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ARTICLE *in* ENVIRONMENTAL SCIENCE & TECHNOLOGY · AUGUST 2015

Impact Factor: 5.33 · DOI: 10.1021/acs.est.5b03060 · Source: PubMed

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Environmental Science & Technology

Critical Review

pubs.acs.org/est

Urban Metabolism: A Review of Current Knowledge and Directions for Future Study

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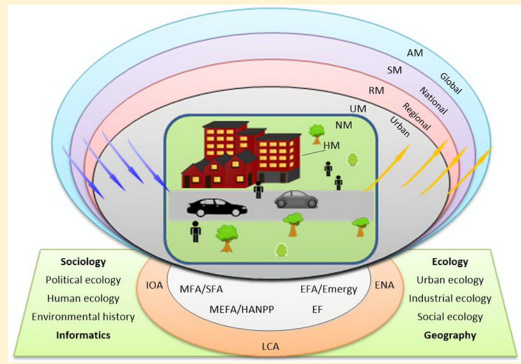
ABSTRACT: During the 50 years since the concept of urban metabolism was proposed, this field of research has evolved slowly. On the basis of an analogy with an organism's metabolism, the concept of urban metabolism has become an effective method to evaluate the flows of energy and materials within an urban system, thereby providing insights into the system's sustainability and the severity of urban problems such as excessive social, community, and household metabolism at scales ranging from global to local. Researchers have improved this approach, evolving from models of linear to cyclic processes and then to network models. Researchers account for flows of energy and materials, ecological footprints, inputs and outputs, and the characteristics of the system's ecological network. However, the practical methods of analysis need to be improved. Future analysis should focus on establishing a multilevel, unified, and standardized system of categories to support the creation of consistent inventory databases; it should also seek to improve the methods used in the analysis to provide standards and guidance that will help governments to achieve sustainable development. Finally, researchers must improve the ability to provide spatially explicit analyses that facilitate the task of applying research results to guide practical decision-support.



1. INTRODUCTION

Cities are regions in which concentrated human activities occur, and because cities represent an important point of contact between natural and socioeconomic systems, unsustainable urban development is creating serious ecological and environmental problems. Given that cities exchange materials and energy with their surrounding environment (analogous to the metabolic activities of natural organisms), researchers have wondered whether cities can mimic the same processes in natural systems and whether the theoretical insights gained from natural systems can provide similar insights that would let urban managers mitigate the environmental problems of these hybrids of artificial and natural systems. If this approach is possible, it raises the question of what urban managers could do to better mimic the metabolism of natural systems. Researchers believe that by describing and understanding the ecological principles that underlie urban processes, it will become possible to find ways to emulate the efficiency and stability of natural systems. In effect, a city can be treated as a giant organism, and its metabolic processes (its "urban metabolism") can be analyzed using the same methods used to study natural organisms and the ecological systems they inhabit.

Since the field of urban metabolism research first appeared, more than 50 years ago, its theoretical foundations have evolved and its scale of application has expanded from local to global. Innovative approaches have been developed to study certain problems, new methods have been developed to better describe the system's complexity, and combining techniques from different disciplines has permitted a more comprehensive analysis of the current state and the past and future evolution of an urban metabolism. To understand the current state of this field of research and where we go from here, it is helpful to understand its history and how its definition and theoretical framework have evolved. In addition, it is important to understand the scales at which this approach has been and should be applied. Finally, it is important to understand the field's unsolved problems and the prospects for its future development. These will be the goals of the present review.

2. HISTORY AND EVOLUTION OF THE URBAN METABOLISM CONCEPT

2.1. Definition. In 1965, Wolman,[1] a water treatment expert, introduced the concept of an urban metabolism into the study of socioeconomic systems and used this framework to understand urban development's effect on the environment and vice versa. He treated the city as an organism with the equivalent of metabolic processes and defined urban metabolism as the inputs of materials and energy into the urban system and the emission of wastes by the system. By examining the

Received: June 30, 2012
Revised: August 29, 2015
Accepted: August 30, 2015
Published: August 31, 2015

DOI: 10.1021/acs.est.5b03060
Environ. Sci. Technol. 2015, 49, 11247−11263

input and output processes of urban systems, he found that as the scale of a city increases, the provision of water to residents, and the associated generation of water and air pollution, would become the three most serious problems. Therefore, it is important to quantify the resources (e.g., food, clothing, fuel, electricity, building materials) needed to sustain the lives, work, and recreation of urban residents and analyze the interactions between flows of materials and energy and the associated environmental problems. Such studies provide insights that lead to solutions and the development of more effective public policies.

The potential of this approach was obvious, leading to an explosion of research on urban metabolism. Since Wolman's pioneering work, many scholars have developed theories based on this kind of analysis. Some focused on processes,[2,3] whereas others focused on interactions and relationships,[4] environmental load assessment,[5] and opportunities and methods for improvement.[6] These researchers treated cities as organisms that consume raw materials, fuel, and water and convert them into the built environment, human biomass, and wastes.[2] This approach combines an analysis of ecological and socioeconomic processes to provide a broad framework that accounts for urban development, energy production, and waste emission, which defines the interactions between the human and natural components of an urban system and that analyzes the input and output flows between cities and their environment.[7−11] In this framework, an urban system is no longer just an architectural space for planning or management but rather a "superorganism" whose metabolic processes must be controlled. These processes arise from and modify dynamic, cyclic flows, and understanding these flows and how they change over time can help planners to reduce the production of wastes or improve the treatment and reutilization of wastes in cities.

The definition of urban metabolism has mostly emphasized the technological metabolic processes of a socioeconomic system and has treated natural systems as nothing more than a kind of fuel or support for these processes, instead of combining natural or organic processes into urban metabolic processes or isolating natural systems as distinct components that also require study. In this review, we will treat urban metabolism as the gathering of all of the city's socioeconomic (technological) and natural (organic) metabolic processes, because some resources related to urban metabolism originate from natural metabolic processes and integrating human activities within socioeconomic systems changes some natural processes; even when these processes are subsequently dominated by technological processes, the natural processes remain indispensable for the city's survival.

Because cities resemble living organisms, but are qualitatively different, it is important to express this metaphor in a manner that informs research rather than leading it astray.[12,13] Bohle[14] was one of the early researchers who pointed out that this metaphor must be constrained by the natural laws that govern social structures and processes. Fischer-Kowalski[15] stated that the concept of metabolism is not just a metaphor but rather a way to emphasize the material and energy flows and the associated processes in a socioeconomic system. Warren-Rhodes and Koenig[5] reminded us that although living beings and urban systems have similarities, they are not the same thing. Because of these differences, other scholars believed that it was not suitable to treat cities as if they were organisms.[16] Instead, they believed that cities represent hybrid systems that combine multiple organisms, including humans, animals, and plants, in ways that are more similar to an ecosystem than to an individual organism.[13,16]

This insight represented a key change in the theoretical framework, and it permitted more practical use of the metabolic metaphor. For example, the relationships between components of the system can be defined using a metaphor based on the roles of the biological organisms in an ecosystem. Using this metaphor, the manufacturing, consumer, and waste disposal infrastructures of a city can be considered analogous to the producers, consumers, and decomposers in a natural ecosystem.[17] It then becomes possible to simulate material cycling and energy flows using knowledge and tools from ecosystem research and to use the insights gained from this analysis to reduce the environmental pressures created by resource exploitation and the resulting waste emission. These insights into a city's structure and function can let managers optimize the components of the system and the flows among them to sustain the city's long-term development.[18] The power of this metaphor is that it allows socioeconomic researchers to introduce the tools developed during more than a century of research on ecological systems and their metabolic processes to improve the processes of socioeconomic systems.

