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Perspective Essay

An expanded urban metabolism method: Toward a systems approach for assessing urban energy processes and causes

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HIGHLIGHTS

- ► We propose an new approach to conducting urban metabolism analysis.
- ► These will strengthen its utility for policy makers.
- ► Data remain difficult to obtain and synthesize, but new approaches are emerging.

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ABSTRACT

The integrated study of energy and urban systems has recently become a critical component of sustainability research and policy. Increasing urbanization of human societies combined with intense energy demands of modern economies have driven a recognition that sustainable practices require a systems approach to both the study and application of sustainability principles. Urban metabolism has emerged as a leading methodology for quantifying energy consumption and use patterns in urban environments. Though typically applied as a method of accounting for total energy and materials inputs and outputs into cities, its interdisciplinary history and methods allow urban metabolism to be expanded in ways that will allow more comprehensive and integrated assessment of the patterns and processes of urban energy systems. In this article, we review the concept of urban metabolism—including its two typical approaches: mass balance and "emergy" methods—and offer a means to expand urban metabolism into a platform that incorporates socioeconomic analysis, policy analysis, and additional quantitative methodologies (such as life cycle assessment). This expanded urban metabolism framework is more comprehensive analytically and builds upon the documented capacity of traditional urban metabolism to account for total energy and materials flows of cities to provide an integrated platform for analysis of both energy patterns and the causal processes that govern energy in contemporary cities.

1. Introduction

With the industrial revolution and the rise of capitalism, the modern world entered an era of resource exploitation and intensity that it had never before experienced. This industrial revolution, coupled with advances in science as well as the growth of cities and the global economy, laid the basis for the prodigal twentieth century (as McNeill, 2000 writes), that invented processes bringing enormously accelerated social and ecological change, predicated largely on the use of fossil fuels. "No other century—no millennium—in human history can compare with the twentieth for its growth in energy use. We have probably deployed more energy since 1900 than in all of human history before 1900" (McNeill, 2000). Human impacts are transforming the very fundamental processes of nature (Vitousek, Mooney, Lubchenco, & Melillo, 1997); humans are biogeophysical forces, unwittingly altering Earth systems with unknown outcomes.

This resource use intensity and massive deployment of fossil energy for human activities, accompanied by exponential population growth and the trend toward increased urbanization, has resulted in remarkable advances in economic growth, innovation, health, and global interconnectivity—particularly in industrialized economies. Still, the resource consumption of the contemporary era is widely recognized to be greater than the planet can sustain indefinitely (Folke, Jansson, Larsson, & Costanza, 1997; Wackernagel & Rees, 1996). In order to bring modern society's energy and resource

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demands into line with the finite resources of the Earth, much more needs to be done to quantify resource use and to understand its political, economic, and ecological context. One promising framework that has been advanced as an approach for quantifying energy and resource use and supply in modern societal systems is that of "urban metabolism." Urban metabolism offers a platform for greatly expanded urban systems analysis. Researchers such as Newman et al. (1996), commissioned by the Australian government to study the trends of per capita resource input and waste metabolism in Sydney, were early pioneers in linking urban metabolic measures to livability and sustainability analysis. Yet the analyses remained at a descriptive level and did not delve into the social and political drivers of urban form and levels of flows. Much of the discussion was exhortative, stating that industrial areas could look at their flows to reduce waste through industrial ecology principles, or that projects could be assessed for their sustainability using extended metabolism analysis. There was little recognition of the structural (political, economic, social) processes and complexity of change. In this paper, we assess the state and value of urban metabolism for influencing urban sustainability and conclude by suggesting that urban metabolism analysis, to be effective, also requires a political–ecological–theoretical framework and an understanding of power and money.

In the discussion that follows, we attempt to make the case for the expansion of urban metabolism to a more encompassing systems approach. While urban metabolism has been explored by a number of different disciplines such as industrial ecology, ecology, chemistry, and urban planning, studies on cities have tended to be done from each disciplinary perspective. The expansion of urban metabolism to a wider systems-oriented approach requires the collaboration of different disciplines in the analysis of a city's metabolism, in matching energy and waste flows to land uses and social-demographic variables, in evaluation of the socioeconomic and policy drivers that govern the flows and patterns, as well as life cycle assessment of the various processes and materials that make up a city's metabolism. This is a difficult undertaking, necessitating harmonization of units of measure, scale, boundary definitions, and the integration of the human element. Urban systems are sustained by resource flows and they generate waste, and these are driven by policy frameworks (explicit and implicit) and human social organization. Linking the resource base of cities to the human decision-making frameworks they exist in—often political—will provide insights about the contexts that support how urban areas work.

We begin with an overview of urban metabolism first as discussed by Marx, and much later as applied by industrial ecologists and others. We provide an overview of its applications in the current literature and its limitations. We then suggest a new approach to urban metabolism, modified and augmented by socio-demographic and spatially explicit data, greater integration of ecological impacts, considerations of systems-based policies (e.g., climate change and energy), and the situating of urban metabolisms in current political ecology theory (Castree, 2008; Francis, Lorimer, & Racko, 2011; Heynen, Kaika, & Swyngedouw, 2006; Pickett, Buckley, Kaushal, & Wiliams, 2011; Robbins, 2004; Zimmerer, 2006). This "expanded urban metabolism" approach is inherently interdisciplinary, requiring the techniques of life cycle assessment, ecological assessment, economic analysis, sociology and policy studies, and the uncovering of systemic interdependencies and interactions that undergird urban energy patterns and processes. It recognizes the multi-level governance challenges faced by cities, including the opportunities for experimentation and learning (Corfee-Morlot, Cochran, Hallegatte, & Teasdale, 2011; Evans, 2011) as well as the limitations due to the politicized nature of systems policies (i.e., climate change) and declining public sector fiscal capacity. Indeed, expanded urban metabolism is a science and data driven systems approach that should also include how policies at many levels may create specific energy/materials flows. Expanded urban metabolism can help to address one of the most important issues of the day: how to sustain the quality of life for humans without permanently exhausting planetary resources or altering the planetary dynamics that support civilization.

