Quantifying the Urban Food–Energy–Water Nexus: The Case of the Detroit Metropolitan Area

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Supporting Information

ABSTRACT: The efficient provision of food, energy, and water (FEW) resources to cities is challenging around the world. Because of the complex interdependence of urban FEW systems, changing components of one system may lead to ripple effects on other systems. However, the inputs, intersectoral flows, stocks, and outputs of these FEW resources from the perspective of an integrated urban FEW system have not been synthetically characterized. Therefore, a standardized and specific accounting method to describe this system is needed to sustainably manage these FEW resources. Using the Detroit Metropolitan Area (DMA) as a case, this study developed such an accounting method by using material and energy flow analysis to quantify this urban FEW nexus. Our results help identify key processes for improving FEW resource efficiencies of the DMA. These include (1) optimizing the dietary habits of households to improve phosphorus use efficiency, (2) improving effluent-disposal standards for nitrogen removal to reduce nitrogen emission levels, (3) promoting adequate fertilization, and (4) enhancing the maintenance of wastewater collection pipelines. With respect to water use, better efficiency of thermoelectric power plants can help reduce water withdrawals. The method used in this study lays the ground for future urban FEW analyses and modeling.

INTRODUCTION

Food, energy, and water are three essential resources for meeting basic human needs. The efficient provision of food, energy, and water is important but challenging due to the complex interdependence of these three systems. For example, water is required for food and energy production; energy is needed for food and water production, as well as wastewater treatment; and industrial agriculture and food production lead to the oversupply of nitrogen and phosphorus in the water system from fertilizer uses. Such complex interdependence makes the food–energy–water (FEW) nexus a complex system of subsystems. Changing components of one system may lead to ripple effects (desired or undesired) on other systems. Therefore, policy and technology solutions addressing challenges in individual FEW systems need to be evaluated through the lens of the FEW nexus to identify co-benefits and avoid unintended consequences. Ultimately, instead of examining FEW subsystems individually, we need to examine them simultaneously—as an integrated whole—when developing policy and technology solutions.

As of 2017, 55% of the world’s population lives in urban areas, a proportion projected to increase to 66% by 2050, with the expected addition of 2.5 billion people to cities. Cities have become the primary users of FEW resources. Managing FEW resources wisely in cities can contribute significantly to the sustainable management of FEW resources at the global scale. To help a city better manage its FEW resources, the first and foremost step is to understand how FEW resources flow across and within a city. Accounting for FEW resource flows and stocks of a city provides a quantitative wiring diagram of the city’s FEW nexus, allowing the city to measure the efficiency of its utilization of FEW resources, to identify critical processes that are key for the demand of FEW resources, and to develop policy and technology solutions accordingly.

Previous studies at the urban scale either analyze FEW systems individually (e.g., nutrient flows, energy flows, etc.) and avoid unintended consequences. Ultimately, instead of examining FEW subsystems individually, we need to examine them simultaneously—as an integrated whole—when developing policy and technology solutions.

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and water flows\cite{26–28}, or examine two of the three FEW systems (e.g., water–energy nexus\cite{29–41} and food–water nexus\cite{42–44}). Only a few studies consider all three FEW systems, and then only to evaluate the impact of one system on the other two, such as how innovations in the urban water sector change food and energy flows.\cite{45–47} Studies have also examined environmental footprints of an urban system by life-cycle-based approaches.\cite{48,49} However, the inputs, intersectoral flows, stocks, and outputs of FEW resources within the integrated urban FEW system have not been synthetically characterized. This synthesis can lay a solid ground for subsequent studies on the investigation of structural characteristics of the urban FEW nexus and to evaluate the consequences of specific policies or technology solutions. Despite the importance of measuring urban FEW flows and stocks, we lack case studies and, more importantly, a standardized specific accounting method to describe the integrated FEW system of cities.

