Chapter 3: Understanding, Implementing, and Tracking Urban Metabolism Is Key to Urban Futures

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3.1 Introduction

Eighty percent of the world's population is expected to live in urban areas by 2050 and will demand a high density of infrastructure in order to meet human development aspirations. Occupying nearly 3 percent of the total global land surface, cities are also the centers for nearly 80 percent of the global domestic product, or GDP (UNEP 2012) (see Chapter 6). Meanwhile, cities are also global catalysts for 50 percent of solid wastes, 75 percent of natural resource consumption, and between 60 and 80 percent of greenhouse gas, or GHG, emissions (UNEP 2012). These functions present a plethora of infrastructure-related opportunities for efficiency integration, as infrastructure provides access to essential goods and services that are linked to human development and health. Yet, infrastructure, while essential, is also the source of many environmental problems caused through direct and indirect emissions. It is estimated that present-day infrastructure is responsible for 122 gigatonnes (Gt) CO_2, with developed countries owning a per capita infrastructure footprint five times larger than their developing country counterparts (Müller et al. 2013). Moreover, Müeller and colleagues estimate that if all infrastructure needs are met using typical Western technologies, the environmental impact would amount to 350 Gt CO_2, or seven times the current global GHG emissions of 50 Gt CO_2.

Urbanization will continue to be the stimulus for new infrastructure; although global average annual urbanization rates in 2050 are projected to occur at half of today's rate (from 2 percent today to 1 percent in 2050), urbanization in *less-developed regions* will occur at an annual rate of change of approximately 1.5 percent, while it will occur at a rate of *more-developed regions* at a rate of 0.25 percent, leading to a continued high demand for infrastructure in developing regions. What is not as clear, and what is often overlooked, is where the impacts of urbanization will be most observed. And while large urban agglomerations, for a host of reasons, are often centers of research about urbanization phenomena, we should also consider the suite of smaller urban areas that are in the midst of substantial transformations of their own. Of the global urban population, most – 51 percent – of urban dwellers reside in communities of less than 500,000 inhabitants (see Figure 3.1). Moreover, by 2030, almost 40 percent of the global urban population will be located in communities of less than 300,000 inhabitants, many of which will demand infrastructure and whose activities may incur substantial environmental impacts, if not adequately designed. Thus, in the face of urbanization and infrastructure development, it is imperative that we understand the effects that urbanization and associated infrastructure development can have on the material and energy demands associated with cities and communities everywhere. Such an understanding may trigger efficiency gains related to the services that infrastructure provides. One way to understand and measure changes in efficiency gains is through the concept of "urban metabolism."

In this chapter, we discuss the concept of urban metabolism and how it has been and can be used to understand the resource flows and environmental impacts associated with cities. Even though in this chapter we loosely adopt the commonly used nomenclature of urban metabolism to represent all communities, it is important to note that urban and rural communities alike, have

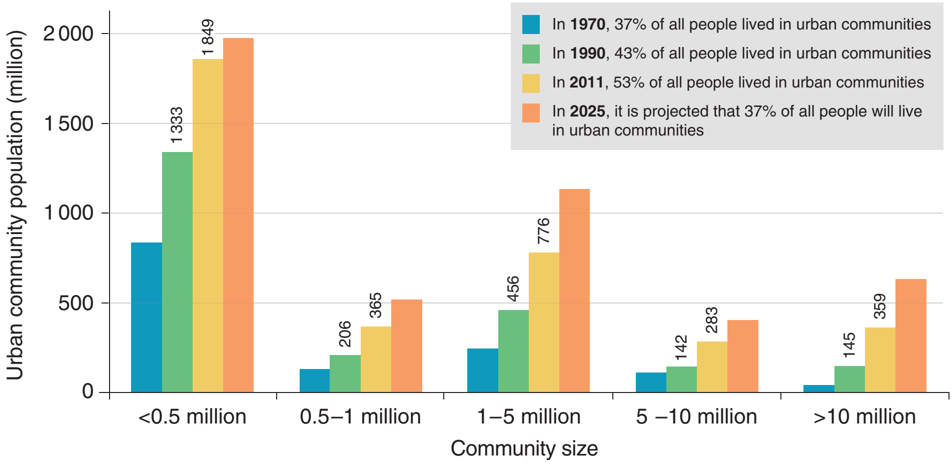

Figure 3.1 Urban population by community size for cities of five unique sizes. Note that smaller cities/communities of 500,000 inhabitants or less will continue to house the majority (approximately 50 percent) of the world's urban population. Source: Jerker Lokrantz/Azote, modified after Chávez (2017).