Although the composition and structure of a city are clearly not organic, urban metabolism research tries to find ways to increase the resemblance of a city to organic systems in an effort to relieve the pressure of the city on its ecological environment. Urban metabolism is an important concept because it provides new research perspectives and an effective way to trace the social, economic, and natural processes that occur in cities and to relate waste emission to consumption and transformation of raw materials. It treats the city as a collection of systematic and related processes, identifies resource utilization problems and the associated environmental problems using indicators of metabolic throughflows and efficiencies, and lets researchers propose effective suggestions to promote sustainable development.

Urban metabolism can be divided into anabolic processes, such as resource consumption to produce products, and catabolic processes, such as decomposition and recycling of wastes.[19] It can also include biological and technological metabolic components.[20,21] These different ways of categorizing urban processes reflect the different metabolic roles of a system's components and the exchanges among them.[22] In this context, metabolic flows refer to the flows of water, energy, materials, and nutrients and include both "resource" flows and "waste" flows. "Resources" refer to materials, energy, information, and services that can be used to produce some tangible (e.g., materials) or intangible (e.g., information) product. "Wastes" refer to the byproducts of a component of the system that are not reused by that component. These "wastes" often become important resources both for the component itself (e.g., recovery of waste paper by pulp and paper plants) and for other components (e.g., burning waste paper by another industry to generate energy). This is a sufficiently important concept that eco-industrial parks have been developed to greatly increase reuse of such wastes by the associated industries, thereby turning what would otherwise become a pollution problem into an important resource. Zhang et al.[23] provide a detailed discussion of this field of research and examples of how urban metabolism research has informed the development of eco-industrial parks.

In addition to these flows (which are dynamic processes), storage (a static process) can also be considered, and both the

DOI: 10.1021/acs.est.5b03060
Environ. Sci. Technol. 2015, 49, 11247−11263

flows and the change in storage (the "stock") can be calculated on a scale suitable for the purposes of a given analysis, such as the calendar year, and can be summarized in mass units for materials and energy units for flows of energy.[7,24,25] For example, studies of Hong Kong,[21,26] of municipalities in the Toronto region,[27] of 425 cities in the United States,[28] and of Bogotá[29] were all based on the accumulation rate of materials or energy, and the researchers analyzed the dynamic characteristics of these rates.

To more fully understand a city, its resource flows can be compared with those of other cities to determine whether the city's metabolism is more or less sustainable and whether its environmental impacts can be reduced.[30] Various indicators have been introduced to quantify a system's metabolic efficiency and facilitate such comparisons.[16] Metabolic efficiency represents the ratio of outputs to inputs, where "output" represents the quantity or value of the products or services from an urban system and "input" represents the environmental load created by the consumption of resources and energy, such as water consumption and the resulting waste emission. Researchers have used the concept of metabolic efficiency to study cities such as Taipei,[31] Shenzhen,[32] Shanghai,[33] Limerick,[34] Rome,[35] and Beijing.[36] Other researchers have analyzed the relationships between metabolic efficiency and human well-being.[37,38] They found that this can be an indicator of the potential sustainability of an urban system because metabolic efficiency represents the relationship between economic development and the severity of the associated environmental impacts.[39,40] The resource flows in urban metabolic processes, and the impacts of the associated outputs on environmental quality can be related to the services and products produced by the urban system.

Metabolic efficiency research developed from the study of material balances and metabolism and thus, provides insights into the sustainability of an urban metabolism. Although there are many unsatisfactory characteristics of urban systems, such as their excessively high resource consumption and low resource utilization efficiency, such systems also offer some advantages. For example, the high density of socioeconomic activities will concentrate resource consumption and waste emission, but it can also increase the efficiency of energy utilization and material recycling compared with dispersed rural populations.

Several researchers have attempted to combine or build on these previous approaches from the perspectives of technology, development history, and the contribution to sustainable development. For example, Weisz and Steinberger[41] reviewed flows of materials and energy in an urban system based on the potential of changes in urban morphology, urban building stock, and urban consumption patterns to reduce material and energy flows. Barles[42] analyzed the research methods used in analyses of flows of materials, of energy balances, and of environmental footprints and pointed out that analyses of urban metabolic processes can help us to understand the system's influence on the biosphere (direct or indirect) and provide support for urban sustainable development. In the context of the discipline of industrial ecology, Kennedy et al.[39] found that the research had been divided into two main areas: emergy analysis (which we will discuss in section 1.2.1) and material flows. Pincetl et al.[25] adopted insights from industrial ecology and political ecology and proposed that there had been two generations of urban metabolism research: research based on developing appropriate methodologies and research based on life-cycle assessment and a consideration of the spatial and socioeconomic elements of the system. In this context, Zhang[43] described a framework based on accounting for flows of energy and materials, development of a simulation model, and optimization of flows.

Most research on the flows of materials and energy has concentrated on traditional accounting methods and on establishing a technical framework. Few studies have analyzed urban metabolism at multiple scales or have applied its techniques in practice.[44] Thus, this research was difficult to use as a practical application of the concept of urban metabolism. In the present review, we will highlight model development and changes in the models based on the use of a technical framework combined with accounting for material and energy flows, particularly when such research was combined with a case study to illustrate its application at one or more scales. This approach reveals the current limitations of practical analysis of urban metabolism and suggests ways that future research can promote the application of this approach to guide sustainable urban development.

2.2. History of Urban Metabolism Research. In this section, we will describe the evolution of urban metabolism research to provide context for our discussion of scale and research methodologies. We will also describe the problems that have been solved during this evolution, which will lead to our final description of some of the problems that remain to be solved.

2.2.1. Initial Period (1965 to 1980). The quantitative analysis of urban metabolism began with Wolman's work,[1] which was based on a virtual city with a population of thousands rather than millions. Few researchers were interested in this approach during its early stages of development. The first practical research on urban metabolism began in the early 1970s, with studies of Miami,[45] Tokyo,[46] Brussels,[47] and Hong Kong.[21] In addition to quantifying the artificial metabolism of the human systems in these cities, researchers included aspects of a city's biological metabolism (natural energy balances, energy storage in plant biomass, and conversion processes). In this research, authors used methods of material- and energy-flow analysis and used either mass or energy units to quantify the flows of materials and energy through an urban system.[24] Urban metabolism emphasizes the ecological changes that result from a city's socioeconomic activities, the provision of resources and treatment of wastes, and the role of socioeconomic activities as a component of the overall ecosystem. Therefore, technological metabolism and organic metabolism (the socioeconomic and natural metabolic components, respectively) are both important.