This study addresses these gaps by developing a method to quantify these urban FEW flows and stocks and their interactions. We develop this method on the basis of material and energy flow analysis (MEFA), which quantifies flows and stocks of a substance, a group of substances, bulk materials, or energy within a system during a given period of time.\cite{50–52} Applying this method enables a mathematical representation of the urban FEW nexus, which can be the foundation of further analyses and modeling of these systems. We demonstrate this method using the Detroit Metropolitan Area (DMA) in 2012 as a case study. The DMA grew rapidly in the 1950s and then declined significantly. Now it is experiencing a rebirth, with redevelopment plans and projects that are reshaping flows of food, energy, and water. Thus, the DMA typifies a city-region that has changed significantly over the past decades and offers a dynamic case to demonstrate the method’s flexibility. We also developed an Excel-based template to streamline the data compilation process, largely using publicly available sources, for easy adoption by other cities, particularly cities in the United States.

**MATERIALS AND METHODS**

MEFA quantifies the amounts of materials and energy flowing in to and out from an economic system as well as the flows and stocks of materials and energy within the economic system. In other words, MEFA traces the flows and stocks of materials and energy of an economic system,\cite{50–52} based on mass and energy balance principles. In this study, we use MEFA to characterize the urban FEW nexus by tracking and quantifying the flows and stocks of food (represented by the amounts of nitrogen and phosphorus embedded in food), water, and energy in an urban area during a certain period of time.

In this study, we focus on the interconnections among processes of FEW subsystems rather than just interconnections among different flows. For example, the energy–food nexus refers to energy flows from processes of the energy subsystem to processes of the food subsystem (e.g., energy use by food production) and food flows from processes of the food subsystem to processes of the energy subsystem (e.g., electricity generation from food wastes). As such, FEW subsystem processes are interconnected through FEW flows, and interventions in a process of a subsystem can have ripple effects through other internal and external processes.
Urban Food—Energy—Water Flows. Figure 1 panels a–c conceptualize the flows and stocks of food, energy, and water systems, respectively. The food system consists of eight processes: fertilizer production, plantation, feed production, husbandry, food processing, food retail, domestic consumption, and solid waste management (Figure 1a). Given the variety of food crops and products, we use nitrogen (N) and phosphorus (P) flows as the currency to represent the flows of materials in the food system. Plantation and husbandry processes fix N and P from the environment and discharge N and P to the environment through N/P loss, N/P embedded in wastewater, and N/P embedded in landfilled solid wastes.

The energy system (Figure 1b) extracts fossil fuels or utilizes renewable resources (e.g., hydrological, solar, and wind power) to produce electricity. After production, waste heat, air pollutants, and solid wastes are discharged. Solid wastes are either reused or landfilled.

The water system primarily consists of water treatment and supply, wastewater collection and treatment, and residual processing (Figure 1c). Water treatment processes withdraw surface and groundwater and supply treated water to businesses and households for use. Wastewater is collected from businesses and households, treated, and discharged to natural water bodies. There are water and wastewater losses in water distribution and wastewater collection processes. Sludge from water and wastewater treatment facilities is treated by chemical-facilitated residuals processing before discharge.

Figure 1d shows the flows and stocks of the integrated FEW system. The food system uses energy produced by the energy system; the energy system uses solid wastes and landfill gas from the food system to produce electricity. The food system also uses water from the water system and generates wastewater collected and treated by the water system. The energy system provides energy for the water system to use and generates wastewater collected and treated by the water system. The urban FEW systems are also connected with the outside regions through imports and exports of products.

In this study, we first quantify the flows and stocks of individual FEW systems for major processes (Figure 1) across the urban system. Second, we identify and measure the flows connecting the individual FEW systems. Finally, we characterize each individual FEW system as a network of processes connected by resource and energy flows. We integrate the three individual FEW flow networks as a network of three subnetworks. Subsequently, we get an integrated FEW flow network that provides a topological representation of the urban FEW nexus.

