Environmental Research Letters

EDITORIAL • OPEN ACCESS

Urban food–energy–water systems: past, current, and future research trajectories

To cite this article: Joshua P Newell and Anu Ramaswami 2020 *Environ. Res. Lett.* **15** 050201

IOP Publishing Environ. Res. Lett. 15 (2020) 050201 https://doi.org/10.1088/1748-9326/ab7419

Environmental Research Letters

CrossMark

OPEN ACCESS

PUBLISHED
5 May 2020

EDITORIAL

Urban food–energy–water systems: past, current, and future research trajectories

Joshua P Newell[1] and **Anu Ramaswami**

[1] Author to whom any correspondence should be addressed.

E-mail: jpnewell@umich.edu

With cities producing 80% of global GDP and housing more than half of the world's population (United Nations Human Settlements Programme UN-Habitat 2016, p. 264), urban processes now drive global flows of food, energy, and water, causing unprecedented disruptions to the planet's biogeochemical cycles. The procurement of food, energy, and water (FEW) often occurs outside urban boundaries, leading to geographic and sectoral interactions from local to global scales. These unforeseen and complex interactions degrade air and water quality, drive resource use, and exacerbate greenhouse gas emissions (GHGs). FEW-provisioning systems also have profound impacts on the economy and on human health and well-being. The linkages between the systems that supply FEW to cities and the outcomes related to human and planetary well-being are the focus of this special issue.

The issue consists of nine articles, each of which presents emerging research on interconnected FEW systems as they relate to cities and regions. The papers are interdisciplinary, multiscalar, and cross-sectoral as they consider the effects of FEW interactions on the health of cities, their inhabitants, and the distant peoples and places from which they source their resources. As a set, including this introduction, the special issue covers the following topics:

1. Research to date on urban FEW systems and promising approaches
2. Urban agriculture and energy–water dynamics
3. Conventional agriculture and FEW dynamics
4. The energy foodprint of the American diet
5. Key areas for future research

In the pages that follow, we briefly summarize each of the articles in this special issue, clustering them by topical areas. We conclude by identifying what we view as crucial research gaps needing further studies in the realm of urban FEW systems.

1. Research to date on urban FEW systems and promising approaches

The focus issue begins with a review article by Newell *et al* (2019), which catalogues four decades (1973–2017) of academic literature on the FEW nexus (1399 publications). The bibliometric review reveals six distinct research communities, involving primarily scholars in the fields of environmental science, with social science domains underrepresented. The authors conduct an in-depth analysis of the most influential papers in terms of modeling approach, the spatial and temporal scale of analysis, and governance and policy. Most papers deployed quantitative (rather than qualitative) approaches, especially the use of integrated assessment and systems dynamics modeling. Despite their influence on FEW systems, considerations of institutional structure, governance, equity, resource access, and behavior were largely absent from existing studies.

One of the six communities is a nascent urban FEW community, with 80% of its papers having been published since 2010. Scholars in industrial ecology are especially prominent in this community. They tend to quantify FEW flows of the urban metabolism in isolation rather than as a nexus, largely ignoring the political and socioeconomic factors shaping these flows. The authors call for advancing research on 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) coproduction of knowledge with stakeholders. Toward that end, the review paper concludes by proposing urban FEW metabolism as a boundary object to draw in diverse scholarly and practitioner communities.

The second paper in the collection, by Ramaswami *et al* (2017), is an example of the integrated research on urban FEW systems that Newell *et al* (2019) are calling for. The paper offers a generalizable systems framework that connects in-boundary and transboundary interactions, quantifies multiple environmental impacts of FEW provisioning to cities, and visualizes FEW supply-chain risks that cities face. They demonstrate the framework's applicability through a case study of the food, water, and energy supply for consumption in Delhi, India. Their analysis reveals that the city is highly dependent on transboundary flows for food (~90% of total), energy (76%), and water (86%). The study also develops spatially explicit energy–water–GHG footprints of FEW provisioning to Delhi. Such coupled footprints can simultaneously quantify the impacts of urban actions on water, energy, and land use, and identify where these impacts occur. Agricultural products contribute significantly to both the GHG footprint (19%) and the water footprint (72%–82%) of Delhi's FEW provisioning, driven largely by milk, rice, and wheat. Analysis of FEW interactions within Delhi found that >75% in-boundary water use for food is dedicated to urban agriculture and >76% in-boundary energy use for food is from cooking fuels. Visualizing supply chains shows that >75% of water embodied in Delhi's FEW supply is extracted from locations that overdraft ground water, illustrating the water and climate vulnerability of Delhi's food system. These baseline data enable evaluation of future urban FEW scenarios, comparing impacts of demand shifts, production shifts, and emerging technologies and policies, both within and outside of cities. Key data gaps for Indian cities involve food waste to energy ratios and the energy intensity of commercial and industrial food preparation. The urban FEW framework derives from an interdisciplinary social-ecological-infrastructural systems perspective. The authors suggest further expansion of the framework to address interactions among social actors and the governance of FEW systems in different cities.

