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Emerging challenges and opportunities for the food–energy–water nexus in urban systems

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Urban systems draw on food, energy, and water outside of their physical boundaries, and create environmental impacts which extend beyond city borders. All three of these resources face growing demand, supply constraints, and are of substantial importance to a sustainable world. Our world is increasingly urbanized, with cities having large and concentrated environmental impacts, but also the opportunity to implement unique sustainability solutions at scale. The interactions between food, energy, and water are best captured through a nexus view, identifying the full interactions between these resources. Topics of growing significance to urban systems are identified with their nexus connections. These connections facilitate complex sustainability challenges, but also can also be harnessed to promote coordinated solutions.

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Introduction

The coming years present a time of immense change: not only in our climate and environment, but also in our physical and social infrastructures. Prospective analyses are crucial to understanding the direction in which our world is evolving, and what can be undertaken to facilitate the best possible outcomes for all people.

Food, energy, and water are essential to human life. Understanding how these resources interact and managing their environmental impacts will be a paramount task for creating a sustainable future. The food–energy–water (FEW) nexus is a valuable apparatus for viewing the connections between these critical resources. Our world is increasingly urban, with cities having unique properties requiring specialized study and consideration. To produce fully informed analyses for urban sustainability, it is essential that studies take a nexus view, encompassing the full relationship between these resources.

This paper provides an overview of emerging FEW nexus topics relevant to urban systems. Specific interactions (food–energy, food–water, water–energy) are addressed, followed by topics relating to all elements of the nexus. Key studies are summarized, and critical connections between these resources and urban areas are described.

An increasingly urbanized world

In 2014 the United Nations estimated that 54% of the world population lived in urban areas, a figure predicted to rise to 66% by 2050 [1]. Urban areas are net consumers of materials and energy [2], requiring the support of ecosystem services and resources from non-urban areas [3]. For example, cities worldwide are estimated to require 27–621 times their physical urban boundary to supply their sustainable water needs [4].

While urban areas are connected with environmental problems including increased levels of air and water pollution and biodiversity loss, they have the potential to be less environmentally impactful on a per capita basis through planning [3]. Cities have substantial, concentrated environmental impacts, consuming large quantities of resources in a small area. However, the per capita impacts of cities can be small, with population density facilitating decreased impacts per-person [5,6]. This duality provides challenges in designing solutions to urban sustainability problems, but also opportunities for implementing uniquely innovative solutions.

Urban metabolism, input–output models, and the food–energy–water nexus

All elements of the FEW nexus have rapidly growing demand, billions of people lacking access to quantity and/or quality of each, resource constraints, operate in heavily regulated markets, differ in regional availability, and have strong interdependencies with climate change and the environment, among other properties [7••]. The engineering community will be increasingly called upon to provide robust analysis and develop solutions to these issues, particularly in response to greater urbanization. This paper highlights research where urban challenges have been addressed via a nexus approach for overall system benefit and identifies challenges where a nexus approach is essential to avoid problem-shifting. Urban metabolism and Input–output (IO) studies have been particularly successful means for integrating the connected properties of the FEW nexus into studies addressing cities.

Urban metabolism is a structure for characterizing inflows, outflows, stocks, and production related to socio-economic and technical processes of cities [8]. A metabolistic framework can facilitate insights into opportunities for synergistic sustainability improvements. As an illustrative example, a metabolic study of London found that urine separation in the sewage system could recover nitrogen from consumed food, provide revenue from the production of fertilizer, and create biofuels and potential revenue by collecting food waste together with algae in wastewater treatment plants [2]. Urine separation benefits from economies of scale: reaping benefits from nexus relationships not possible on a smaller scale. In this respect, urban areas have unique opportunities for implementing innovative systems for sustainability improvement.

Integrating urban metabolism with life cycle assessment, Ramaswami *et al.* present a 'social-ecological-infrastructural systems' framework for examining the transboundary impacts of infrastructure supply chains, water, energy, and emissions for cities. Key contributions of this framework include viewing actions by policy actors and infrastructure users in addition to multi-scale risks such as climate change, pollution, and the urban heat island effect in conjunction with the materials stocks and flows comprising a city's metabolism across both life cycle and geographic scales [9••].

The FEW nexus is shaped by value chains and markets which do not sufficiently internalize environmental externalities [10]. Input–output models [11] are increasingly used to estimate environmental footprints of a region. IO models capture the global supply chains connecting urban systems with external regions, and can trace the transboundary environmental impacts of urban systems. Production processes of food, energy, and water have not only direct environmental impacts but also indirect environmental impacts embodied in production inputs. Constructing IO models for the food, energy, and water supply chains can capture nexus and trade-related effects of urban FEW uses. However, it is a challenge to compile IO tables for urban systems, mainly due to the unavailability of related data [12]. Future research should focus on developing estimation methods for urban IO data. Moreover, national and local governments should improve their statistical systems to collect required data for urban IO tables. These actions can benefit the comprehensive assessment of environmental impacts of urban FEW systems.

Food, land use, and energy

Food interacts with nearly every global system. Seto and Ramankutty provide a brief yet comprehensive overview of the explored and numerous unexplored system-wide linkages between urbanization and food systems; illustrating the striking extent to which the relationships between these areas are unaddressed in the literature [13•]. The implications of these connections for urban areas are summarized and addressed.

Urban food demand and agricultural land

An important spatial consideration is the connection between food demand and agriculture-connected deforestation [14], where growing demand from an urban area can have serious environmental impacts in a far-removed region [15].

The expansion of urban areas is expected to result in a 1.8–2.4% loss of croplands worldwide by 2030, with the lost cropland being 1.77 times more productive than the global average [16]. Bajželj *et al.* find that even after closing yield gaps, projected increases in demand for food will not be met, driving further agricultural land expansion [17]. Improving food distribution and supply in developing cities is an important means for improving the lives of the urban poor [18] and does not require cropland interventions. An additional potential for meeting increased demand is urban agriculture.

Orsini *et al.* provide a review on urban agriculture in the developing world, noting the positive social and economic benefits it can provide for the poor [19•]. However, some empirical studies caution against overestimating its potential, citing potentially limited contributions to income and overall agricultural production [20], and food security when considering urban land constraints [21]. Faciliting urban agricultural systems is a key task for improving urban food security.

While urban agriculture is feasible in the developed world in terms of land use constraints [21], high land prices are identified as a challenge, resulting in part from scarcity, and from land use policy [22]. The opportunity costs of urban agricultural land and its effects on population density remain a gap in the literature. There is also the promise of vertical farming, where greenhouses growing crops can be stacked on top of each other [23], which would decrease the ground land use.

Urbanization, dietary shifts, and energy generation

Urbanization and increasing incomes facilitate shifts to diets which are higher in refined sugars, refined fats, oils, and meats [24]. If unchecked, these dietary shifts would be a significant contributor to an increase in emissions