This method does not consider material and energy flows embodied in imports and exports, because there are already established methods37 and abundant case studies.54,55 Such methods can be easily integrated with our method in the future. Moreover, stakeholders in an urban area have limited control of material and energy flows in other regions. Thus, examining material and energy flows closely associated with an urban system is more likely to provide information to guide actionable policies for cities.

Data for Detroit Metropolitan Area Food—Energy—Water Nexus. We use the city-region concept to define the system boundary for the urban FEW nexus. A city-region denotes a metropolitan area and hinterland, typically an urban area with multiple administrative districts but sharing resources like water and energy infrastructures.56 The system boundary of the city-region in this study—the Detroit Metropolitan Area (DMA)—is the Metropolitan Statistical Area (MSA) of Detroit–Warren–Dearborn and comprises six counties: Lapeer, Livingston, Macomb, Oakland, St. Clair, and Wayne. We characterize the urban FEW nexus for the DMA in 2012, the most recent year for which data are available.

In 2012, the DMA was ranked 14th in population (4.3 million people), 13th in gross domestic product (GDP, $218.5 billion), 109th in per capita income ($42,168/capita), and 95th in per capita GDP ($50,893/capita) among all MSAs in the United States.57 Data used to construct the DMA FEW nexus network are primarily from publicly available sources. Estimations were made when data were unavailable. Table S1 summarizes data sources and estimation methods for constructing the DMA FEW nexus network in 2012.

Data for food flows of the DMA FEW nexus network are mostly from the U.S. Department of Agriculture (USDA).58,59 Given the variety of food crops and products, we use the amounts of nitrogen (N) and phosphorus (P) contained in these crops and products as the currency to represent the food flows. Flows of the crops and products are converted into N and P flows by multiplying their weight by N/P content parameters.60–62 In particular, food imports and exports of DMA are from the Commodity Flow Survey.63 Data for crop straws, fertilizers, and biological fixation of N/P are estimated on the basis of agricultural activity levels.64–66 Stock changes of N and P related to animal and human body weight changes are estimated by mass balance.

Data for water withdrawal and supply are from the U.S. Geological Survey (USGS).70 In particular, USGS water data are updated every 5 years, and the latest data are for 2010. We used the 2010 USGS data for DMA as a proxy for 2012. We assume that water used by each process mostly became wastewater. The amounts of treated wastewater and generated sludge were obtained from the Detroit Water and Sewerage Department (DWSD).71 Water losses from water distribution and wastewater collection are estimated by water loss rates.

Data for fossil fuel extraction are from the USDA Economics Research Service.73 Data for electricity generation and fuel uses are from the U.S. Energy Information Administration (EIA).74,75 Data for oil refinery in the DMA come from Marathon Petroleum.76 The USDA Census of Agriculture only has aggregated energy use data for agricultural activities. We estimated energy use of each agricultural process by multiplying agricultural activity data by corresponding energy intensities.57,58 DWSD provides data for gasoline used to support water and wastewater treatment.71 Data for electricity uses for water treatment, wastewater treatment, and residual processing were estimated by activity data and electricity use intensities.57 Data for electricity use by households is from the EIA.80 Data for energy imports and exports are from the Commodity Flow Survey.83

This study uses the DMA as a case to illustrate the processes for data collection and estimation, but the method and data used are not unique to the DMA. For example, most of the data sources used in this study (e.g., USDA, USGS, Commodity Flow Survey, and EIA) contain not only the data for the DMA but also the data for each MSA in the United States. Moreover, there may be differences in the statistics of different countries. However, by properly adjusting certain data estimation methods and parameters, the proposed methods and templates can also be used in FEW nexus analyses of other countries.
RESULTS

Food–Energy–Water Flows in Detroit Metropolitan Area. Table 1 shows the inputs and outputs of FEW resources in the DMA in 2012. Household consumption and related services are the main drivers within the city-region. Upstream processes including extraction, plantation, processing, and manufacturing are primarily located outside the city-region for food and energy. In particular, total inputs of N and P were 119 Kt (83% imported) and 16 Kt (94% imported), respectively. Energy inputs were 1270 PJ, of which 99% was imported. In contrast, water inputs (5 billion t) were totally withdrawn from local water bodies.