In the third paper in the collection, Sherwood *et al* (2017) calculate the relative FEW intensities of metropolitan areas in the United States using the environmental input-output life cycle assessment (EIO-LCA) model. The research team analyzed every economic sector to determine FEW intensities—water resource use (kgal), energy resource use (TJ), and food resource use (kg and kcal)—for the 382 metropolitan statistical areas (MSAs). They also conducted a longitudinal study of the Los Angeles MSA to understand trends over time. Results from the modeling reveal a strong correlation between GDP and energy use and between food and water use across the MSAs. There is also a correlation between GDP and GHGs. The Los Angeles MSA had previously experienced a decoupling of economic growth and smog emissions, leading the researchers to consider whether similar decoupling of GDP and food, energy, and water use had occurred. Although study reveals an apparent decoupling, the authors attribute this primarily to a shift in the industrial mix, from manufacturing to a service sector based economy, rather than resource use efficiencies per se. Despite common limitations associated with I-O modeling (e.g. assuming a linear model of the economy, accounting for only domestic production, exclusion of capital investments), the authors do provide a promising approach for studying FEW interactions at the metropolitan scale and for identifying intergrative policies that foster resource efficiencies across the three FEW sectors.

2. Urban agriculture and energy–water dynamics

Producing and consuming food represents nearly 15% of the total energy demand in the United States (US). One area of research that needs more evaluation is energy use in urban agriculture, since the practice is of intense interest among city agencies, industry, and the public. The paper by Mohareb *et al* (2017) evaluates the energy and GHG implications of scaling up urban agriculture in high-income countries. The paper catalogues the various forms of urban agriculture, from residential and community gardens to vertical farms and periurban agriculture, and reveals the relationships between farm form and energy-use profiles. The authors also utilize this cataloguing to suggest practical strategies (e.g. building code changes) to decouple energy use from urban food production. The paper concludes by identifying potential gains in energy efficiency by co-locating urban agriculture operations near waste streams, such as wastewater, compost, and combined heat facilities, to promote synergistic FEW interactions that reduce urban resource loads and waste generation.

This potential for interactions among wastewater, energy, and agriculture as they affect environment and human health is considered in the paper by Miller-Robbie *et al* (2017), who evaluate the feasibility of harvesting nutrients and water in treated wastewater for use in urban agriculture. The authors conducted a field study in Hyderabad, India, that examined trade-offs in water use, energy use, GHG emissions, nutrient uptake, crop pathogen quality, and type of irrigation water (treated versus untreated versus groundwater). The research reveals some surprising results. First, treating and reusing wastewater led to a 33% reduction in system-wide GHG emissions when compared to discharging untreated water into surface streams, which are anoxic and hence produce methane emissions from waste. Second, due to land constraints, less than 1% of nutrients from the city's wastewater can be used in urban agriculture. Third, although treating wastewater reduces virtually all pathogens, the crop pathogen content was reduced by much less, largely due to environmental contamination, farmer behavior, and harvesting practices. The paper provides a real-world empirical example of interactions between the FEW nexus, environmental impacts, health risks, and human behavior.

3. Conventional agriculture and FEW dynamics

Bell *et al* (2018) consider the energy and emissions implications of using alternative water sources (recycled water and desalinated water) to produce four high-value crops—strawberries, avocados, lemons, and celery—in water-scarce southern California. The results of the spatially explicit life-cycle assessment (LCA) indicate that switching from conventional irrigation (groundwater and surface water) to recycled water increases GHG emission by 14%, 7%, 59%, and 9% for the four crops, respectively, and that shifting to desalinated water increases the GHG emissions by 33%, 210%, 140%, and 270%, respectively. By contrast, changing how strawberries are packaged (which entails energy-intensive PET 'clamshells') would lead to significant GHG reductions. One advantage of switching to recycled water would be lower salinity, which has been shown to produce significant yield increases for some crops. Using alternative water sources would reduce groundwater withdrawals, thereby helping to alleviate Oxnard's saltwater intrusion problems. Co-locating high-value crops, like strawberries, and using alternative water sources would increase economic suitability by overcoming the significant cost of transporting water. The study recommends similar spatially explicit LCA modeling at the national and global scales by using regionally specific life-cycle crop footprints and local water data.