associated metabolic flows; some scholars have begun articulating the concept of community metabolisms (Chávez 2017) and rural metabolisms (Haas and Krausmann 2015). Thus, the urban metabolism framework is a form of modeling and assessing community processes, whether individually or in aggregation, to gain greater understanding of material and energy flows associated with communities. Since the seminal work of Abel Wolman (1965), many lines of research inquiry about urban metabolism have been undertaken, and some cities have adopted the concept to study their own resource flows associated with material and energy in their aims to integrate efficient, sustainable, and resilient material and energy flows. As we will show later in this chapter, urban metabolism analysis has also undergone its own transitions in terms of its definition of the urban boundary – early studies took a strictly "boundary-limited perspective," whereas the latest studies define the boundary to include a community's hinterlands, encompassing the supply chains associated with a community. The chosen definition of boundary has substantial impacts on the scope of resilience that must be incorporated to hedge against resource shocks.

We will begin by presenting an overview of research focusing on urban metabolism. Then, recalling that urban metabolism is ultimately concerned with measuring material and energy stocks and flows, we will describe some of the conceptual and methodological advances that have emerged from the urban metabolism foundation. Next, we will present how communities have and might consider incorporating the metabolism framework for sustainable and resilient system development. Last, we will comment on the challenges that lie ahead.

3.2 Urban Metabolism: Material and Energy Flows

3.2.1 A Historical Perspective and Updated Understanding

Urban metabolism is a socionatural metaphor originally developed in the 1960s by Abel Wolman as a form to study city-scale material and energy flows. Though various concepts central to urban metabolism have been present since the nineteenth century, Wolman's work (1965), in which he attempted to quantify the material and energy flows for a hypothetical US city of one million people, organizes them under one idea: a city's metabolism, which he defined as "all the materials and commodities needed to sustain the city's inhabitants at home, at work and at play" (Wolman 1965). Since then, there has been an intensification of urban metabolic research yielding several new questions and novel understanding of city metabolic flows. Figure 3.2 represents a modern urban metabolism concept.

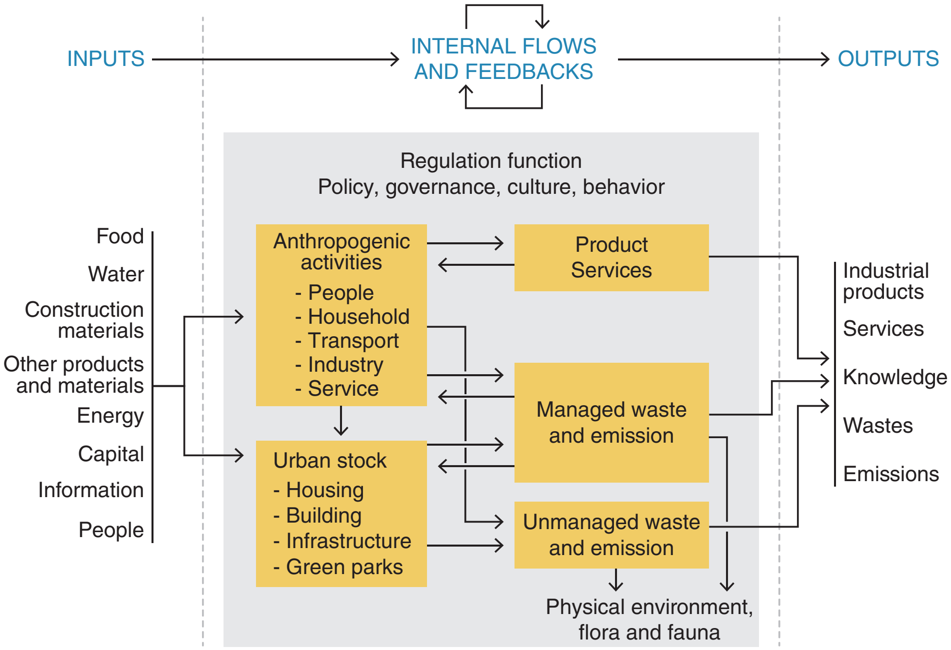

Figure 3.2 Conceptual diagram of urban metabolism. A proportion of the resources that flow into cities become urban stock, while others enable and drive various anthropogenic functions and eventually produce intended or unintended outputs that stay within the system boundary or are exported beyond the boundary, with various impacts on the physical environment, flora and fauna, and associated ecological processes. Urban metabolism is shaped and regulated by factors such as urban policy, urban governance, culture, and individual behaviors. Source: Jerker Lokrantz/Azote, modified after Bai (2016).