E.P. Odum[48] is considered one of the pioneers of quantitative ecosystem theory, as he gradually developed a model of an urban system's heterotrophic characteristics,[49] thereby laying the foundation for quantitative analysis of an urban metabolism. H.T. Odum,[50] who was a system ecologist, built on this previous work by using metabolic energy to represent the production of organic matter (photosynthesis) and its consumption (respiration) by the metabolic processes of ecological systems, and analyzed the relationship between humans and their environment from an energy perspective. He proposed the concept of embodied energy ("emergy").[51] Emergy is a type of available energy that is consumed in both the direct and the indirect transformations needed to make a product or service.[11] Using emergy, he compared different kinds of flows (materials, energy, and currency) using a consistent system of units, and this allowed a more

DOI: 10.1021/acs.est.5b03060
Environ. Sci. Technol. 2015, 49, 11247−11263

comprehensive study of the relationships between socio-economic systems and their external environment; one of the early studies was for the city of Miami.[45] Although emergy analysis can solve problems related to the selection of which elements to track during the flows through a system and how to combine materials, energy, and money, some problems remain; these include double counting,[11] apportioning emergy among the outputs of multioutput systems,[52] and the inaccuracy of the transformity values used to convert mass, energy, and economic units into emergy values.[53] Researchers are trying to improve emergy analysis by separating products to avoid double counting, identifying associated and symbiotic products, and improving transformity values (using the rules of "emergy algebra"),[52] and this has led to expanded use of emergy analysis.[39]

2.2.2. Growth Period (1981 to 2000). Urban metabolism research continued to develop, but at a slower rate, during this period. Researchers developed new methods, and as a result, standardization became a problem; that is, it became difficult to compare the results of studies conducted using different methods.[54] H.T. Odum[55] introduced the concept of hierarchies among the components of a system. Following Zucchetto's[45] Miami study, which used the emergy analysis method, H.T. Odum[56] began to conduct research on Paris since 1850 using the emergy method and data provided by Stanhill.[57] E.P. Odum[58] introduced the concept of urban parasitism to account for nonreciprocal relationships within an urban system. In contrast to this focus on flows of energy, other researchers used material-flow analysis to account for the storage and flows of resources. For example, Baccini and Brunner[24] emulated the metabolic concept as the "metabolism of the anthroposphere" and Baccini and Bader[59] used the concept of "regionaler stoffhaushalt" (regional material budgets) to account for flows of nutrients, materials, and substances such as water in the urban hydrologic cycle. (In the context of the present paper, "nutrients" refers to substances that are used to sustain or increase plant growth.) In fact, UNESCO's 1971 Man and the Biosphere Programme[60] led researchers to analyze the status of Rome, Barcelona, and Hong Kong in 1970.[26,60,61] In this research, cities were treated as ecosystems, and researchers analyzed urban metabolism from the perspective of treating cities as consumers of resources and producers of wastes, considered interactions between nature and humans, and detected the complex relationships and material flows (energy, water, nutrients, wastes) in an urban system.[62,63] The objective was to conduct comprehensive and multidisciplinary research on sustainable development and other important ecological values such as biodiversity conservation in urban systems,[64] instead of analyzing a single problem from a single perspective.

In 1993, the first international urban metabolism symposium was held in Kobe, Japan. However, it focused only on analyses of food systems from the perspective of urban metabolism.[14] Afterward, Girardet,[65] an environmental scientist, analyzed the interaction between urban metabolism and sustainable cities based on the research of Wolman[1] and the Rio Summit in 1992.[3] This provided a basis for subsequent adoption of methodologies from industrial ecology.

Akiyama[66] pointed out there were two main methods for urban metabolism analysis, with different objectives: the black box model (in which the internal components of the system were not considered) and the subsystem model (in which the black box was "opened" to reveal its components). The black box model and subsystem analysis provided by Akiyama[66] focused on the risks to human health. The other models of metabolism that were developed during this phase included a circular (i.e., recycling) metabolic model of a sustainable city,[65] and a livability metabolic model that accounted for social goals.[6] Black box models reflect the overall inputs and outputs of a city and its activity intensity and scale to provide a macroscale indicator, analogous to human information such as weight, temperature, and blood pressure. Black box models can be used when little data is available and provide an overview of urban metabolic efficiency and the degree of sustainability. In contrast, subsystem models describe details of the flows among subsystems and the factors that influence these flows and are analogous to examining individual human organ systems (e.g., the heart and blood vessels); however, this requires much more detailed data. The advantage of subsystem models is that they provide more direct support for diagnosing problems and suggesting measures to solve the problems, such as how to increase the efficiency of flows of energy and materials, how to increase the quality of life, and how to sustain development.

As an example of a black box model, Girardet[65] proposed a circular metabolic model for a sustainable city that explicitly considered the difference between linear (one-way) and circular (recycling) metabolic flows and analyzed how the interpretation changed. Girardet represented natural metabolic processes as circular flows, from inputs to outputs, then back to inputs, because he realized that a linear sequence with large throughputs and low resource-utilization efficiencies would increase the emission of wastes; in contrast, circular flows permitted reuse (recycling) of wastes that would otherwise be transferred to the environment. However, he also acknowledged that some flows are potentially linear; for example, nutrients can be removed from soil by plants but cannot be replaced unless specific measures (e.g., composting, use of sewage as fertilizer) are implemented to provide this return. Girardet noted that an emphasis on linear metabolic processes in a city would accelerate the global sustainability crisis.

The consumption of resources and emission of wastes is clearly related to the sustainable development of a city. Flows that are predominantly linear or that form open loops (i.e., losses from the system) are not sustainable. Therefore, it is essential to encourage circular material flows and, as much as possible, transform wastes into resources. Ideally, there should be fewer consumers in a city and more transformers. For example, it is possible to change some consumers into transformers, and doing so changes the linear process of consumption into the circular process of transformation and recycling. By increasing recycling and reuse of the byproducts of urban metabolism, cities can more closely mimic the circular nature of natural systems, thereby decreasing waste emission and resource consumption.[67]

Newman[6] noted that it is possible to achieve sustainability goals for a city by reducing resource utilization and waste emission, thereby keeping the impacts within the ability of the regional or worldwide ecosystem to sustain these impacts and that doing so would also improve human well-being. He extended the traditional input-output metabolic model to account for the dynamics and livability of communities and established a metabolic model in terms of social objectives that better combined the social and economic perspectives on urban systems. One of his key insights was that urban sustainability not only represents a decrease of metabolic flows (the inputs of resources or outputs of wastes), but also an increase in human vitality (infrastructure and health). One consequence of this

DOI: 10.1021/acs.est.5b03060
Environ. Sci. Technol. 2015, 49, 11247−11263

Table 1. Objectives and Content of Significant Large Research Projects That Focused on Urban Metabolism