Total N output of DMA was 114 Kt (73 Kt discharged to local environment and 41 Kt exported to other regions), and N stock in DMA increased by 5 Kt. Total P output of DMA was 16 Kt (12 Kt to local and 5 Kt exported), and P stock in DMA increased by 0.1 Kt. Used water was discharged into natural water bodies in the form of treated wastewater (4342 Mt), water loss from distribution (140 Mt), and wastewater loss from collection (193 Mt). Energy outputs included heat loss during energy use (916 PJ) and energy product exports to other regions (354.7 PJ).

Figure 2 compares per capita N and P intakes of the DMA with those of other cities reported in the literature. Per capita N intake of the DMA (7.3 kg/capita) is at the medium level among studied cities: lower than Beijing, Paris, and Vienna and higher than Linkoping and Toronto. Per capita P intake of DMA (0.9 kg/capita) is higher than most of the studied cities (e.g., Harare, Chaohu Watershed in 1995 and 2012, Busia, Linkoping, and Thachin Basin). However, it is lower than the Chaohu Watershed in 1978 (1.1 kg/capita) and Phoenix during 2005–2010 (1.0 kg/capita). These comparisons indicate that there are still potentials to reduce the pressures of N/P demands in the DMA.

Figure 3 compares per capita N and P emissions to water bodies in DMA with those in other cities reported in the literature. Per capita N emissions to water bodies in DMA were 4.0 kg/capita, the highest among investigated cities (e.g., Beijing, Paris, and Linkoping). Per capita P emissions to water bodies in DMA were 0.4 kg/capita, at the medium level of investigated cities: lower than the Chaohu Watershed, Beijing in 1998 and 2008, and Tianjin but higher than Beijing in 1978 and 1988. P emission level of the DMA was much better than other cities reported in the literature. However, N emission level of the DMA was much worse than other investigated cities. Thus, reducing per capita N emissions should be of particular concern in the DMA.

Figure 4 shows N, P, energy, and water flows of the integrated FEW system in the DMA. N and P flows (Figure 4a,b) are mainly attributable to five processes: plantation, food processing, food retail, domestic consumption, and solid waste management. The largest N and P flows are those embedded in fly ash from solid waste incineration, S3 and 9 Kt, respectively. The second largest N flow is embedded in imports of processed foods from other regions (42 Kt), while the largest P flow is embedded in imports of agricultural products from other regions (8 Kt).

Energy flows (Figure 4c) are mainly related to liquid fuel/coke production. Top three largest energy flows are imports of liquid fuel/coke (513 PJ), liquid fuel/coke use by other sectors (452 PJ), and heat release from other sectors to the environment (769 PJ).

Water flows (Figure 4d) are mainly related to electricity generation, water treatment and supply, and wastewater collection and treatment processes. Electricity generation withdrew 3256 Mt of water from local water bodies for cooling purposes. The used water was then returned to surface water bodies or evaporated to the atmosphere. Other major water flows are water withdrawal and supply (872 Mt), wastewater collection (1209 Mt), and wastewater treatment (1016 Mt). In particular, water flows related to the food system are relatively small in the DMA, because agricultural activities mainly occur outside of it.

Food–Energy–Water Nexus in Detroit Metropolitan Area. Figure 4 also shows the nexus among individual FEW systems. In particular, the food system used 425 Mt of water, and it discharged 424 Mt of wastewater, 4 Kt of N, and 1 Kt of P to the water system through wastewater flows. Food wastes, sludge, and landfill gas were in part used to generate 8 PJ of electricity. On the other hand, the food and water systems used 63 and 4 PJ of energy, respectively. Moreover, the energy system withdrew 3262 Mt of water from the environment and returned the same amount of used water to the environment.