In another paper on agricultural production, Dozier *et al* (2017) consider how urbanization in the arid American West leads to the transfer of water rights from agricultural to urban uses and the mechanisms by which this transfer often becomes permanent. Since it raises the cost of water, among other complications, this transfer has implications for rural communities that depend on agriculture for their livelihoods. The study offers an integrative framework to assess the effects of population growth and land-use change on agricultural production and the viability of alternative management strategies. The results from the partial equilibrium model reveal that, in many instances, it is more profitable to simply sell the water rights rather continue agricultural production. The study concludes that rural livelihoods can be sustained through alternative water-transfer methods in the short term and that long-term solutions need to focus on water conservation in these growing cities.

Berardy and Chester (2017) also focus on agriculture in the American West, this time in the context of the interdependent water and energy systems that enable its production. Their focus is the state of Arizona, which, despite being highly arid, produces agricultural products year-round and is a main source of vegetables during winter months for major cities, including Phoenix, Los Angeles, Las Vegas, and San Diego. Electricity powers the irrigation systems essential to producing these crops, so failures in either system have ramifications for food availability in the region. To understand the vulnerability of this FEW nexus in the context of climate change, the authors evaluate the impacts of higher temperatures and related water and energy disruptions on agricultural production (specifically yield, water use, and energy use). Based on dynamic simulations, an increase in temperature of 1°C results in a 1%–12% decrease in yield, depending on the crop, and a 2.6% increase in irrigation inputs for all major crops. Irrigation systems are a particularly vulnerable node in the agricultural system in Arizona. The study identifies the need for more efficient use of water and energy to increase the resilience of agriculture to climate change in Arizona and the American West.

4. The energy foodprint of the American diet

The final paper in the collection by Birney *et al* (2017) quantifies the environmental footprint, which they call the 'foodprint,' of the average American diet, including associated food loss and waste. This foodprint is measured in terms of GHG emissions and energy, water, and fertilizer use. Profligate food loss and waste represent an enormous portion of the overall foodprint—34% of total GHG emissions. The study also calculates the impact if diets were to shift to meet USDA food consumption guidelines (i.e. more fruits, vegetables, and dairy, and less red meat, fat, and sugar). Surprisingly, such a purportedly healthy dietary shift would actually increase the foodprint, leading to higher energy use (34%) and more GHG emissions (7%). This is because such a shift would result in the consumption of more kilograms of food, including energy-intensive dairy. Changing the diet would also increase fertilizer use, assuming the amount of food loss and waste remains constant. At the consumer level, roughly 95% of all food thrown away ends up in landfills, the second largest source of methane emissions in the US. The key strategy, therefore, lies in reducing food loss and waste. A reduction of 50% would effectively offset the increased resource use associated with the healthier USDA-recommended diet. Although not covered in the study, it should be noted that the high dairy requirements in the USDA diet are not necessarily nutritious or realistic (Heller *et al* 2013, Ernstoff *et al* 2017). Moreover, the impact of dietary substitution on the foodprint hinges critically on the choice of replacement proteins. For instance, a more balanced shift from meat to vegetal protein sources (e.g. legumes) alongside dairy would likely produce a net reduction to the foodprint and increased health benefits (Aleksandrowicz *et al* 2016).

5. Key areas for future research

Informed by the papers in this special issue and other recent literature on the FEW nexus and urban sustainability, we conclude by identifying four fruitful areas for future research:

5.1. Ecosystem services of urban agriculture

To date, research has focused on whether urban agriculture can produce viable amounts of food for a given population and, to a lesser extent, on quantifying the environmental footprint of production practices. Some articles in this special issue indicate that increasing urban agriculture may even exacerbate local environmental stresses (e.g. in Delhi and Hyderabad). Thus, the promise of increasing urban agriculture may not necessarily lie in resource efficiency and pollution mitigation but, rather, in the other benefits of urban food systems: access to fresh fruits and vegetables, job creation, import substitution through food processing, and other health, community, and well-being benefits. Research is needed to evaluate these other ecosystem services so urban designers and policy makers can better understand how scaling up urban agriculture affects the sustainability and resilience of cities and regions.

5.2. Resource recovery in the urban FEW nexus

Curbing edible food loss and waste and reducing packaging may be more effective leverage points for improving resource efficiency in the food system than previously understood. Birney *et al* (2017) highlight the need to address food loss during production and transport, since avoiding these losses can have simultaneous benefits across all three systems (food, energy, and water). Reducing food packaging is also shown to have a comparable benefit to certain environmental concerns for some crops (e.g. GHG). Given the efficiency of US agriculture, the majority of food loss and waste occurs during the retail and consumption phase of the life cycle. Cities are therefore both concentrated areas of food waste production and potential sites of resource recovery. Further research identifying and providing clarity on the major levers for resource recovery in urban FEW systems writ large will be extremely valuable.