Following Sayer (2000), we are proposing methods that provide concrete analyses of processes that create geographically distinct outcomes. So while there are global trends showing an increasingly urban world (over half of the world's population now lives in cities (UNFPA, 2007), and cities have large impacts on the environment due to their concentration of human populations and resource use (Alberti, 2008), each urban system has its own specificities, including the mix of resource use and social organization as well as governance and position in larger systems (e.g., nation-states or climate zones). The tools of urban metabolism analysis can provide an effective lens into the biophysical processes that are harnessed by cities and conditioned by political–economic structures. This paper proposes that the political and economic forces that make cities grow or shrink are an intrinsic part of the urban metabolism, though complex and highly integrated with nested and tiered political–economic institutions and systems that range from the local to the global (Fig. 1).

We conclude by suggesting that a more interdisciplinary approach to urban metabolism will reveal heretofore hidden ways in which nature is enlisted in the service of urban and economic growth, and that geographic specificity is important. Each place will differ and so will the specific composition of resources and their use. However, localities are no longer isolated and autonomous, thus the ways in which they intersect and are imbricated in larger networks—from resource chains to capital flows—matters to a UM analysis. In this paper, we outline an integrated socio-ecological and socio-technical (Smith & Stirling, 2010) approach to measuring and managing the inputs and outputs of today's urban regions.

2. Urban metabolism: context and history

Urban metabolism (UM) researchers have compared cities to biological organisms. Organisms need energy and resource inputs, transform them to do work, and produce waste, much like cities do (Bettencourt, Lobo, Helbing, Kuchnert, & West, 2007; Pataki, 2010). Defined as "the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" (Kennedy, Cuddihy, & Engel-Yan, 2007), UM emerged in the late twentieth century as a systems-based approach to understand urban trajectories of resource use, waste production, and associated impacts on the environment. Some ecologists have been uncomfortable with the urban metabolism framework as they point out that only individual organisms have a metabolism and thus UM is improper biological analogy. Instead, some have suggested that cities are more like ecosystems—the summing up of many metabolisms (Golubiewski, 2012; Pataki, 2010). Yet urban metabolism is the term of art in the industrial ecology community, and increasingly in geography, planning, and other related disciplines, and it offers a vivid image that many understand. Thus urban metabolism provides a metaphorical framework to examine the interactions of natural-human systems (Barles, 2007b; Kennedy et al., 2007; Odum, 1996; Wolman, 1965) and provides a basis upon which to consider sustainability implications.

The intellectual development of urban metabolism can be traced back at least to Marx. Contemporary critical urban theorists such as Sywngedeou, Kaika, and Heynen, among others, have approached urban metabolism from a neo-Marxist perspective, using Marx's approach to "analyzing the dynamic internal relationships between humans and nature" (Heynen et al., 2006).

Fig. 1. An urban metabolism is situated in a nested and tiered system that is interconnected, interactive, and interdependent.

They then tie this analytic framework to political ecology, which combines the concerns of ecology and political economy with the impacts on society. Marx employed the concept of metabolism to refer to the actual metabolic interactions between nature and society that take place through human activity. Humans (especially before the petroleum age) exerted animal and physical labor to transform the Earth for their food and shelter. As they did so, they altered biophysical processes while supplying the metabolism of human activities. Marx used the term to describe the complex, dynamic, and interdependent set of needs and relations brought into being and reproduced through the concrete organization of human labor (the organizational structures of work and industrial processes, driven by capital flows). In his analysis, metabolism took on both a specific ecological meaning and a wider social meaning (Foster, 2000). Marx wrote that man lives from nature—and is a natural being himself—but in addition, he also transforms nature to produce his material needs (Marx in Foster, 2000). It is this transformation that changes the Earth's systems, of which climate change is perhaps the most dramatic example. "The concept of metabolism, with its attendant notions of material exchanges and regulatory actions, allowed [Marx] to express the human relation to nature as one that encompassed both 'nature-imposed conditions' and the capacity of human beings to affect this process" (Foster, 2000).

Hayward (1995) discusses the way in which Marx's notion of socio-ecological metabolism captures a human's existence as natural and physical, including the energetic and material exchanges between humans and their natural environment. Hayward explains that Marx saw metabolism emerging from the regulation of the metabolic relationship by natural laws governing physical processes, and from society by institutionalized norms: rules, regulations, conventions, process methods, and so forth. Marx was aware of the scientific advances of his time in physics, such as the thermodynamic law of the conservation of energy. He was also informed about developments in physiology, including cellular metabolism, and drew from these scientific insights for his own use of the concept. There is, as Foster notes, a lineage of use of the concept of metabolism from the 1840s to the present in systems theory approaches to the interaction of organisms and environments.