Building on Wolman's foundation, the 1970s produced the first set of actual urban metabolism case studies. Under the UNESCO Man and Biosphere Program, researchers applied urban metabolism approaches in Brussels (Duvigneaud and Denaeyer-De Smet 1977), Hong Kong (Newcombe et al. 1978) and Tokyo (Hanya and Ambe 1976). After a hiatus in the 1980s, interest in urban metabolism reemerged in the 1990s with research by Stephen Boyden and Peter Newman for Australian cities (Boyden et al. 1981; Newman 1999); in Austria and Switzerland with work by Peter Baccini and Paul Brunner (Baccini and Brunner 1991); and with work by French ecologist Herbert Girardet (Girardet 1992). As more studies emerged, Kennedy et al. (2007) conducted a comparison of the metabolisms of eight metropolitan regions, identifying metabolic processes that potentially undermine the sustainability of cities, including changing groundwater levels, build-up of toxic materials, exhaustion of local materials, heat islands, and accumulation of nutrients. Barles completed a metabolic assessment for Paris (Barles 2009) and later explored the relation of urban metabolism to sustainable urban development (Barles

2010). Standardized and quantitative urban metabolism models also emerged from this work (Niza et al. 2009). In this body of work, we observe a progression of urban metabolism research based on increasing understanding of coverage, scale, links to socioeconomic contexts, and spatial and temporal variations of metabolic flows (Bai 2016).

From the first urban metabolism studies to today's cross-cutting research, urban metabolism has witnessed much transformation. Earlier, urban metabolism studies developed and applied methods that measured "economy-wide" material flows that were primarily defined by a community's physical boundary. These studies, including Wolman's 1965 work, considered water and fuel inputs coupled with outputs such as sewage and air pollutants. With time, the scope of economy-wide activities expanded to include additional inputs such as land, food, and building materials, along with a set of emerging socioeconomic indices by which to benchmark cities' metabolic flows (see Newman 1999, for example). More recently, a growing amount of research has examined the metabolisms associated with biogeochemical fluxes due to their substantially higher resource intensities, even though such fluxes represent only a small portion of a city's material flows. Flows of nitrogen and phosphorus, for instance, have been shown to merit additional research because their impacts transcend a city's boundaries (Baker et al. 2001; Metson et al. 2015; Lin et al. 2016; Cui et al. 2015). Finally, as the understanding of the true inputs and outputs associated with a typical community has evolved, so has the collective understanding of what "economy-wide" means. Early urban metabolism studies frequently adopted a purely boundary-limited definition (that is, a purely jurisdictional definition) of a community and accounted for direct flows only. However, more recent applications of the urban metabolism approach conform with global standards, which call for the inclusion of indirect or embodied flows. For example, Chester et al. (2012) were one of the first research teams to couple the concept of urban metabolism with life cycle analysis, offering twofold benefits: providing a robust perspective on a community's metabolism while assisting in avoiding the shifting of burdens or responsibilities to other communities.

The usefulness of urban metabolism studies increased with the recognition that they provided the necessary activity data required to conduct greenhouse gas inventories for cities (Kennedy et al. 2009, 2010). Some studies have used the urban metabolism framework to develop measures of resource efficiency in cities (Baccini and Oswald 2008; Zhang and Yang 2007; Browne et al. 2009). Bai (2007) emphasizes the importance of policy and regulations in regulating metabolic flows. Other applications of urban metabolism include the development of sustainability indicators, mathematical modeling for policy analysis, and use as a basis for design (Newman 1999; Kennedy et al. 2011; Chávez and Ramaswami 2013).

The literature on urban metabolism has increased substantially in the past decade. A search using Scopus, a database of peer-reviewed literature, showed that the number of papers on urban metabolism increased from about two per year in 2000 to about 50 per year in 2014 (Kennedy 2015). This is encouraging for efforts to make collection of metabolism data a mainstream activity for cities (Kennedy and Hoornweg 2012). Included among the later literature are spatially disaggregated studies within cities, studies about life cycle extensions of urban metabolism, and various studies considering particular components of the urban metabolism; for instance, moving away from the early work's limited focus on specific flows, bulk, and boundary-limited scope, more recent work has measured above- and below-ground infrastructure-related material flows (see Tanikawa and Hashimoto 2009, for example) as well as delving into cross-cutting, multidisciplinary, and life-cycle-based research (see Kennedy 2015 and Chávez and Ramaswami 2013). The study of urban metabolism now includes increasingly broader interdisciplinary contexts, engaging urban planners, engineers, political scientists, ecologists, and industrial ecologists, among others (Castán Broto et al. 2012; Newell and Cousins 2014).