project	funding	timeline	research objectives	research content	refs
Sustainable Urban Metabolism for Europe (SUME)	European Union	2008−2011	to plan and design future urban systems based on minimizing the environmental effects, and evaluate the potential of urban construction and transformation of the spatial structure, and to reduce resource and energy consumption	from the perspective of the construction environment, to analyze the influence of the spatial structure on resource utilization	Schremmer and Stead[84]
SustainaBle uRban plannIng Decision support accountinG for urban mEtabolism (BRIDGE)	European Union	2008−2011	provide plans for European cities from the perspective of biophysical science, and develop a decision-support system to sustain the development of urban systems	quantify flows of energy, water, carbon, and wastes, identify problems, formulate policies, and evaluate the outcomes by considering the influences of the environment and society.	Chrysoulakis[85]
MEMO−Evolution of the Lisbon metropolitan area metabolism. Lessons toward a Sustainable Urban Future	Center for Innovation, Technology and Policy Research, Portugal	2013−2015	compare the metabolic flows through different urban structures during different industrial periods in Lisbon, and identify drivers for metabolic processes and promote the sustainable development of the city	use material-flow and substance-flow analysis methods to evaluate the changes of urban structures.	http://www.umsc.pt/?page_id=1080
Energy baselines—The Urban Metabolism of Los Angeles County	California Energy Commission and Los Angeles County		create a community-wide energy-use protocol and comprehensive energy baselines for California communities, and provide data on current energy-use patterns of California communities based on both real-time information and model projections	integrating life-cycle accounting offered an assessment of how decisions result in effects within and beyond political borders; capturing direct, indirect, and supply chain energy flows; overlaying the flows with land-use information; and enabling the mapping of energy use based on land-use and demographic information.	http://sustainablecommunities.environment.ucla.edu/1474-2/
The Ancient Pre-Inca City of Caral	Holcim Foundation Seed Funding		examination of an ancient city to determine the drivers from nonfossil fuels to fossil fuels, and propose an effective scenario for developing a more efficient urban system	use the material intensity per service to compare the resource consumption characteristics and intensity of ancient and modern cities in Peru	Fernández[79]
Bombay Metabolism	Indira Gandhi Institute of Development Research		understand the most important processes in urban systems and help to formulate policies, and provide a framework to account for the stock and flows in urban systems	analyze the input flows, transfers, and wastes or products to calculate resource-utilization efficiency	Reddy[82]
an urban metabolism survey design for megacities	Enel Foundation		identify organic and physical characteristics of megacities, and summarize the ways that megacities can attempt sustainable development	collect data on energy, water, material, and waste flows for 10 to 15 megacities and determine their relationships with the public infrastructure	Kennedy et al.[83]

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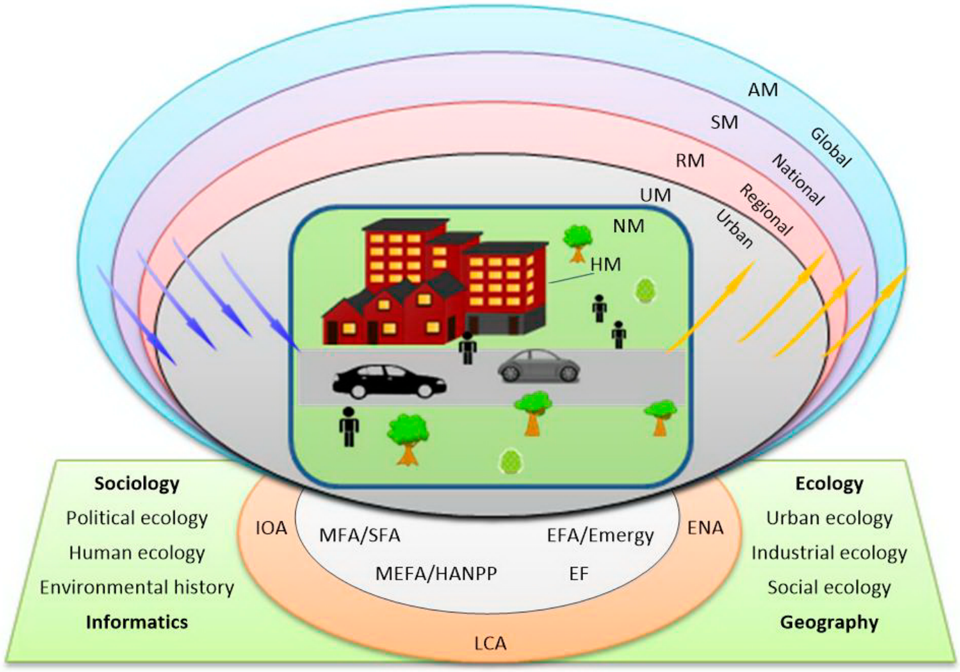

Figure 1. Illustration of the multiple scales and disciplines that should be considered in studies of an urban metabolism. Notes: AM, anthroposphere metabolism; EF, ecological footprint; EFA, energy-flow analysis; ENA, ecological network analysis; HANPP, human appropriation of net primary production; HM, household metabolism; IOA, input−output analysis; LCA, life-cycle assessment; MEFA, material- and energy-flow analysis; MFA, material-flow analysis; NM, neighborhood metabolism; RM, regional metabolism; SFA, substance-flow analysis; SM, social metabolism; UM, urban metabolism.

research was the development of a livability model of Sydney, Australia, which became an important tool in generating Australia's State of the Environment reports.[6,68]

Case studies became more frequent in the late 20th century, including studies initiated by the EU to examine material flows in Prague, Sweden, the Swiss lowlands, and Vienna.[69,70] Studies elsewhere in the world examined five coastal cities,[71] Taipei,[72] Sydney,[6,73] Brisbane,[74] and 25 cities from around the world.[2] The analyses of material and energy flows were primarily conceptual, including different kinds of materials, energy, and pollution,[75] and this made comparisons of different urban metabolisms difficult. It remains difficult to reliably combine the results of different studies,[76] and this problem has constrained the development of research on urban metabolism. It will be necessary to develop a uniform methodology to account for material and energy flows and to clarify the basic data requirements so that researchers can begin integrating the large body of available knowledge.

2.2.3. Rise Period (2001 to the Present). During the third phase of urban metabolism research, journals, conferences, collaborative projects, and reports began to provide a more consistent approach to studying urban metabolism.[39] For example, in 2007, the *Journal of Industrial Ecology* published a special issue on urban metabolism.[77] In 2008, the ConAccount Conference emphasized that urban metabolism was a vital tool to quantify the ecological characteristics of cities.[78] In 2011, the American Geophysical Union held a conference on Characterizing, Modeling, and Extending Urban Metabolism. In addition, several projects were initiated. Table 1 summarizes significant large research projects that focused on urban metabolism. Under these projects, researchers published several technical reports, including reports on the urban metabolism of the ancient city of Caral in Peru,[79] the relationship between urban metabolism and flows of water and energy,[80,81] the urban metabolism of Bombay,[82] and the urban metabolism of megacities.[83] This kind of research can provide a basis for identifying different urban characteristics and formulating management tools and standards, can demonstrate the benefits of collaboration between stakeholders and scientists, and can reflect the practical application of urban metabolism.

Simulation models have also improved as researchers accounted for circular metabolic flows,[86−89] for livability,[10,90] and for the network characteristics of systems.[91] On the basis of the material and energy flow processes in an urban metabolic system, the metabolic roles can be abstracted as nodes, and the flows among roles can be abstracted as paths, allowing researchers to describe the real world using a network model. Network models go beyond the traditional black box approach to analyze the internal characteristics of an urban metabolic system (i.e., they are a form of subsystem model) and the interactions among the components of the system's structure by transforming processes and nodes into mathematical descriptions of the flows among pairs of components. Examples of network models include an allometric scaling traffic network model for an urban system,[28] an urban water metabolic model,[92] an energy metabolic model,[91,93] and a materials metabolic model.[94]

In addition to static models that focused on the value of a parameter such as metabolic efficiency at a given point in time, researchers have developed dynamic models that account for changes over time. Examples include a dynamic material-flow analysis model for a built environment,[95] a dynamic evaluation and simulation model for metropolitan subprocesses in Toronto,[96] and a dynamic metabolic model for urban water.[97,98] Although different kinds of models have been developed for different purposes, it has been difficult to use

DOI: 10.1021/acs.est.5b03060
Environ. Sci. Technol. 2015, 49, 11247−11263

them in planning applications, due especially to a lack of spatially explicit analysis.[99] Therefore, it will be necessary to combine "bottom-up" approaches that provide sufficient resolution to study individual cities with "top-down" approaches that provide sufficient spatial coverage to study the region surrounding a city. It will also be necessary to promote the development of simulation and optimization models that combine policy scenarios with the setting of parameter values for the model and to use case studies to support the simulation results.