3. Urban metabolism in the twentieth century

In 1965, Abel Wolman wrote a pioneering article, "The Metabolism of Cities," re-launching the UM concept for the engineering community. Wolman (1965) developed a model of a hypothetical American city of one million people to actually calculate the inputs of materials and outputs of waste for such an urban system, taking UM to a quantitative proof of concept. He advanced the notion that urban footprints were no longer constrained to the geographic or political boundaries used to define them. Thus cities, through the use of resources and the generation of waste and pollution, impacted the environment on broad local and regional scales. Wolman was concerned about the pressures an expanding and more affluent population placed on natural systems and resources. He was particularly concerned about fresh water supplies for cities and showed how a theoretical city sourced its inputs from afar and left a footprint of impacts well beyond its geographic boundaries. Published in *Science*, Wolman reached a broad audience. While Marx put the emphasis on the social organization of harvesting of Earth's materials, Wolman concentrated on the physical limits of the materials themselves and their patterns of utilization.

4. Measurement methods

Forty-five years after this pioneering work by Wolman and his contemporaries, UM has evolved into two distinct approaches: mass balance accounting and Odum's *emergy* method. The first is the more widely used energy-materials flux approach (discussed in greater detail below). It is closely associated with the Industrial Ecology and Engineering fields. It incorporates tools of material flow analysis (MFA) to assess the movement of urban materials (and energy) through the urban system (Barles, 2007a, 2009). It also accounts for the energy necessary to transform raw materials and resources into material goods to meet demand needs and the associated waste flows (Huang, Lee, & Chen, 2006). The latter approach, discussed immediately below, is based on H.T. Odum's conceptualization of energy in which all measures are normalized to standard units based on solar energy.

Odum (1983) accounted for metabolic flows by measuring the available solar energy used directly or indirectly to make a product or deliver a service. He called this method *Emergy*. *Emergy* is measured in solar *emergy* joules (seJ). As a systems ecologist, he wanted to emphasize the dependence on the source of almost all energy on the planet—the sun. *Emergy* researchers were trying to show that there are qualitative differences of mass or energy flows that were ignored by previous UM researchers. As pointed out by one of the reviewers of this paper, one ton of cement and one ton of sand are different for construction activity, just like one ton of meat (beef) and one ton of vegetables provide different nutrients and calories for people's diets. *Emergy* accounting draws attention to the fundamental dependence of cities on ecological processes that themselves are possible only due to solar energy (Huang et al., 2006; Huang & Chen, 2009). *Emergy* is a measure of energy flow (i.e., analogous to thermodynamic work) by nature and humans to generate products and ecological services. For Odum it was the basic and ubiquitous common metric of environmental and economic values (Odum, 1996; Odum & Odum, 2006).

The *emergy* method emphasizes standard units for all materials, energy, nutrient, and waste flows in biophysical systems. While theoretically possible, it is practically difficult to express all urban processes in common units. *Emergy* accounting faces challenges of inadequate or disparate data as well as difficulties of integrating and/or comparing materials and energy represented in different units. The complexity of this approach and its resulting limited application is due to converting flows to the seJ metric (Huang, 1998; Huang & Chen, 2009; Huang & Hsu, 2003; Odum, 1996). Thus, the energy-material flux method, which emphasizes quantifying as much of an urban system's materials and energy flows as possible, regardless of units, is the more common urban metabolism approach.

Among urban metabolism studies that employ an energy-material flux approach, widely used quantification methods include material flow analysis (MFA), mass balance, and, increasingly, the joining of life cycle assessment (LCA) to UM. MFA is based on the principle of mass conservation where *mass in = mass out + stock changes*. MFA measures the materials flowing into a system, the stocks and flows within it, and the resulting outputs from the system to other systems in the form of pollution, waste, or exports (Sahely, Dudding, & Kennedy, 2003). Materials enter, or flow into urban systems, they are consumed to create biophysical structures—human bodies, artifacts, buildings, roads, machines, tools, agricultural crops and livestock, export products—and create waste (Haberl, Batterbury, & Moran, 2001). Within the concept of industrial or societal metabolism, sustainability problems are viewed as problems of the material and energetic relationships between society and nature (Fischer-Kowalski & Haberl, 1997).

Mass balance is based on the fundamental physical principle that matter can neither be created nor destroyed, merely transformed. Therefore the mass of inputs into a process, industry, or region, balances the mass of outputs as products, emissions, and wastes, plus any change in stocks. In the process, the matter changes in form and function: 'mass balance' is used to describe this type of analysis. Standard mass units are used to quantify energy flows such as kilograms, tons, or joules (energy being a transformation of mass as elucidated by Einstein). MFA analysis also can be used to point out the degradation of resources through use. For example, fossil fuel is burned and transformed into atmospheric gases (including pollution) and heat (a form of energy). Neither can be returned to the original state.

Life-cycle assessment (LCA) is used to provide a cradle-to-grave accounting of direct, indirect, and supply chain effects of resource transformation and use. LCA also can take into account the associated environmental impacts from extraction to final disposal (Chester, 2010; Solli, Reenaas, Stromman, & Hertwich, 2009) Thus, LCA analysis integrates the inventorying part of materials flows analysis to capture the indirect and direct supply chain impacts of cities beyond their borders to assess the movement of materials through the urban system (Barles, 2007a). Importantly, LCA offers a practical suite of methodologies and tools for quantifying the materials of an urban metabolism, including the processes generating inputs and outputs.