Compared with other states in the United States, water withdrawal for generating unitary thermoelectric power in DMA [34.8 gallons (kW·h)^−1] was at a relatively higher level (Figure 5). In contrast, water withdrawals for unitary N and P in DMA crops (0.03 and 0.21 gallon/g, respectively) were lower than those in most states (Figure 5).
DISCUSSION

This study developed a standardized and specific accounting method to synthetically characterize the inputs, intersectoral flows, stocks, and outputs of FEW resources from the perspective of an integrated urban FEW system. This method can help identify key processes for improving FEW resource efficiencies of urban FEW systems. It also lays the ground for future urban FEW analyses and modeling.

Policy Implications for the Detroit Metropolitan Area.

We quantified the FEW nexus of the DMA and compared its FEW resource efficiencies at certain processes with those in other cities reported in literature. Our results help identify key processes for improving FEW resource efficiencies of the DMA.

The DMA has a relatively high per capita P intake, indicating that domestic consumption is a key process for improving P use efficiency. Thus, it is necessary to optimize the dietary habits of households in the DMA: for instance, using a certification scheme (e.g., green labeling of goods and services) to educate households about P footprints of their purchased products.

Moreover, the DMA has relatively high per capita N emissions to water bodies. Wastewater treatment, plantation, and wastewater collection are three major sources of N emissions in the DMA. Potential solutions to reduce N emission levels can be improving effluent-disposal standards for N removal, promoting adequate fertilization, and enhancing the maintenance of wastewater collection pipelines.

Electricity generation is the largest water user in the DMA. The DMA has a relatively high level of water withdrawal for unitary thermoelectric power. Thus, improving water use efficiency of thermoelectric power plants in DMA can help reduce water withdrawals.

Since food, energy, and water systems are interconnected with one another, changing components of one system may lead to ripple effects (desired or undesired) on other systems. For example, using air-cooled units in place of water-cooled units in power plants can reduce water use but would increase the demand for energy materials and subsequent emissions of carbon dioxide. Thus, the effectiveness of potential solutions must be assessed in the context of the urban FEW nexus.

Currently, government departments of most countries make policy decisions individually. The nexus of FEW subsystems is not fully taken into account. The findings in this study inform governments to coordinate FEW-related policies of different departments to maximize cobenefits and avoid unintended consequences. The method developed in this study can serve as a basic tool for FEW resource management of urban governments.

Data Availability, Applicability for Other Regions, and Uncertainties.

We proposed a method to quantify urban FEW nexus based on MEFA. This method uses publicly available data including government statistics and peer-reviewed estimation methods. This makes it easy to adopt this method to quantify urban FEW nexus across multiple years and multiple cities, although this study only used the DMA in 2012 as a demonstration. In particular, this method is more adoptable by cities in the United States, because data sources and parameters for estimations are more relevant to the U.S. context.
Some data required for quantifying FEW nexus are not readily available for urban areas. We need to estimate those data by peer-reviewed estimation methods, energy and mass balances, or proxies of other cities or national averages. These estimations bring uncertainties to the results. Improving urban statistical systems in the future can help reduce these uncertainties.

**Templates for Urban Food—Energy—Water Nexus Accounting.** To encourage the adoption of the proposed method for urban FEW nexus accounting, we developed a set of Excel-based templates to streamline the data compilation process (Supporting Information). These templates consist of three Excel files for N and P flows, energy flows, and water flows, respectively, and one Excel file for final balanced tables and summarized results. Each of the former three Excel files includes several sheets for data inputs, predefined parameters, intermediate calculations, and initial result outputs. The latter Excel file mainly balances initial results on the basis of mass and energy balances and then summarizes the final results. Users can input data for a particular city or region, adjust parameters by use of region-specific data if available, and then get the final results quantifying the FEW nexus.