3. MULTISCALE CONSIDERATIONS

Urban systems exchange materials both among the components of the system and between the system and its external environment. As a result, the systems can be examined at a range of spatial scales, from those of individual households and the city itself to regional, national, and even global scales.[25,100−102] Analyses of an urban metabolism and its sustainability must therefore consider the utilization of energy and materials within a hierarchy of spatial scales.[25] Researchers have moved from an examination of the global metabolism,[103] to an examination of human metabolism,[24] and then to an examination of social metabolism at the national scale.[104−106] In addition, recognition of the fact that cities have social, economic, and natural components strongly suggests the need for cooperation among researchers from each of these areas of study; that is, future research should embrace a multidisciplinary approach, such as that of Wachsmuth.[107] Figure 1 illustrates the concept of scale and the associated diversity of disciplines that can contribute to a fuller understanding of urban metabolism.

3.1. Analysis at the Scale of an Urban Agglomeration or Individual Metropolis. One important effect of scale relates to the fact that all cities exist within a specific environmental context; thus, it is difficult to understand the characteristics of an urban metabolism by examining only the city. The problems faced by an urban system are also created by its relationships with its external environment, such as transfers of resources and wastes across the system's border and the consequences of the ecological footprints caused by utilization of resources upstream and downstream of the city. Thus, it is necessary to consider urban systems within a hierarchy that accounts for multiple scales (Figure 1). On the other hand, many problems with an urban metabolism arise from internal processes, and these processes are obscured when the system is examined only at a regional scale. For example, consider China's Jing-Jin-Ji urban agglomeration, in which Beijing is a consumer and Hebei Province is a producer. Beijing utilizes the nutrients and materials supplied by Hebei, and this process causes potentially huge ecological problems for Hebei that result from unsustainable consumption and the resulting generation of large amounts of wastes.[108] It is impossible to solve these problems only by controlling resource utilization within Beijing, but considering these problems at the scale of the overall urban agglomeration (i.e., including flows between Beijing and Hebei province) provides more holistic insights. For example, if Beijing introduced new technologies to produce its products with greater resource utilization efficiency, this would benefit both the urban agglomeration and Hebei Province by decreasing pressure on Hebei to supply these resources, and Hebei could also benefit by receiving funding produced by savings in Beijing and using that funding to strengthen its ecological service (support) functions. The improved overall resource utilization efficiency of the agglomeration would improve its sustainability. This example illustrates how achieving sustainable development will require improvements in socioeconomic and ecological efficiency by considering social, economic, technological, and resource efficiency for the whole region affected by the urban system; this consideration may even include the system's roles in global sustainable development.[109]

In the context of urban scale, the research on metropolises and urban agglomerations has become a hot topic, particularly in countries with a large population such as China.[110] Because of a lack of data, there have been few case studies of Chinese cities. These include using input-output life-cycle analysis to conduct research on the Su-Xi-Chang agglomeration[111] and an energy metabolic analysis of the Jing-Jin-Ji agglomeration based on input-output analysis.[108] Research in other countries has mostly been based on individual metropolises and has focused on dynamic changes in metabolic flows, ecological footprint evaluation, analysis of the relationship between a city's social and economic elements, and analysis of the corresponding metabolic processes. Examples include a metabolic analysis of Toronto,[27] the metabolic changes in 12 metropolises,[112] the energy metabolic processes of Melbourne,[113] the historical dynamics of metabolic processes in eastern Rhode Island,[114] historical changes in the food and water metabolisms of the New York−New Jersey−Pennsylvania region,[115] the metabolic processes in Asian cities,[44] the establishment of a metabolic flow model and accounting for both flows and stocks in Lisbon,[76] an energy input and output analysis for the social and ecological processes in San Juan, Puerto Rico,[116] and the investigation and description of megacities.[83]

However, each of these studies failed to comprehensively account for the metabolic flows through natural components of the system. Others used ecological footprints to describe the influence of a city on its environment, such as an ecological footprint assessment of London,[117] carbon footprint analysis from consumption perspectives for Helsinki and Porvoo,[118] analysis of the relationship between the metropolis and its surrounding environment for 11 western cities,[119] and the ecological footprint of Vancouver.[120] Previous research on the mechanisms that underlie an urban metabolism only analyzed the mechanism for one or a few factors, such as transportation, urban structure, and land use. Examples include analyses of the relationships between greenhouse gas metabolism and transportation in Toronto,[121] between the urban structure and greenhouse gas metabolism in Toronto,[122] between the socioeconomic metabolism and land use in Taipei,[123] between the degree of urban expansion and metabolism in Rhine-Main,[117] and between the economic and urban structures of Brisbane, in southeastern Queensland, using extended input-output analysis.[124] The analysis of a metropolis' metabolism can promote the development of more effective public policies.[125−127] For example, the European Union evaluated application of the SUME and BRIDGE projects,[128] and analysis of water provisioning and wastewater management provided guidance for formulating standards.[129] Ma et al.[130] proposed measures to create a closed metabolism (i.e., with the maximum possible recycling of materials and energy within the system) based on an analysis of the metabolic processes in Phoenix.

3.2. Analysis at Community and Household Scales. When it is necessary to consider urban metabolism at a larger scale, researchers usually treat cities as homogeneous structures and use data compiled at a relatively coarse resolution (e.g.,

DOI: 10.1021/acs.est.5b03060
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using top-down methods) and ignore the differences within the city, such as differences between central and suburban areas.[106] In addition, few researchers have combined studies of material and energy flows with the locations of the flows or with the activities and humans that produce them.[25] This has resulted in a lack of research based on high-resolution data (e.g., bottom-up methods). However, there has been some research at community and household scales to analyze the influence of differences in community morphology on food, water, and energy consumption and on carbon emission. The influence of sustainable design on community livability has been studied for Sydney and other Australian communities,[131] for 79 Irish communities,[132] for four typical communities in Toronto,[133] and for the Sunset community in south-central Vancouver.[134] There have also been studies of the influence of different household models on water and energy consumption and on carbon emissions. Researchers have used this perspective to study The Netherlands,[135] Saint Gall, Switzerland,[24,136] Sydney,[137] cities in China,[138] the Minneapolis−St. Paul metropolitan area,[125] Xiamen,[139] India,[140] and Managua.[89]

3.3. Scope of an Urban System. The scope of an urban system is difficult to define because the boundary between humans and nature is not obvious.[25] Tello and Ostos[141] treated the current municipal boundary as the physical boundary of the Barcelona urban system, even though Parés et al.[142] and Barracó et al.[143] considered this approach to be controversial. Because the practical functions of an urban system extend beyond the city's limits, it is reasonable to consider the city's political boundary, particularly since this has clear implications for sustainability.[144] In this context, "city" includes all structures within the administrative boundary, which often extends beyond the boundary of the built-up area, thereby including human activities within both the urban area and the rural areas that surround it.[17,145]