Whether MFA, mass balance, and LCA are used separately or in conjunction, the energy-material flux approach to UM involves quantification and tracking of mass and energy flows (e.g., raw materials, nutrients and food) in standard units (e.g., kilograms, tons, joules) as they enter, accumulate, and exit the urban system. LCA is formalized in the ISO 14044 standards, which specify requirements and provide guidelines for life cycle assessment for businesses (the principles are widely accepted by the full range of LCA practitioners). There are dedicated software packages that have been developed to conduct LCAs, including GaBI, developed by PE International, and SimaPro, developed by PRé Consultants. In addition, in the U.S. at the product level, the National Institute of Standards and Technology (NIST) Building for Environmental and Economic Sustainability (BEES) tool is one among several building design LCA accounting tools. The premier US life cycle inventory database is the federal National Renewable Energy Laboratory's LCI Database. One important caution is to realize these databases are geographically specific, that is GaBI and SimaPro evaluate European data, and the NREL LCI Database is US-specific. There are few comprehensive datasets available, thus LCA's tend to be specific to each country or region (e.g., the EU). LCAs can help businesses reduce cost by identifying wasteful practices or processes. However, LCAs have only begun to be applied to urban processes, primarily to complement and to supplement UM.

A city's physical metabolism can be described by quantifying energy flows. These are traditionally defined to include energy itself, water, materials, nutrients, and wastes. Researchers have utilized the "energy-material flux" urban metabolism framework to analyze different urban areas and system components for over forty years (Kennedy, 2010). The study of UM has enabled researchers to understand a variety of phenomena in cities, regions, and neighborhoods around the world. Table 1 shows a comparative merits and drawbacks of each UM method. Methods are often coupled, such as LCA with MFA and mass-balance, since they describe different aspects of the metabolism of cities and not one method captures the complex system issues. While the *Emergy* method is still being used, especially in China, its complexity and unproven measurement methods have meant that it is not as often practiced in the U.S. and the West.

Table 1
Comparative urban metabolism measurement methods.

Method	Merits	Drawbacks
Emergy	Draws attention to ecosystem and natural resource basis of flows; unsubstitutable role of solar energy for life processes. May be best used for non-urban analyses such as agricultural production as the calculations are straightforward.	Difficult to operationalize in seJ metric due to inadequate data, difficulty in integrating and expressing different urban processes in one similar unit. Neglects geotechtonic or climatic processes, nuclear energy, and qualitative factors (Smil, 2008; Cleveland, Kaufmann, & Stern, 2000).
Material flow analysis	Can be used to derive aggregated indicators for sustainability, especially those relating to pressures on the environment. Quantifies inputs and outputs of numerous commodities.	Requires data about materials extraction and use and the ability to interpret and utilize for policy changes. Does not by itself integrate multiple materials transformational processes.
Mass balance	Draws attention to degradation of resource through use. Can track resource flows of industries, geographical regions, materials or products and how these resource flows change over time.	Lack of consistent classification of data has frequently been a major barrier to the amalgamation of datasets. Integration into other methodologies still being developed (such as ecological footprinting).
Life cycle assessment	Provides cradle-to-grave accounting of resource use and associated environmental impacts from extraction to disposal.	Defining the boundaries must be made explicit. How far upstream to take the analysis still problematic. Continued debate on the appropriate application of different LCA methods to urban systems.
Economic Input–Output Life Cycle Assessment (EIO-LCA)	Adds economic factors to the LCA, and provides ability to link to dollar metrics.	Requires significant, nationally specific data. Utilizes economic (capital) metrics as a proxy for many materials and processes that are often difficult to integrate with material flows or mass/energy balance.

The flexible nature of the UM framework has lent itself to broader and more complex examination of processes within urban systems. For example, the development of livability measures in Sydney demonstrated a practical application of urban metabolism metrics and methods to problems posed by the Australian government (Newman, 1999; Newman et al., 1996). These reports, followed by subsequent annual accounting reports, were the first independent nation-wide assessment on the state of Australia's environment. They were created to aid Australian decision makers in government, as well as industry and community groups (Newman et al., 1996). Newman's analyses provided some of the data for Australia's first national sustainability plans. Significantly, Newman showed that larger cities were more sustainable in terms of efficient per capita use of resources; they were also more livable as demonstrated by better scores for indicators as income, education, housing, and accessibility. However, these cities were also more likely to reach unsustainable carrying capacity limits, with increasingly large inputs required from the hinterlands. According to the livability indicators, the quality of life deteriorated from the core to fringe suburbs (Newman, 1999; Newman et al., 1996). Newman also demonstrated that settlement location affected sustainability trajectories. Ex-urban and coastal settlements were the least sustainable of all developments due to resource needs and the inefficiencies of decentralized urban systems.

With the rise of cities as the prime home of humans, as well as a recognition of their substantial resource demands, UM had a resurgence in interest at the turn of the century (Kennedy, Pincetl, & Bunje, 2010). However, because UM has continued to be largely an accounting tool measuring inputs and waste flows, there has been little ability to explain differences among cities or reasons for the changes in the urban metabolism of cities (Barles, 2009; Gasson, 2002; Sahely et al., 2003). For example, as Warren-Rhodes and Koenig (2001) observed, when Hong Kong was a manufacturing center, its urban metabolism was lower than when it shifted to a consumption based economy. But they included no comparison of population numbers, income, or other socioeconomic factors in the UM to be able to determine what causal factors lead to differences between the two economic types.

UM has been applied to determine resource impacts by political ecologists and others (Baker, 2009; Gandy, 2004; Hermanowicz & Asano, 1999) and to determine certain material stocks and flows (Barrett, Vallack, Jones, & Haq, 2002; Hammer & Giljum, 2006; Kennedy et al., 2009; Niza, Rosado, & Ferrao, 2009; Schulz, 2007) use UM to examine the role that location, urban form, technology, and economics can play in GHG inventories. UM has been used by several urban designers to provide material flow analysis and a framework to envision more sustainable communities and cities (Kennedy, 2010; Oswald, Bacchini, & Michaeli, 2003; Quinn, 2007). Codoban and Kennedy (2008) have explored the relationship between design and metabolism at the neighborhood scale. Their study of the urban metabolism of four representative Toronto neighborhoods showed that different neighborhood forms, including the construction of energy-efficient buildings and development of public transit, had different implications for neighborhood metabolisms. Further research must be conducted to evaluate whether unintended consequences impact nearby areas. Climate change, which will differentially affect regions of the globe, adds yet another dimension of resource use that UM studies can usefully inform. For example, Mediterranean climate cities are likely to experience greater heat incidents and water scarcities. Understanding patterns of water use and energy requirements (e.g., for cooling) through UM, coupled with water and energy policy, could greatly inform metropolitan adaptation and mitigation strategies.

