University of Arizona Press)
Driessen P P J and Glasbergen P 2002 *New Directions in Environmental Politics: Concluding Remarks Greening Society: The Paradigm Shift in Dutch Environmental Politics* ed P P J Driessen and P Glasbergen (Dordrecht: Kluwer) pp 245–62
Ericksen P J 2008 Conceptualizing food systems for global environmental change research *Glob. Environ. Change* **18** 234–45
Fargione J, Hill J, Tilman D, Polasky S and Hawthorne P 2008 Land clearing and the biofuel carbon debt *Science* **319** 1235–8
Feng Y Y, Chen S Q and Zhang L X 2013 System dynamics modeling for urban energy consumption and CO_2 emissions: a case study of Beijing, China *Ecol. Modell.* **252** 44–52
Fitzherbert E B, Struebig M J, Morel A, Danielsen F, Brühl C A, Donald P F and Phalan B 2008 How will oil palm expansion affect biodiversity? *Trends Ecol. Evol.* **23** 538–45
Flach R, Ran Y, Godar J, Karlberg L and Suavet C 2016 Towards more spatially explicit assessments of virtual water flows: linking local water use and scarcity to global demand of Brazilian farming commodities *Environ. Res. Lett.* **11** 075003
Foley J A *et al* 2005 Global consequences of land use *Science* **309** 570–4
Folke C, Jansson A, Larsson J and Costanza R 1997 Ecosystem appropriation by cities *Ambio* **26** 167–72
Foran T 2015 Node and regime: interdisciplinary analysis of water-energy-food nexus in the Mekong region *Water Altern.* **8** 655–74
Frantzeskaki N and Kabisch N 2015 Designing a knowledge co-production operating space for urban environmental governance—lessons from Rotterdam, Netherlands and Berlin, Germany *Environ. Sci. Policy* **62** 90–8
Gandy M 2002 *Concrete and Clay* (Cambridge, MA: MIT Press)
Giampietro M *et al* 2013 *An Innovative Accounting Framework for the Food-Energy-Water Nexus: Application of the MuSIASEM Approach to Three Case Studies* (Rome: Food and Agriculture Association of the United Nations)
Golubiewski N 2012 Is there a metabolism of an urban ecosystem? An ecological critique *Ambio* **41** 751–64
Grimm N B, Faeth S H, Golubiewski N E, Redman C L, Wu J, Bai X and Briggs J M 2008 Global change and the ecology of cities *Science* **319** 756–60
Guillaume J, Kummu M, Eisner S and Varis O 2015 Transferable principles for managing the nexus: lessons from historical global water modelling of central Asia *Water* **7** 4200–31
Hellweg S and Milà i Canals L 2014 Emerging approaches, challenges and opportunities in life cycle assessment *Science* **344** 1109–13
Hendriks C, Obernosterer R, Muller D, Kytzia S, Baccini P and Brunner P H 2000 Material flow analysis: a tool to support environmental policy decision making. Case-studies on the city of Vienna and the Swiss lowlands *Local Environ.* **5** 311–28
Heynen N, Kaika M and Swyngedouw E 2006 Urban political ecology: politicizing the production of urban natures *In the Nature of Cities: Urban Political Ecology and the Politics of Urban Metabolism* Metabolic Urbanization) ed N Heynen *et al* (London: Routledge) ch 2 pp 1–20
Hoff H 2011 Understanding the nexus *Background Paper for the Bonn 2011 Nexus Conf.*
Holling C S 1973 Resilience and stability of ecological systems *Annu. Rev. Ecol. Syst.* **4** 1023
Hooper D U *et al* 2005 Effects of biodiversity on ecosystem functioning: a consensus of current knowledge *Ecol. Monogr.* **75** 3–35
Horta I M and Keirstead J 2017 Downscaling aggregate Urban metabolism accounts to local districts *J. Ind. Ecol.* **21** 294–306
Howells M *et al* 2013 Integrated analysis of climate change, land-use, energy and water strategies *Nat. Clim. Change* **3** 621–6
Hubacek K, Feng K, Minx J C, Pfister S and Zhou N 2014 Teleconnecting consumption to environmental impacts at multiple spatial scales: research frontiers in environmental footprinting *J. Ind. Ecol.* **18** 7–9
International Water Management Institute 2007 *Water for Food, Water for Life—A Comprehensive Assessment of Water Management in Agriculture* ed D Molden (London: EarthScan and Colombo: International Water Resource Institute)
Karlberg L *et al* 2015 Tackling complexity: understanding the food-energy-environment nexus in Ethiopia's lake tackling complexity: understanding the food-energy-environment nexus in Ethiopia's Lake Tana sub-basin *Water Altern.* **8** 710–34