Textbooks by Ferrão and Fernández (2013) and Baccini and Brunner (2012) provide extensive details on the urban metabolism. Literature reviews on urban metabolism include those by Kennedy et al. (2011), Holmes and Pincetl (2012), Zhang (2013), Bai (2016), and Beloin-Saint-Pierre et al. (2016). Weisz and Steinberger (2010) discuss the challenges of reducing material and energy flows in cities. Kennedy (2012) provides a simple mathematical model broadly linking the quantity and performance of infrastructure stocks to urban metabolism.

On a more conceptual level, Bai (2016) argues that the approach and empirical findings of urban metabolism studies have the potential, although not fully realized, to contribute significantly to the understanding of cities as human dominant, complex socioecological systems. In an attempt to build conceptual bridges between urban metabolism studies, which views the city as an organism, and urban ecosystem studies, which view cities as an ecosystem, Bai (2016) identified eight urban ecosystem characteristics that urban metabolism research reveals: energy and material budget and pathways; flow intensity; energy and material efficiency; rate of resource depletion, accumulation, and transformation; self-sufficiency or external dependency; intrasystem heterogeneity; intersystem and temporal variation; and regulating mechanisms and governing capacity.

3.2.2 Urban Boundaries

One of the cross-cutting questions in all of the urban studies is where to draw the boundary around a city, recognizing that the boundary itself has most likely changed over time. Drawing the boundary too narrowly carries the risk of insufficient recognition of the "urban system." Drawing it too broadly can dilute the unique elements of the urban core. Because researchers approach urban issues from so many different disciplinary directions, many overlapping approaches and tools arise that can lead to confusion and need to be sorted out.

Recent iterations of urban metabolism have redefined the definition of "economy" to extend the urban boundary beyond the traditional boundary-limited approach, which has allowed for the inclusion of linkages between cities and their hinterlands – where the hinterland itself can vary between regional to global (for example, Pichler et al. 2017). While still considered urban metabolism, said studies yield a footprint such as ecological, water, or carbon footprints. Moreover, these footprints can include industrial and/or supply-chain impacts further up the chain of production, but can also be focused on consumption-based footprints involving households and governments in cities, which are the "final consumers" of what has been produced whether locally or imported from outside (Chávez and Ramaswami 2013; Ramaswami et al. 2012). For example, in a study looking at consumption-based (that is, household) GHG emissions, Lin et al. (2013) found that up to 70 percent of GHGs can be attributed to regional and national activities beyond the urban boundaries that support household consumption (see Pichler et al. 2017).

Expanding the boundary of a city, and thus the scope of urban metabolism research, from purely boundary-limited to including the hinterlands is captured by transboundary footprinting. The method of transboundary footprinting recognizes that there are often key infrastructural facilities, such as power plants, landfills, and airports, that may not be within the city limits, but nevertheless are part of what keeps the city operating and producing, and which could be counted as part of the city's overall environmental impact. Both transboundary footprinting and urban metabolism use material flow accounting and analysis and can trace an array of substances through the system under study (Zhang 2013). Some have suggested the addition of life cycle accounting to further analyze external supply relationships to match specific urban areas and the places on which they depend (Pincetl et al. 2012).

One particular greenhouse gas, carbon dioxide (symbolized as CO_2), is the focus of a great deal, but not all, of urban metabolism and transboundary footprinting studies. Indeed, there is a peer-reviewed and robust protocol for city-scale greenhouse gas inventorying in cities called the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories, or GPC, that is increasingly being adopted. It is a joint project by ICLEI, the World Resources Institute, and the C40 Cities Climate Leadership Group, with additional collaboration by the World Bank, UNEP, and UN-Habitat. As a global reporting standard, the GPC enables cities and communities to consistently measure and report greenhouse gas emissions and to develop climate action plans and low-emission urban development strategies while using coupled production and consumption-based approaches (ICLEI 2016).

Finally, urban metabolism helps a city understand the physical basis of what occurs within its boundaries by measuring its inputs and outputs. There are many more social, political, and economic elements to examine beyond cities and their hinterlands, but urban metabolism is an essential aspect for understanding important biophysical interactions.