In addition to environmental, land use, and urban quality parameters, urban metabolism analyses have the capacity to reveal which inputs present an unsustainable balance between demand and supply as well as pollution flows that result at an aggregate scale. Additionally, these energy and material flows can be related to provisioning and sustaining functions, such as resource sources and sinks, that ecosystem services provide to communities. The ecosystem services component of UM remains less well developed, however. To date, UM has generally conducted a raw accounting of pollution generated by the city, with little further study of the environmental impacts (e.g., water pollution, atmospheric nitrogen deposition) on the surrounding hinterlands (or beyond). The expanded urban metabolism framework described in this paper seeks to facilitate the explicit incorporation of these assessments into urban metabolism studies.

5. Urban metabolism, the second generation: upgrading the analytical framework by adding spatiality, ecology, and people

In this section we discuss the additional elements UM needs to provide more complete analysis, as well as the theoretical framework to connect its powerful information gathering capacity to the local political, economic, and social context driving these urban systems. It is difficult to set clear boundaries around the intertwined human–natural interactions that need additional studying. How urban ecosystems are created over time, for example, reflects political, economic, natural, and social organization, as well as how near-by and far-off ecosystems are enlisted to fuel urban systems. One could, therefore argue that a city's UM has both physical spatiality, and longitudinal space: history. We lay out each topic individually and attempt to show how an expanded urban metabolism framework can bring the necessary analytic synthesis.

6. Urban ecosystems and ecosystem impacts

Urban activities create novel urban ecosystems. These ecosystems have extensive social and built complexes that have a dramatic effects on ecosystem form and function (Francis et al., 2011; Pickett & Grove, 2009). Anthropogenic urban nature provides ecosystem services, e.g., shading, habitat for fauna, food, purification for water, etc. This kind of human-mediated mixing of species and built complexes is most intense and frequent in urban regions. "Networked global cities exchange organisms, materials and ideas in unique biogeographical ways with significant ecological consequences" (Francis et al., 2011) that are not insignificant in an urban area's metabolism, but are not investigated or accounted for either. Such ecosystem services as biodiversity (whether human induced or native), cultural and/or spiritual wellbeing from nature in the city, urban heat island and stormwater mitigation from tree canopy cover, and carbon sequestration or water purification by soils, are only beginning to be quantified, and have not yet been incorporated into UM. Novel urban ecologies are widely replicated across almost all biogeographical, climatic, cultural, and economic regions in the same way, but interact with local ecologies and bioregions differently (Francis et al., 2011). This raises research questions about those dynamics, and also the impacts of such bio-cultural ecosystems on regions. UM is a framework for integrating these questions into the understanding of specific urban systems.

Beyond the created urban ecosystem, the metabolism rates of cities across the world involve increasingly large material and energy flows of food-waste streams, imports, solid-waste accumulation, paper, plastics and building materials from areas outside the boundaries of the urban system (Kennedy et al., 2007). The metabolic cycles of cities are both open and unsustainable due to the rates of materials consumption, but also because rates of waste production do not match assimilation rates (Grimm et al., 2008; Martinez Alier, 2002). Take, for example, the water quality impacts of decades of air pollution in the Los Angeles basin. When one of the major watersheds burned for the first time in sixty years, decades of air pollutants sequestered in the soils were released. The heavy metal load—lead, cadmium and mercury—in the runoff concentrated decades of air pollution deposits, including pre-Clean Air Act regulations. The implications for drinking water are significant, and the disposal costs and complexities of contaminated run-off debris are daunting.

The inflows sustaining urban systems have nearby and far-flung impacts as well. In the Los Angeles case, again, water is imported from the Owens Valley, 250 miles away, the Sacramento River Delta, 400 miles away, and the Colorado River, 300 miles away. Each water conveyance system has deeply altered the areas of origin, changing ecological and hydrological processes. As the Los Angeles Region moves toward greater water self-reliance and the use and management of autochthonous ground water resources, there will be other changes in this already highly contaminated resource (in certain areas) due to the legacy of war-related industries (military manufacturing used highly toxic petrochemicals—such as methyl ethyl ketone—which were largely disposed of locally on the soil of the small manufacturers, this has led to serious ground water pollution). Legal structures such as ground water management rules need to be created, political/economic questions of water ownership will need to be addressed, and scientific issues such as reinfiltration rates and sustainable rates of extraction, will also need to be integrated. Such ecological impacts (and their political/economic regulatory aspects) are amplified through the consumption and supply chains to a global scale that includes mining, drilling, harvesting, and manufacturing the items that are imported into the city-region.

Resource inputs—and the impacts of extraction—from far-flung places can be parameterized in a UM analysis with life cycle assessment. LCA is a tool for assessing the cradle-to-grave effects of products, processes, services, activities, or the complex systems in which they reside (in this case a city's urban metabolism). LCA can be integrated with UM through either the process- or economic input–output (EIO)-based approaches.