Keil R and Boudreau J-A 2006 *Metropolitcs and Metabolics: Rolling out Environmentalism in Toronto In the Nature of Cities: Urban Political Ecology and the Politics of Urban Metabolism* ed N Heynen, M Kaika and E Swyngedouw (New York: Routledge) pp 41–62
Kennedy C A *et al* 2015 Energy and material flows of megacities *Proc. Natl Acad. Sci.* **112** 5985–90
Kennedy C, Cuddihy J and Engel-yan J 2007 The changing metabolism of cities *J. Ind. Ecol.* **11** 43–59
Kennedy C and Hoornweg D 2012 Mainstreaming urban metabolism *J. Ind. Ecol.* **16** 780–782
Kennedy C, Pincetl S and Bunje P 2011 The study of urban metabolism and its applications to urban planning and design *Environ. Pollut.* **159** 1965–73

King C W 2014 A systems approach for investigating water, energy, and food scenarios in East-Central Maui *Report* (Austin, TX: The University of Texas at Austin)
Kitchin R 2014 *The Data Revolution—Big Data, Open Data, Data Infrastrucutres and Their Consequences* (London: Sage)
Kraucunas I *et al* 2015 Investigating the nexus of climate, energy, water, and land at decision-relevant scales: the platform for regional integrated modeling and analysis (PRIMA) *Clim. Change* **129** 573–88
Kubitza C, Krishna V V, Alamsyah Z and Qaim M 2018 The economics behind an ecological crisis: livelihood effects of oil palm expansion in Sumatra, Indonesia *Hum. Ecol.* **46**
Leck H, Conway D, Bradshaw M and Rees J 2015 Tracing the water–energy–food nexus: description, theory and practice *Geogr. Compass* **98** 445–60
Loreau M *et al* 2001 Biodiversity and ecosystem functioning: current knowledge and future challenges *Science* **294** 804–8
Lu Y, Chen B, Feng K and Hubacek K 2015 Ecological network analysis for carbon metabolism of eco-industrial parks: a case study of a typical eco-industrial park in Beijing *Environ. Sci. Technol.* **49** 7254–64
MacDonald G M 2010 Water, climate change, and sustainability in the southwest *Proc. Natl Acad. Sci.* **107** 21256–62
McDonald R I *et al* 2014 Water on an urban planet: urbanization and the reach of urban water infrastructure *Glob. Environ. Change* **27** 96–105
Meerow S, Newell J P and Stults M 2016 Defining urban resilience: a review *Landsc. Urban Plan.* **147** 38–49
Miara A, Pienkos P T, Bazilian M, Davis R and Macknick J 2014 Planning for algal systems: an energy-water-food nexus perspective *Ind. Biotechnol.* **10** 202–11
Mohtar R H and Daher B 2014 A platform for trade-off analysis and resource allocation the water-energy-food nexus tool and its application to Qatar's food security (London: Chatham House)
Mukuve F M and Fenner R A 2015 Scale variability of water, land, and energy resource interactions and their influence on the food system in Uganda *Sustain. Prod. Consum.* **2** 79–95
Muñoz-Erickson A T, Miller A C and Miller R T 2017 How cities think: knowledge co-production for urban sustainability and resilience *Forest* **8** 203
Newman M 2010 *Introduction Networks: An Introduction* (New York: Oxford University Press) pp 1–14
Newman M 2003 The structure and function of complex networks *SIAM Rev.* **45** 167–256
Newman M E J 2006 Modularity and community structure in networks *Proc. Natl Acad. Sci.* **103** 8577
Newman P W G 1999 Sustainability and cities: extending the metabolism model *Landsc. Urban Plan.* **44** 219–26
Noyons E C M 2001 Bibliometric mapping of science in a science policy context *Scientometrics* **50** 83–98
Obidzinski K, Andriani R, Komarudi H and Andrianto A 2012 Environmental and social impacts of oil palm plantations and their implications for biofuel production in Indonesia *Ecol. Soc.* **17** 25
Odum E P 1969 The strategy of ecosystem development *Science* **164** 262–70
Perrson O, Danell R and Schneider J W 2009 *How to use Bibexcel for Various Types of Bibliometric Analysis Celebrating Scholarly Communication Studies: A Festschrift for Olle Persson at his 60th Birthday* (Copenhagen: International Society for Scientometrics and Infometrics)
Pincetl S, Bunje P and Holmes T 2012 An expanded urban metabolism method: toward a systems approach for assessing urban energy processes and causes *Landsc. Urban Plan.* **107** 193–202
Polis G A, Anderson W B and Holt R D 1997 Toward an integration of landscape and food web ecology: the dynamics of spatially subsidized food webs *Annu. Rev. Ecol. Syst.* **28** 289–316