3.3 Global and National Trends in Material and Energy Flows

Our knowledge of historical resource use trends gives us an imperfect guide to the future. This knowledge is imperfect because a number of countries are entering an unprecedented phase of socioeconomic maturity, while others are poised to undertake rapid urban development. The latter have the opportunity to avoid the resource-intensive path taken by the developed world in the twentieth century, but this outcome is far from certain.

Globally, trends in material and energy flows present interesting metabolic challenges. Overall, when resource use is divided by the number of people on Earth, as of 2010, each person yearly demands 10 tons of materials. Using the standardized System of National Accounts, UNEP (2016) illustrates the vast disparities in material use between economies in the Global North and those in the Global South. In North America and Europe, each person requires approximately 20 and 14 tons, respectively – far exceeding material demand across other economies. Regional contexts offer critical insights into understanding these material flows at finer scales.

Several studies have looked closely at physical material flows at the scale of disaggregated world regions. Using distinct methodological approaches, Krausmann et al. (2009), Schaffartzik et al. (2014), and Wiedmann et al. (2015) each examined global scale material flows that uncovered parallel trends by material type (that is, minerals, ores, fossil energy, biomass, etc.). Others have examined flows for specific regions: Gierlinger and Krausmann (2012) studied the United States; Weisz et al. (2006) studied Europe; Krausmann et al. (2011) studied Japan; Russi et al. (2008) studied some of Latin America; Gonzalez-Martinez and Schandl (2008) studied Mexico; and Giljum (2004) studied Chile. And while these several studies illustrate that the overall rate of material flows is accelerating, the following important dimensions merit careful understanding.

Until 2000, Japan's total energy needs were generally always rising, but since then there has been a persistent decline. Europe's total primary energy demand has declined more than 8 percent since 2005 (3 percent between 2013 and 2014) (EEA 2015). While Africa and South Asia are entering a phase of industrialization that will likely lead to an increase in construction, some contend that China's construction of residential buildings will plateau after 2035. Although China is expected to add another 225 million urban dwellers, its national population will peak and start to decline in the next 10 years, which could influence the direction of China's urban expansion (for example, driving lower-density development or new settlements). The centrality of China's construction and manufacturing sectors is likely to be replaced over the next 15 years with more service-oriented production (NBSC 2016; Magnier 2016); this has broad implications for material and energy flows from the buildings sector (You et al. 2011; Hu et al. 2010).

To highlight some of the material and energy flow challenges facing China, between 2011 and 2013 China consumed more cement (6.6 Gt) than the United States did between 1901 and 2000 (4.5 Gt) (Smil 2014). This rate far exceeded prior expectations (Fernández 2007), and it is uncertain if this trend can persist. The International Energy Agency (IEA) estimates that although China will remain the largest producer and consumer of coal and overtake the United States in oil consumption, it will require 85 percent less energy to produce each future unit of economic growth (that is, energy/GDP will decrease by 85 percent) (OECD/IEA 2015). Accounting for six main construction materials used in urban residential buildings in Beijing from 1949 to 2008, Hu et al. (2010) report that a total of 510 million tons of material were imported into the city, of which 470 million tons (or 92.5 percent) were retained in new stocks, that is, built environment and infrastructure; 33 percent of those new stocks emerged between 2003 and 2008.

Since record-keeping began, the United States has had the world's largest total primary energy supply, a trend that had been increasing until 2009, when China took over this rank. The United States has since seen a decline in both per capita and overall energy needs (OECD/IEA 2014) and there has been a similar decrease in domestic material consumption (UNEP 2016).

From a global urban perspective, Africa and India combined will add more than one billion *new* urban residents by 2040 (UNDESA 2014). To provide electricity for these residents, India's power sector needs to quadruple by 2040; this will likely lead India to becoming the world's biggest importer of coal. In developing countries, urbanization will demand materials to create infrastructure, vehicles, and buildings. China has experienced a rapid expansion of builtup urban area, which is both driving and driven by economic growth in and around the cities (Bai et al. 2011), with the built-up urban area growing much faster than the urban population (Bai et al. 2014). Müller et al. (2013) estimate that if the developing world proceeds to construct its new cities with the same intensity and type of infrastructure we see in developed countries, the potential carbon cost is more than a third of the world's cumulative carbon budget to 2050 (if we seek to restrain global warming to 2°C above preindustrial averages).