Process-based LCA is the dominant and preferable approach for assessing cradle-to-grave effects with high process, temporal, and geographic representative data (Rowley, Lundie, & Peters, 2009). Process-based LCA requires a great deal of primary data collection tracking each process step-by-step. There are software and databases that have been developed to facilitate this task for different processes and technologies; process-based LCAs tend to be more labor intensive, and likely yield more realistic accounting of the life cycle of a product or flow because they address the specific commodities or process directly, whereas an EIO-LCA utilizes aggregate economic data (Rowley et al., 2009).

There is a potential to link urban economic flows with EIO-based LCA to complement process-based LCA. In the U.S., EIO-based LCA can be applied broadly by joining the approach with North American Industrial Classification System (NAICS) economic data, the standard used by Federal statistical agencies in classifying business establishments for the purpose of collecting, analyzing, and publishing statistical data related to the U.S. business economy. The Carnegie-Mellon Green Design Institute has developed an Economic Input–Output Life Cycle Assessment (EIO-LCA) method that estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in the economy for each of the NAICS categories of economic activities. This approach applies only to the U.S. economy. The EIO-LCA method was theorized and developed by economist Wassily Leontief in the 1970s based on his earlier input–output work from the 1930s for which he received the Nobel Prize in Economics. Researchers at the Green Design Institute of Carnegie Mellon University operationalized Leontief's method in the mid-1990s, once sufficient computing power was widely available to perform the large-scale matrix manipulations. "Results from using the EIO-LCA on-line tool provide guidance on the relative impacts of different types of products, materials, services, or industries with respect to resource use and emissions throughout the supply chain. Thus, the effect of producing an automobile would include not only the impacts at the final assembly facility, but also the impact from mining metal ores, making electronic parts, forming windows, etc. that are needed for parts to build the car," based on dollar values. The Green Design Institute website (http://www.eiolca.net/) takes the EIO-LCA method and transforms it into a user-friendly on-line tool to quickly and easily evaluate a commodity or service, as well as its supply chain. It must be noted, however, that this approach cannot capture nuance. For example, plastic used in an automobile will be considered the same as plastic used for a water bottle, though there are real life-cycle differences in those materials.

Whether process or EIO-LCA is chosen (or a blend; see Rowley et al., 2009), integration of LCA with urban metabolism provides a heretofore undocumented linkage between the activities of urban

Table 2
Theories of political ecology and political economy as framework for understanding drivers of UM (after Gibbs, 2002).

Political ecology	Political economy
Uses political economic theoretical categories but Focuses on: The transformation of energy and materials and the environmental and social impacts of that transformation. Rules that guide resource exploitation (lack of rules is a type of mode of regulation).	An approach that focuses on institutions, rules, money and power that shape economic forces and flows of wealth. For example the organization of the world market for rare minerals: China produces the vast majority of them, and regulates their sale, despite GATT agreements for 'fair trade.'
From *Urban Regime Theory* Will draw attention to the ways governing coalitions will work together for land development and access to resources such as water, power, and fiscal supports in the form of transportation funding, water infrastructure assistance (sewage treatment plants), and their impacts on near and far-flung resources like watersheds or ecosystems.	*Urban Regime Theory* Insight into characteristics of local governing coalitions: Interactions among firms, local politicians, environmental enforcement agencies (local and national), environmental pressure groups and the public. Describes flows of money and power, especially as they relate to urban form and real estate development.
From *Regulation Theory* Can include: weak to strong ecological modernization (materials substitution, factor 5 energy efficiency improvements), including open or closed decision making with participation and involvement spanning democratic to autocratic.	*Regulation Theory* Integrates the structural dynamics of capitalism with the institutional forms of society. Focuses at the macro level to understand the accumulation process and ensemble of institutional forms and practices that make the economy function. Examines: *Mode of production* – public or private ownership of land/firms or other economically productive assets. *Regime of accumulation* – currently founded on growth and mass production for mass consumption, requiring massive supplies of raw materials and energy. *Mode of regulation* – social institutions and governmental regulations (e.g. mining policy on public lands). The local and national state governments actors that mediate among the economic forces.
Political ecology includes detailed ecological information about sources of materials and flows and impacts (can be done with LCA) and human impacts, such as labor conditions and wages, health impacts.	n/a

systems and their cradle-to-grave materials and energy inputs. Building LCA accounting into urban metabolism will reveal the relationships between specific urban areas and places that supply them. It provides the basis for further investigating the ecological, social, and political impacts of a set of activities in one place on another.

7. Disaggregating metabolism

Most urban metabolism studies use highly aggregated data—often at the city or regional level—that provide a snapshot of resource or energy use, but no correlation to locations, activities, or people. Often this is due to a lack of ground-up (disaggregated) data. For various reasons, utilities and other energy managers generally do not provide data at the census block or track level, much less to the resolution of individual bills. Thus there is a fundamental blindness about how much energy is used in specific localities for specific purposes. Without being able to attribute flows to people, places, and uses, it is nearly impossible to determine the metabolism of a specific city. Thus another step that is needed for UM to become more useful, and meaningful, is to superimpose the flows with specific locations—places of production and consumption—and then overlay census data as well as the activities and land uses that are metabolizing the inputs and generating the outputs within cities. In other words, understanding *who*-is-using-*what*-flows-*where*-to-do-*what* (and the concomitant waste produced) needs to be added to UM analyses.