5.3. Equity, social actors, and governance of the FEW nexus

Equity is increasingly important to researchers and policy makers in terms of food justice, energy justice, and water access. Considerations of social equity are alluded to in this special issue, as are those of transboundary equity (i.e. equity across the supply chain when urban agriculture potentially supplants rural livelihoods). Also important are considerations of resource access within urban areas in the context of food, energy, and water insecurity. Although these themes are indicated as important lines of research in this special issue, they are underexplored in the current FEW literature. Studies have communicated the environmental benefits of more informed food, energy, and water consumption and reduced waste, but research on how to motivate more sustainable behavior by individuals is wanting. Similarly, more research is needed on the complexities of governing soiotechnical systems across sectors and scales, for instance, through social network analysis. The application papers in this issue highlight the types of physical interactions across sectors and scales, but the human dimensions of sustainably managing the nexus represent a blind spot in the literature.

5.4. The food–energy–water–health nexus

The myriad ways in which FEW systems influence health and well-being have emerged as a key area for further research. Due to density of settlement, changes to urban FEW systems often have significant (and unanticipated) impacts on the residents who live close to FEW infrastructures. Fertilizer-related air pollution, pathogen risk in wastewater treatment and reuse, and the health effects of undernutrition, overnutrition, and food-related microbial contamination all represent areas of rich future research at the food–energy–water–health nexus.

Acknowledgments

This article was made possible due to grants from the National Science Foundation, specifically the following awards: FEW Workshop: Scaling-up Urban Agriculture (#1541838); Sustainability Research Network and (SRN, #1444745): and Belmont Forum Collaborative Research Food-Water-Energy Nexus (#18929627).

ORCID iDs

Joshua P Newell https://orcid.org/0000-0002-1440-8715

References

Aleksandrowicz L, Green R, Joy E J, Smith P and Haines A 2016 The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: a systematic review *PLoS One* **11** e0165797

Bell E M, Stokes-Draut J R and Horvath A 2018 Environmental evaluation of high-value agricultural produce with diverse water sources: case study from Southern California *Environ. Res. Lett.* **13** 025007

Berardy A and Chester M V 2017 Climate change vulnerability in the food, energy, and water nexus: concerns for agricultural production in Arizona and its urban export supply *Environ. Res. Lett.* **12** 035004

Birney C I, Franklin K F, Davidson F T and Webber M E 2017 An assessment of individual foodprints attributed to diets and food waste in the United States *Environ. Res. Lett.* **12** 105008

Dozier A Q, Arabi M, Wostoupal B C, Goemans C G, Zhang Y and Paustian K 2017 Declining agricultural production in rapidly urbanizing semi-arid regions: policy tradeoffs and sustainability indicators *Environ. Res. Lett.* **12** 085005

Ernstoff A S, Stylianou K S and Goldstein B 2017 Response to: dietary strategies to reduce environmental impact must be nutritionally complete *J. Clean. Prod.* **162** 568–70

Heller M C, Keoleian G A and Willett W C 2013 Toward a life cycle-based, diet-level framework for food environmental impact and nutritional quality assessment: a critical review *Environmental Science & Technology* **47** 12632–47

Miller-Robbie L, Ramaswami A and Amerasinghe P 2017 Wastewater treatment and reuse in urban agriculture: exploring the food, energy, water, and health nexus in Hyderabad, India *Environ. Res. Lett.* **12** 075005

Mohareb E, Heller M, Novak P, Goldstein B, Fonoll X and Raskin L 2017 Considerations for reducing food system energy demand while scaling up urban agriculture *Environ. Res. Lett.* **12** 125004

Newell J P, Goldstein B and Foster A 2019 A 40-year review of food–energy–water nexus literature and its application to the urban scale *Environ. Res. Lett.* **14** 073003

Ramaswami A, Boyer D, Nagpure A S, Fang A, Bogra S, Bakshi B 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

Sherwood J, Clabeaux R and Carbajales-Dale M 2017 An extended environmental input–output lifecycle assessment model to study the urban food–energy–water nexus *Environ. Res. Lett.* **12** 105003

United Nations Human Settlements Programme (UN-Habitat) 2016 *Urbanization and Development: Emerging Futures: World Cities Report* 2016 (Nairobi: United Nations Human Settlements Program)