Qi C and Chang N-B 2011 System dynamics modeling for municipal water demand estimation in an urban region under uncertain economic impacts *J. Environ. Manage.* **92** 1628–41
Ramaswami A, Boyer D, Nagpure A J, Fang A, Borga S, Bakshi B, Cohen E and Rao-Ghorpade A 2017 An urban systems framework to assess the trans-boundary food-energy-water nexus: implementation in Delhi, India *Environ. Res. Lett.* **12** 025008
Ramaswami A, Weible C, Main D, Heikkila T, Siddiki S, Duvall A, Pattison A and Bernard M 2012 A social-ecological-infrastructural systems framework for interdisciplinary study of sustainable city systems *J. Ind. Ecol.* **16** 801–13
Rasul G and Sharma B 2016 The nexus approach to water–energy–food security: an option for adaptation to climate change *Clim. Policy* **16** 682–702
Rees W E 1992 Ecological footprints and appropriated carrying capacity: what urban economics leaves out *Environ. Urban.* **4** 121–30
Renger M, Kolfschoten G L and De V G 2008 *Challenges in Collaborative Modeling: Advances in Enterprise Engineering* ed J L G Dietz (Berlin: Springer) pp 61–77
Sahely H R, Dudding S and Kennedy C A 2003 Estimating the urban metabolism of Canadian cities: greater Toronto area case study *Can. J. Civ. Eng.* **30** 468–83
Schenk P M, Thomas-Hall S R, Stephens E, Marx U C, Mussgnug J H, Posten C, Kruse O and Hankamer B 2008 Second generation biofuels: high-efficiency microalgae for biodiesel production *BioEnergy Res.* **1** 20–43
Searchinger T, Heimlich R, Houghton R A, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D and Yu T H 2008 Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change *Science* **319** 1238–40
Serat-Capdevila A S, Valdes J B and Gupta H V 2011 *Decision Support Systems in Water Resources Planning and Management: Staleholder Participation and the Sustainable Path to Science-Based Decision Making Efficient Decision Support Systems: Practice and Challenges from Current to Future* ed C Jao (London: InTechOpen Limited)
Seto K C, Reenberg A, Boone C G, Fragkias M, Haase D, Langanke T, Marcotullio P, Munroe D K, Olah B and Simon D 2012 Urban land teleconnections and sustainability *Proc. Natl Acad. Sci. USA* **109** 7687–92
Shibata N, Kajikawa Y, Takeda Y and Katsumori M 2009 Comparative study on methods of detecting research fronts using different types of citation *J. Am. Soc. Inf. Sci. Technol.* **60** 571–80
Siegfried T, Sobolowski S, Raj P, Fishman R, Vasquez V, Narula K, Lall U and Modi V 2010 Modeling irrigated area to increase water, energy, and food security in semiarid India *Weather Clim. Soc.* **2** 255–70
Small H 1997 Update on science mapping: creating large document spaces *Scientometrics* **38** 275–93
Spiegelberg M, Baltazar D E, Sarigumba M P E, Orencio P M, Hoshino S, Hashimoto S, Taniguchi M and Endo A 2017 Unfolding livelihood aspects of the water–energy–food nexus in the dampalit Watershed, Philippines *J. Hydrol. Reg. Stud.* **11** 53–68
Strogatz S H 2001 Exploring complex networks *Nature* **410** 268–76
Swyngedouw E 2006 Metabolic urbanization *In the Nature of Cities: Urban Political Ecology and the Politics of Urban Metabolism (Questioning Cities)* ed N Heynen *et al* (London: Routledge) pp 20–39
Swyngedouw E 2004 *Social Power and the Urbanization of Water: Flows of Power* (Oxford: Oxford University Press)
Swyngedouw E and Heynen N C 2003 Urban political ecology, justice and the politics of scale *Antipode* **35** 898–918
Tidwell, Vincent C and van den Brink C 2008 Cooperative modeling: linking science, communication, and ground water planning *Ground Water* **46** 174–82
Tilman D, Cassman K G, Matson P A, Naylor R and Polasky S 2002 Agricultural sustainability and intensive production practices *Nature* **418** 671–7
Townsend A 2014 *Smart Cities* (New York: W W Norton)
USDA 2018 (Economic Research Services) Dietary recommendations and calorie consumption (loss-adjusted food availability)

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 *Ecohydrol. 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 Vandenberghe 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, Sharpley 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* ed D Waughray (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)