8. Theory for complex bio-social urban systems

The biggest challenge facing urban metabolism is the integration of political, demographic, economic, and geographic factors that govern or influence a city or region's urban metabolism. Any city's metabolism is the result of human agency—the ability to exploit ecosystems and their services. This involves scales of governance, institutional rules and conventions, multiple economic forces, and capital flows that shape specific places. Here is where the UM framework is weakest and needs the most theoretical development. Political ecology and urban political economy offer a theoretical framework for beginning this integrative process, framed by a critical realist philosophical perspective (Table 2). Critical realism is an approach that draws attention to the need for multidimensional accounts based on the synthesis of major significant elements. It is about how actors, actions, and contexts interact over space and time and about the necessary and sufficient conditions that allow certain urban political constructs to be successful (Sayer, 2000). Critical realism is a theoretical position that posits that specific places differ in important ways that need to be understood in and of themselves. It points to the importance of contingency and that human agents operate within social structures that they themselves create but then constrain future action. It seeks to understand causal relationships and therefore is especially suited to unravel complex urban systems.

Political ecology emerges from anthropology and is concerned with how humans organize themselves to interact with nature. In small-scale societies this tends to lead to analyses of the organization of the management of subsistence resources, who has rights and responsibilities, how the society is organized internally, and the distribution of resources. For contemporary societies the approach draws on political economy, but adds in the material basis of the economy—the environment—and the specific conditions of places at certain times. Political ecology accounts for and conducts research to understand and evaluate the influence of variables acting at a number of scales, nested within another, with local decisions influenced by regional policies, in turn within global politics and economics, and then also from the local scale up (Robbins, 2004) (see Fig. 1). Relying on systematic empirical data gathering, description and exploration, political ecology explains linkages in the condition and change of social/environmental systems by examining the organization of these systems and how they work to metabolize the biophysical environment for human use. The appropriation of nature that produces social and environmental conditions arises out of historical, political, and economic processes, and of course, the constraints of the natural world itself. The rise of industrialization was possible with the harnessing of fossil energy contingent on the coupled growth of scientific knowledge and the emergence of capitalism as an economic organization. European expansion across the globe and huge international migrations and explorations identified new resources and new markets. The exploitation of fossil energy and natural resources, over time, has enabled humans to live on the planet at a level of material intensity never before experienced. This dramatic 250-year transformation is largely taken for granted, but must now be examined for its future sustainability in the context of localities (cities) and their nested hierarchies (regions, nations, the globe) of material and energy use, a task that an expanded urban metabolism framework is poised to undertake.

9. Establishing an expanded urban metabolism framework

Urban metabolism is uniquely poised to offer a unifying framework for quantifying, analyzing, and influencing urban form, function, process, and sustainability. Though the traditional accounting methods described above are insufficient for understanding process and meaning in urban energy patterns, the UM framework lends itself to greater interdisciplinary contributions for the integration of methods and theories that build an understanding of complex urban systems. By integrating the theoretical and methodological strategies described above—including, but not limited to, LCA, political ecology, and ecosystem services—urban metabolism can begin to organize the patterns and processes of complex, non-discrete urban systems into comprehensible assessments of energy and material use in cities. This in turn becomes the starting point for a true study and practice of urban sustainability.

We suggest the need to expand the urban metabolism method into a more comprehensive framework that both analyzes the biophysical material and energy parameters of cities as well as the human, social, policy, economic, and related systems that both structure and govern specific urban metabolic process (Fig. 2).

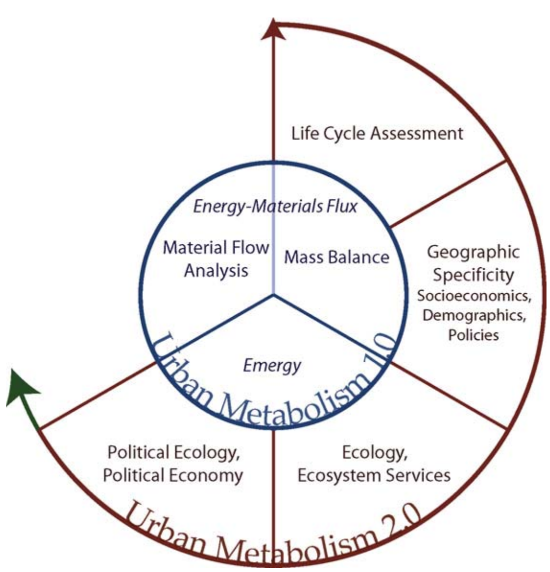

Fig. 2. Describing the additional elements of an expanded urban metabolism framework. Based on the spiral model of software development, urban metabolism can serve as a platform for incorporating relevant and appropriate methodologies for quantifying elements of an urban system that characterize that systems' metabolism. The additional elements in the expanded platform allow for a more thorough evaluation of the causal, scalar/hierarchical, and process-based characteristics of urban systems.

A sustainable metabolism would not exceed the hinterland's ability to produce the energy and materials (electricity, building materials, food, etc.) or absorb the wastes (waste water, solid waste, toxic chemicals, urban heat island effect, etc.) that are necessary to sustain an urban area. But to effectively achieve more sustainable urban systems, it is necessary to expand the variables that urban metabolism analyzes to include demography, economy, health, mobility/accessibility, equity, community quality, policies and regulations, employment, and education. Such analysis would be useful to decision makers who are responsible for effecting urban sustainability, including designers, engineers, planners and municipal officials. It would permit targeted interventions by these change agents. For example, urban ecosystem services could be used to augment local water supplies through reinfiltration zones, or the implementation of energy conservation measures could be focused on excessively high users or low income neighborhoods that could benefit from energy conservation programs.