This is an important perspective because the rural and agricultural areas surrounding an urban system provide food, fuel, water, and other materials to the city; they also often serve as a location for disposal of the city's wastes. This perspective also demonstrated the need to pay more attention to interactions between cities and their external environment. Examples of such research include the first analysis of municipal metabolism in Toronto,[27] of carbon footprints based on consumption in Helsinki and Porvoo,[118] of changes in the food provisioning areas for the municipalities of the Paris agglomeration,[146] and of 11 Western municipalities and their surrounding environment.[119] Zhang et al.[90−93,147] treated the areas surrounding a city as areas that performed at least two metabolic roles (supplying resources to the city and receiving its wastes) and analyzed the interactions between this external region and the city's socioeconomic system. Zhang[43] improved the identification of metabolic processes by showing that urban metabolism is analogous to both the internal metabolism within an organism and the external metabolism that links the organism with its external environment.[17]

4. RESEARCH AREAS AND METHODS

4.1. Metabolic Flows. The metabolic processes considered in analyses of an urban metabolism include flows of nutrients, energy, water, and materials.[3] Researchers have also studied the consumption of resources per person[5] and the characteristics of these flows at various scales.[148] Water is an indispensable element both to sustain humans and as part of the social structure's metabolism.[149,150] For example, on the basis of the relationships among water, energy, and carbon flows in Oslo, Venkatesh et al.[97] analyzed the roles of the system's water-related components. On the basis of the relationships among energy, water, and food in London, Walker et al.[151] designed a new configuration for the city's wastewater infrastructure. Similarly, water metabolism sensitivity analysis has been conducted for Beijing,[92] four cities in Australia,[152] and Lisbon.[129]

In addition to water, the importance of urban energy and carbon metabolisms is increasingly recognized, particularly in the context of climate change. Thus, researchers have investigated these metabolisms in Beijing,[93] Mexican cities,[153] Paris,[106] Toronto,[154] and Syracuse.[155] Others have investigated the relationships between green buildings and the urban thermal metabolism.[156] In addition, researchers have studied the direct carbon emissions by private cars and heating systems in the municipalities of Toronto[122] and carbon emissions of 10 global cities,[112] as well as embodied (indirect) carbon flows.[157] Other researchers have studied the urban infrastructure,[3,88] the role of decomposers in terms of the urban water and wastewater infrastructure,[97,158,159] the transportation infrastructure,[28] and the solid wastes infrastructure.[160] Because excess release of nutrient elements such as N and P from crops and food can cause environmental problems,[161] other researchers have investigated nutrient metabolism in cities such as Stockholm,[162] Bangkok,[163] Paris,[8,164] Toronto,[165] Linköping,[166] and Xiamen.[161]

4.2. Accounting Methods. Material-flow analysis has been an important tool in urban metabolism analysis. For example, it was included in official EU statistics[167] and has been applied for Lisbon[168] and to compile primary data for describing the urban metabolic characteristics of York;[169] of Hamburg, Vienna, and Leipzig;[170] of Singapore;[171] of eight municipalities;[7] of European cities.[84] In industrial ecology, most researchers have instead used substance-flow analysis to analyze the metabolism of metals, including heavy metals in Stockholm,[172] of urban nitrogen,[8,164] of carbon in Vienna,[173] and of copper in Vienna and Taipei.[174] Substance- and material-flow analysis are related concepts but use different methodologies. Substance-flow analysis uses Euler's method and the Lagrangian method from hydromechanics to trace the path followed by a particle and observes the changes in the substance flows among different life-cycle stages.[175] In contrast, material-flow analysis investigates the quantity and state of cross-sectional data at different life-cycle stages. Therefore, substance-flow analysis "opens the black box" and traces flow quantities, especially along reuse and recycling paths, more easily than material-flow analysis, and it is also more effective when evaluating the potential for improving resource utilization efficiency.[176] In contrast, material-flow analysis provides an external and static analysis. Because some materials flow through a system in many forms, it is more difficult to obtain enough data for material-flow analysis. Although material-flow analysis needs a large quantity of data, it can estimate metabolic throughflow comprehensively, can reflect the intensity and scale of urban activities, and can be used to compare cities. Substance flow analysis traces the changes of a specific element during transition periods of a socioeconomic system; for example, copper and iron are vital materials for a modern economy, and lead and mercury have serious adverse consequences for the environment. This method only focuses on one substance instead of analyzing urban metabolic problems from an overall (holistic) perspective.

DOI: 10.1021/acs.est.5b03060
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Scholars have categorized urban metabolism methods in different ways: as material and nonmaterial approaches,[25,102] as inventory analysis (material- and substance-flow analysis), and as biophysical methods such as exergy and emergy.[173] Emergy analysis is particularly interesting because it accounts for the flows of materials and energy in different forms by quantifying the embodied energy. It has been applied successfully for Taipei,[31,72,177] Beijing,[178] Rome,[4] and Xiamen.[179]

Using the human appropriation of net primary production indicator, which is based on material- and energy-flow accounting,[180−183] researchers have analyzed the ecosystem appropriation by 29 municipalities in the Baltic basin,[184] the spatial distribution of the food consumption imprint in Linköping,[185] utilization of the areas surrounding Vienna,[186] and the "foodprint" (i.e., the ecological footprint of food consumption and production) in Paris.[164] Other scholars have characterized urban metabolism using the ecological footprint method. Kenny and Gray[187] and Sovacool and Brown[188] used a matrix that linked consumption with land use to analyze urban metabolism in terms of the ability of each land area to provide one or more resources and the pressure exerted on each land area by the consumption activities that it supports. Areas studied using this approach include Liverpool,[189] London,[190] Cape Town,[191] Cardiff,[192] 121 cities in the United States,[193] Paris,[194] and Metro Vancouver.[120]

4.3. Modeling Methods. In addition to direct consumption and utilization, some research has modeled the resource consumption in processes that occur upstream of a city,[96] which represents an indirect contribution to the flows. This allowed researchers to modify input-output analysis to model both direct and indirect consumption of resources for cities such as Lisbon,[195] Suzhou,[160] and Beijing.[196] The main difficulty is how to convert monetary input-output tables into physical tables that represent the quantity of a material implied by the monetary value of a flow; this is an important tool because high-resolution economic data is generally more easily available than data on physical flows. For an urban system, it is necessary to identify inputs from its external environment, as well as imports and import areas for long-distance flows, before one can account for the effects of differences among regions in manufacturing technologies, which affect the conversion factors used to convert monetary values into physical quantities. Because many flows come from outside the urban system, this requires data from a larger scale than the urban system alone.[196] For example, to analyze the inputs and imports by a city, the database should be based on national and global input-output tables and must account for both the input and import paths and the different technologies (since different technologies imply different conversion factors) used in the different source areas.[43]

Ecological network analysis can also be used to account for both direct and indirect flows. Because the exchanges of materials and energy among the components of an urban system usually involve multiple agents and flows in multiple directions and because some flows pass through one or more components of a system before they reach their final destination, the city can be abstracted as a network of nodes that are connected by paths with a length of 1 or more.[91−93] (Here, a path length greater than 1 means that the flow passes through at least one intermediate node.) Ecological network analysis uses the components of this network and the linkages among them to model the flows of materials and energy among the components. This has been shown to be an effective method for analyzing the structure and function of urban systems.[197−200] This method can also be combined with emergy analysis or material-flow analysis, as was done for water in Beijing,[92] energy in Beijing,[93] four typical Chinese cities,[91] comprehensive multisubstance processes,[201] and carbon-related processes in Vienna.[173] These analyses used a metabolic framework to understand the processes related to resource exploitation and waste generation and established a network model to consider both the direct and indirect influences on the system; the result was an improved understanding of the structure and function of a network based on the contributions by components with different metabolic roles and their relationships, thereby identifying the trophic levels of its components and the resulting productivity hierarchy more comprehensively.