We present the final results in the format of physical input—output tables (PIOTs) to show the mass and energy flows for N, P, energy, and water. There are four main matrices in the PIOTs. The core matrix shows material and energy flows among various processes within the integrated urban FEW system, including various processes related to FEW and “other sectors” processes. The final demand matrix shows FEW stock changes within the system and material and energy flows between the local FEW system and the outside (i.e., FEW imports and exports). The From-Nature and To-Nature matrixes describe FEW flows between the local FEW system and the environment.

![Figure 3. Comparison of per capita N and P emissions to water bodies in the DMA with those of other cities. Detailed data sources are listed in Tables S2 and S3, respectively.](image)

![Figure 4. FEW nexus of the DMA, 2012.](image)
Particularly, the From-Nature matrix shows the biological fixation of N/P, N/P embedded in water withdrawal, water withdrawal, and energy extraction/capture from the environment. The To-Nature matrix shows N/P emissions, wastewater discharge, water loss, and energy loss to the environment. There are row and column balances for each process. Total outputs represent the sum of each row, indicating the total FEW outflow of each process. Total inputs indicate the sum of each column, representing the total inflow of each process. Total output of each process equals its total input, indicating mass or energy balance of each process. The PIOT layout clearly shows transactions and stock changes within the urban FEW system, its interactions with the outside through imports/exports, and its interactions with the environment. The summary sheet shows general inputs and outputs of individual FEW systems and the whole integrated FEW system.

These templates are developed in the basis of U.S. statistical systems for metropolitan statistical areas. Thus, application to other U.S. urban systems is relatively simple. In addition, the templates can also be adapted for urban areas in other countries with necessary but minimal modifications to accommodate specific data sources.

**Future Research.** The proposed method quantifies the urban FEW nexus, which provides the basis for a variety of further investigations of this nexus. First, we can evaluate the holistic features of the quantified urban FEW nexus. The quantified urban FEW nexus can be treated as a network, with processes as nodes and mass/energy flows among processes as links. We can then apply network analysis tools to evaluate the efficiency and resilience of the urban FEW network. We can also detect the community structure of this network, which shows the clustering characteristics of the urban FEW network. The community structure can help policy makers to identify processes that will be strongly influenced by interventions at a specific process, because processes falling into the same cluster are more closely interconnected with one another than with processes outside this cluster.
Second, we can identify critical processes and supply-chain paths within the urban FEW nexus. Applying input–output analysis techniques to the quantified urban FEW nexus, we can identify critical processes from multiple viewpoints (e.g., primary suppliers, transmission centers, and final producers, and final consumers) and critical supply-chain paths that strongly influence FEW demands and wastes/missions of the integrated FEW system. These results identify hotspots for different types of policy decisions (e.g., supply-side measures, demand-side measures, and production efficiency improvement measures).

Third, we can evaluate the consequences of specific policy or technology solutions within the FEW system on the basis of the quantified urban FEW nexus. Since processes are interconnected with one another, interventions at a specific process can lead to cobenefits or unintended consequences at other processes. The urban FEW nexus accounting quantifies these interconnections among processes and describes the equilibrium state of the integrated FEW system by using mass and energy balances. When there is an intervention in a certain process, the whole FEW system will change and reach a new equilibrium state. We can quantify the consequences of specific policy or technology solutions by combining urban FEW nexus accounting with methods like system dynamics modeling.

Finally, current statistics on cities are not detailed enough to characterize the FEW nexus for specific products. For example, the USGS has only aggregated water use data for irrigation at the county level, instead of water use data for each type of agricultural product. Thus, the method used in this study can reveal the FEW nexus at the macro (i.e., regional) and meso (i.e., sectoral) levels, but it cannot yet reveal micro-level processes (i.e., product level). Applying this method at the microlevel will require more detailed statistical data.

## Associated Content

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b06240.

Three tables listing data sources and estimation methods for constructing DMA FEW nexus network and data sources for per capita N and P flows (PDF)

Three Excel files for N and P flows, energy flows, and water flows and one Excel file for final balanced tables and summarized results (ZIP)

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### Notes

The authors declare no competing financial interest.

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