While these expanded metrics may simply add more indicators (not an easy task in itself), to *understand* what these imply for a city's metabolism and to effectuate the kinds of changes that would be required to reduce the urban footprint and ensure a good quality of life, implies shifts in policies and politics. This, of course, could be highly contentious and will be informed by normative perspectives. Technological optimists (ecological modernists) will advocate for technological innovation and a materials substitution strategy. Free market advocates will advocate for market forces to allocate resources according to supply and demand, assuming that efficiency will be achieved with little regard to equity. Political ecologists and political economists will look at how rules are structured and how power and money influence processes to discern where points of intervention to create systemic change can be found. Indeed, there are a number of schools of thought about how change takes place, from a Habermasian processual deliberative approach (communicative rationality) to its radical critique (Mouffe, 2000). What an expanded UM method allows is the application of different normative perspectives to a much more thoroughly described complex urban system. Today policies and politics often take place "content free." While more data does not necessarily translate into better decision-making, it does offer the potential for reducing unintended consequences and improving the basis for policy making.

Critical to our suggested expansion is a recognition of the scalar relationships of urban metabolism. As noted above, the metabolism of a city is largely site-specific and dependent upon the historical, geographic, demographic, economic, and climatic context of a given city. These specificities are further embedded in a hierarchy of systems from the region up to the whole planet. By incorporating both geographically specific metrics as well as methods for quantifying the super-regional impacts (e.g., through LCA or ecosystem services), an expanded UM can serve as a tool for addressing global sustainability. Climate change is a prime example of how local decisions (e.g., land use, transportation, energy intensity) can have global consequences (Corfee-Morlot et al., 2011). By embedding local sustainability metrics into their appropriate global framework, it is possible to more clearly measure and impact things like local greenhouse gas emissions and their summative impact on the global climate.

We hope that this suggestion of an expanded urban metabolism framework will generate substantial debate and theoretical development. In general, we believe this expanded methodology can begin with an urban metabolism analysis of a community's energy system, and then the identification of policy drivers that shape consumption and waste patterns. This integrated process, which includes multiple disciplinary approaches, analytical methods, and scales of analysis, is necessary to ensure more complete assessments—and understanding—of urban systems.

10. Conclusion

Urban centers grow in complex ways due to dynamic and interlinked geographical and institutional forces converging upon them (Grimm et al., 2008). Cities are now nearly entirely dependent on access to resources and ecosystem functions outside of their administrative boundaries. They are also, as a result, the primary driver of global environmental change. This includes greenhouse gas emissions that are causing climate change, the decline of biodiversity, and impacts of resource extraction in far flung places such as mining in Africa for minerals, oil and gas extraction and much more. Urban metabolism analysis can serve to bring to light these resource impacts, and trace the consumption at the city level, back to the place where the resource was originally obtained. Process impacts, that may occur in yet another place, can also be quantified if UM is linked with LCA.

At present, UM studies focus on fairly aggregated physical flows of inputs and wastes at the city level without addressing the LCA, but also not including an analysis of the social and institutional drivers that organize, manage and regulate these flows and outcomes. Data gaps, omitted/hidden upstream flows, uncertainty regarding the appropriate scale of analysis, and segregated information sources continue to constrain fine accounting of the urban metabolism of cities. No studies have yet been able to describe flows into a city and the waste sinks in a way that correlates those flows with the specific residents and their activities, let alone a cradle to grave accounting of the inputs. For example, few cities have data about trash generation by fine-grained geographic scale or by land use type.

Thus to determine what sectors are contributing different types of waste, and the potential of waste reduction is quite difficult. Moreover, without this type of specific information, it is also impossible to know what places and sectors are reducing their flows and could be used as a model for other parts of the city/region. This kind of data gap exists for water use, electricity and gas use, materials intensivity of buildings and other infrastructure as well. The same could be said about ecosystem services. While there is a sense that a region such as Greater Los Angeles (for example) could be far more water self-sufficient due to vast groundwater resources, accurate mapping of optimal groundwater infiltration areas matched to land use is only emerging, and the sustaining capacity of groundwater resources themselves has not been well assessed. Furthermore, change toward greater local water resources use will also necessitate changes in land use regulations, property rights, and groundwater management. Landscape designers and urban planners have an important role to play in these changes. An expanded framework that also incorporates LCA methods will enhance the ability of urban metabolism to characterize urban systems and inform their governance.

Finally, without a corresponding analysis of the social systemic drivers of the flows, little headway will be made toward greater urban sustainability, much less global climate change mitigation. Patterns of resource use today, and the structures that support them need to be unpacked for change to occur. These involve power and money, politics and institutional conventions, as well as increased affluence and population size. Merely describing the flows better cannot make a difference without linking those flows to the complex set of institutions, organizations, and societal relations that shape and guide economic activities, politics, and cultural norms. This expanded urban metabolism framework is an attempt to integrate these diverse research needs and advance the field to incorporate recognized needs and demands for societal relevance.

A final note. Our suggested approach for a more integrated and comprehensive urban metabolism method is complex and requires not only greater data assimilation and analysis, but also political, institutional and economic context setting. As budgets for localities and states decline, this expanded method could be both daunting and impossible to implement. However, there are researchers developing models that accomplish the data integration and whose efforts provide synthetic computational models for localities, planners and policy makers. Universities are good collaborators for these efforts, and provide knowledge and modeling capacity for localities. The European BRIDGE project (http://www.bridge-fp7.eu/) is one example, the UCLA Institute of the Environment and Sustainability collaboration with the Los Angeles Regional Collaborative for Climate Actions and Sustainability (LARC: http://www.environment.ucla.edu/larc/about/), provides another. New partnerships between the research community and the implementation community will surely be part of making this expanded urban metabolism framework succeed as the ways government is able to conduct its business change in response to budgetary constraints, and researchers are increasingly pushed to make their work relevant by funding sources and by the public.

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