4.4. Mechanism (Driver) Analysis. Understanding the drivers responsible for the dynamics of a metabolic network (i.e., the underlying mechanisms) is also important, particularly when the goal of research is to support planning and management of an urban system. Unfortunately, urban metabolism analysis has proven difficult to use in explaining the differences in drivers among cities.[27,126,191] For example, Newman et al.[68] conducted a metabolic analysis of Sydney at a descriptive level and did not consider the urban structure, the social and political driving factors, nor the complex changes in political, economic, and social processes. Pincetl et al.[25] noted that Warren-Rhodes and Koenig[5] did not compare the population, income, or other social factors that affected the urban metabolism of Hong Kong and thus did not determine the reasons for the city's transition from a manufacturing economy to one based on consumption. Some scholars have tried to combine inputs and outputs with the driving factors, such as industrialization, urbanization, lifestyle changes, and changes in technological levels.[29,126,138,202−204] Others have examined how the urban form, density, and infrastructure, as well as changes in land use, influenced metabolic flows and stocks of energy and materials.[205−208] Other researchers have examined how diverse factors such as the urban heat island effect,[3] differences in roof albedo,[209] and urban forests influenced the urban metabolism.[210]

It seems likely that the age of a city, its infrastructure, and its stage of industrial development will also affect its metabolism. As well, effective utilization of climate resources (e.g., abundant precipitation) and plants, development of suitable technologies, development of appropriate construction policies, energy costs, and social attitudes will affect metabolic flows. These influence factors have generally not been studied. In the future, researchers must consider the effects of a wider range of social, economic, technological, and ecological factors when they evaluate an urban system. They must also integrate the effects of these different types of factors, their influences, and their interactions in urban planning and management.

5. PRACTICAL APPLICATIONS

Urban metabolism research attempts to quantify and explain the interactions between human systems and natural systems. In addition to its theoretical interest, such research is necessary to support the development of sustainable public policies and activities.[125−127] However, there has been little research related to urban planning or design or to providing quantitative indicators for urban sustainable development. Researchers from ETH Zurich, MIT, the University of Toronto, and the Turin Polytechnic University have conducted meaningful research in

DOI: 10.1021/acs.est.5b03060
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this area. The first attempt was by Oswald et al.[211] from ETH Zurich, who found ways to mitigate the shortcomings of a core-periphery network model by combining the model with information on the morphology and physiology of the urban network of Netzstadt. The students of the Civil Engineering Department of the University of Toronto used their experience with green construction design and alternative energy sources to design a closed-loop recycling infrastructure for the port of Toronto.[3,133,212] Montrucchio,[213] working at the Turin Polytechnic University, used the analogy of an individual building as a pump to analyze the flows of water, energy, nutrients, and materials through the building, and used the results to support improvements of the building's design. Other researchers combined the "urban harvest" approach with a circular metabolic model to conduct resilient design.[100,101,214] In the urban harvest concept, an urban area decreases its dependence on the external environment to decrease its vulnerability to changes in that environment and increase its ability to cope to with changing conditions by producing some of its resources internally.

In this context, "urban resilience" refers to the ability of a city or urban system to withstand a wide array of shocks and stresses.[100,101] For example, material-flow analysis was used along with an ecological sensitivity analysis to design a more resilient urban system after Hurricane Katrina struck New Orleans.[44,215] In addition, Fernández's team from the MIT Construction School conducted a successful case study of redesign after Hurricane Katrina struck New Orleans.[44,215] It took them more than a year just to examine the city's public housing units and understand the political players and competing interests. They discovered that most of the housing units were already habitable or could be restored but that the decision-making process provided no input from residents on how to perform the restoration. They developed software that let them use material-flow analysis to account for the inputs and outputs of materials and energy, the durability of the housing stock, the costs of different building types, energy consumption rates, waste generation rates, data on population and employment, housing needs and growth priorities. On the basis of this analysis, they proposed goals for rebuilding the city and making it more green. They hope to increase New Orleans' resource-utilization efficiency in a way that provides a model for other cities, while rebuilding the city in a way that balances the needs of the many stakeholders and applies scientific rigor to urban design. Using this tool, New Orleans' urban planners can model the overall green city or target specific neighborhoods and can make better-informed decisions about rebuilding strategies. For example, the software starts by determining how different kinds of buildings reduce carbon emissions, energy use, use of construction materials, and other factors. Such modeling provides incentives for designers, engineers, and builders to adopt innovative approaches to water recovery, on-site energy production, and resilience. As researchers test and improve on this approach, it will serve as a model for other urban centers, particularly those that face challenges created by climate change. These case studies showed that planners need to learn from natural systems, design resilient recycling-based urban systems, and find ways to make the outputs from one component of the system inputs for other components of the system.

Previous analyses rarely considered the impacts of urban policies.[1,31,71] However, it is important for policy makers to understand urban metabolic processes so they can attempt to improve the utilization and recycling efficiencies of water, energy, materials, and nutrients and find measures to mitigate the impacts caused by exploitation of the resources surrounding the urban system.[7] The discipline of political ecology emphasizes the influence of policy development on the environment by using strategic environmental assessment to detect how strategies and planning influence the exchanges of energy, water, carbon, and wastes.[85,128] By combining strategic environmental assessment with urban metabolism, González et al.[128] investigated the influence of policy characteristics on material and energy flows and provided advice on how policymakers could adjust their plans. Pincetl et al.[25] performed an analysis of how to distribute energy and wastes per person, area, or activity in Los Angeles and examined the relationships of these flows with land use, society, and the city's population. In other words, understanding who is using each flow, how and where they are using it, and the resultant waste production should become an essential part of urban metabolism analyses.[25] This approach can explain energy consumers, energy types, and energy utilization activities to policymakers,[39] thereby allowing them to account for these factors in policy development and implementation.

In summary, urban metabolism research has evolved to the point at which it can now provide important insights into the functioning of an urban system. The black box model has been largely replaced by analyses of the internal mechanisms of an urban system (e.g., ecological network analysis) and of its interactions with the surrounding environment at scales ranging from local to global. Top-down and bottom-up analyses can be combined to provide different insights into a system, and there is increasing recognition of the need for a multidisciplinary approach that holistically accounts for all of the social, economic, and ecological drivers that are responsible for the flows among the components of an urban system and the changes in these flows over time. However, several research challenges, described in the next section must be resolved before it will be possible to encourage practical use of urban metabolism research to support decisions and policy development by urban planners and managers.

6. FUTURE DEVELOPMENTS

In this paper, we have described the history and evolution of urban metabolism research as well as the different metaphors, theories, perspectives, and frameworks that have guided this research. This discipline began with black box models that considered only overall inputs and outputs and evolved into detailed models that examined the inner workings of the urban system in increasing detail. Researchers have used aspects of life-cycle analysis, input-output analysis, and ecological network analysis to highlight the relationships among the urban system's components, quantify both direct and indirect consumption of resources, and assess the influence of the human system on the natural environment.

However, many research gaps remain. It will be necessary to consolidate the theoretical foundation that underlies this field of research, unify and standardize the methodology to facilitate comparisons between studies, find ways to explore and combine the results of analyses at different scales, and encourage cooperation among many disciplines. In particular, a systems engineering approach should be introduced to unify and standardize the methods of categorizing and quantifying data; to establish databases that will support investigation, analysis, and evaluation; to obtain multiscale data to meet the

DOI: 10.1021/acs.est.5b03060
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database requirements of such analyses; to improve our understanding of urban metabolic principles and scale effects to support management and policy development and meet the requirements of different stakeholders; to integrate the insights from different fields of research; and to design research that will provide solutions for specific social policy problems, which will guide industrial development and that will promote restoration of the urban ecological balance.

Analysis at multiple spatial scales has become increasingly important, because cities, as the main concentrations of human environmental impacts, play an important role in sustainable development at scales ranging from local to global. To fully understand the impacts of urban ecosystems, researchers should combine the results of analyses performed at a small scale, such as the community and household scale, with the results of larger-scale analyses that account for interactions among scales (Figure 1). This also suggests that we could examine a single industry (e.g., agriculture, primary manufacturing) using the superorganism metaphor. That is, each enterprise or infrastructure component in the industry functions as if it were an organ in a larger superorganism. For example, the lungs might be the components of agriculture that consume and release oxygen (e.g., plants) and the stomach might be the components that digest inputs (e.g., energy, fertilizer). This would allow an examination of each industry as if it were an organism within an ecosystem formed from the agricultural organism and other (e.g., industrial) organisms. That is, the approach can be scaled up from individual industries to the whole city. Unfortunately, research at multiple scales is hampered by problems related to the accuracy of existing data and gaps in the required data.[27] Most research on urban metabolism still uses data with relatively coarse resolution, as in most top-down methods;[18,216] as a result, it cannot provide insights into the problems of specific locations, activities, or populations.[13] For example, the available data for industrial and commercial water and energy utilization is difficult to correlate with land use. Conversely, research at finer resolutions fails to consider the impacts at larger (e.g., regional) scales. This constrains the application of large-scale analysis.[76] Urban metabolism has not been widely used to support urban planning and management because the aggregation of data at urban or regional levels cannot show the details within an urban system that are the target of planners and managers.

Modern technologies should be integrated more effectively with research. For example, geographic information systems, remote-sensing technology, and information network technology (e.g., monitoring using social networks, credit card purchases, and cell phones) can be used to provide the data required to support both bottom-up and top-down methods and to differentiate among urban regions or structures with significantly different characteristics.[217] At the same time, this broad-scale data should be supplemented by information obtained at a community scale to support bottom-up methods. Information network technology (e.g., the Internet) can be used to decrease spatial constraints by identifying the key resource distribution paths of each agent in a city,[218] and monitoring these paths continuously will allow more rapid responses when problems are detected.[219] Data obtained at the community and household scales (a bottom-up method) would allow the simulation of flow interruptions and would support planning to recover from these interruptions.[134] Other research should seek ways to decrease the magnitude of flows by (for example) decreasing resource consumption and waste emission during construction and by encouraging green engineering, landscape-level community design, changes in household consumption modes, and the establishment of closed-loop resource utilization plans.[13]

As a city is a complex ecosystem with natural, social, and economic components, it is necessary to provide biological, human, and technical solutions, respectively, to solve problems related to these components of an urban metabolism from the perspectives of nature, society, and the economy. The biological solutions focus on the natural environment in and around cities, with the goal of protecting or improving the ecosystem service functions and supporting capacity of the natural ecological system. The human solutions focus on social characteristics such as consumer behavior, with the goal of improving ecological consciousness to encourage behavioral changes that lead to the adoption of more sustainable practices. The technical solutions are practical techniques and measures that can be taken to reduce resource consumption and waste emission and to increase waste recycling, with the goal of promoting a transformation from the current economic system to a more sustainable industrial ecosystem. Because of the frequent and large exchanges of materials and energy between the natural and socioeconomic components of an urban system, it is necessary to seek ways to decrease the magnitude of these flows or increase their efficiency. Therefore, the three categories of solution (natural, social, and economic) are intertwined and must be implemented together. Doing so will both improve the ability of the natural components of the urban system to support the system and promote the transformation of a materials-centered city into an ecological city by including ecological goals within economic goals and changing social consciousness to emphasize the establishment of a healthy urban system.

However, few researchers have a high degree of expertise in multiple fields of study, which suggests that (for example) biologists will be needed to study the natural components of the urban system, sociologists for the social components, and economists for the economic components and that all three disciplines will need to work together to fully understand the system. In addition, different combinations of solutions will be required to solve different problems. For example, in the context of water conservation, biological solutions might include increasing green space to increase the capture of rainwater and choosing vegetation types with high water-use efficiency; this would require the expertise of plant ecologists. Human solutions might include encouraging consumers to waste less water by using water more efficiently; promoting this change of attitude would require the expertise of sociologists, psychologists, and possibly knowledge transfer experts. Economic solutions might include providing tax rebates or other financial incentives to purchase high-efficiency toilets and low-flow shower heads can reduce water consumption; this would require the expertise of economists. Technological solutions include development of more efficient toilets and shower heads, combined with finding ways to recycle water, as in the familiar example of using "grey" water to irrigate vegetation; this would require the expertise of engineers and product developers.

As these examples illustrate, it is crucial to understand the natural, social, and economic frameworks in which resources are consumed. To do so, it is necessary to involve both policymakers and local stakeholders in urban metabolism research to ensure that planners understand the implications for

DOI: 10.1021/acs.est.5b03060
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those who will be affected by their plans. It is easier to influence behavior when consumers believe that their needs have been accounted for and that they have played some part in developing the plans. This also decreases the risk of making decisions with serious unanticipated adverse consequences, and where adverse consequences will be inevitable, allows government to plan ways to mitigate the consequences (e.g., through compensation programs). Participation by experts from disciplines that are not traditionally included in decision-making related to resource management will improve the effectiveness of such discussions. For example, in future research, it would be interesting to review the literature to learn how psychologists and sociologists attempt to solve the human aspects of urban problems. We could then integrate these insights with the present technological and ecological approaches. By combining the different perspectives of biology, sociology, economics, and technology, it becomes possible to conduct richer, multidisciplinary research into urban metabolism. Solutions from only a single discipline cannot effectively solve urban problems, but combining solutions from different fields can transform decision-making from activity without consciousness of all problems and solutions to a holistic activity that accounts for all components of the urban metabolism and the needs of all stakeholders. This can also increase the likelihood of success for technical solutions, can improve social consciousness of the need for these solutions, and can increase the sustainability of the urban system by decreasing its impacts on the natural ecology that sustains it. This holistic approach will encourage the practical application of urban metabolism, particularly as success stories become available to provide evidence that this approach works. This can provide more consistent, objective, and effective guidance for political systems, industrial development, urban ecological restoration, and ecological consciousness.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We thank the journal's editors and anonymous reviewers for their efforts to improve the quality of our paper. This work was supported by the Fund for Innovative Research Group of the National Natural Science Foundation of China (Grant No. 51421065), by the Program for New Century Excellent Talents in University (Grant No. NCET-12-0059), by the National Natural Science Foundation of China (Grant No. 41171068), by the Fundamental Research Funds for the Central Universities (Grant No. 2015KJJCA09), and by the National Environmental Protection Commonweal Research Project (Grant No. 201409073).

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