While the direct material needs of the developing world will enlarge and those of the developed world might stabilize – and possibly even decouple from economic activity – it is important to be wary of *indirect* material needs embodied in trade. The overall material footprints of Japan, the United States, and the United Kingdom are all more than 150 percent greater than their direct domestic material consumption (Wiedmann et al. 2015). For residence and service-oriented urban centers that typically import energy and energy-intensive materials and goods, consumption-based approaches, such as input-output footprints, may yield higher energy-use estimates compared to territorial accounting, though the opposite may be true in net-producing urban centers (Chávez and Ramaswami 2013). However, in the end, this may continue to follow the trajectory presented by Bristow and Kennedy (2015) (see Figure 3.3), who portray a strong linear relationship between global energy use and global urban population.

Meanwhile, as we collectively enhance data collection and analysis methods for measuring aggregate and global level material flows, one paramount challenge to robust assessments is likely to persist going forward. Data-rich economies, mostly those in the Global North (also known as "OECD economies"), are the epicenter of most comprehensive material flow and metabolic studies; these studies continue to provide important insights for the planning of new communities. Conversely, communities in the Global South are often restricted

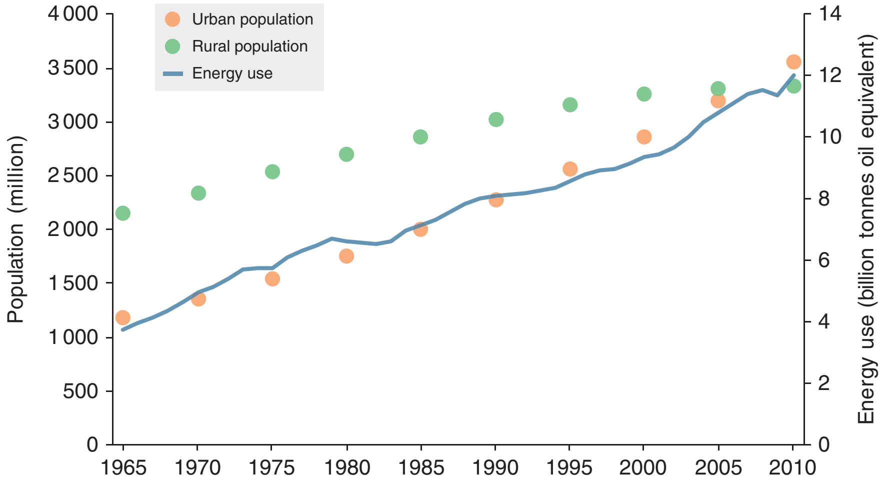

Figure 3.3 Global energy use for urban and rural population, 1965 to 2010. Source: Jerker Lokrantz/Azote, modified after Bristow and Kennedy (2015).

from further metabolic assessments due to their limited available data. Samples of studies show that research-community partnerships are employing a suite of novel data techniques to be able to inform local communities of important challenges, including e-waste in Nigeria (Nnorom and Osibanjo 2008); energy, material, and greenhouse gases for Delhi, India (Chávez et al. 2012); and food consumption for Manila, Philippines (Chakraborty et al. 2016). However, some obvious gaps exist, which elevate the potential for successful open-source data efforts to fill them (see Chapter 11).

3.3.1 Drivers of Material and Energy Flows

Global drivers of material use have generally been linked to both per capita income and per capita consumption (UNEP 2016). At a more granular scale, researchers have proposed various characteristics of cities that drive urban material and energy flows; these driving characteristics can generally be categorized as natural environmental, socioeconomic, urban function and integration energy system characteristics, and urban form (GEA 2012). The global energy assessment indicates that the natural environment relates to attributes of geographic location, climate, and resource endowments, while socioeconomic drivers typically relate to household characteristics, economic structure, and demography.

As of 2010, a study of the material and energy flows of the world's 27 megacities showed that electricity use per capita is also strongly related to urban area per capita. The authors found that the underlying cause of this relationship was the increase in building floor space. As cities sprawl, there is more room for bigger buildings, which consume more electricity. Building floor area per capita also influences heating fuel use in cities, although heating degree days (a measure of coldness below a base of 18°C room temperature) is the dominant driver (Kennedy et al. 2010, 2015).

Researchers have also observed a high level of correlation between drivers. Kennedy et al. (2015) illustrated high correlation ($r^2 > 0.7$) between urbanized area per capita and electricity use, transportation fuel use, and water consumption (Table 3.1; all per capita). There is also, however, a strong correlation ($r^2 = 0.8$) between GDP per capita of the metropolitan region and urbanized acre per person. Hence, GDP has medium to strong correlation with electricity, transportation, and water use. Many of the variables are interrelated, and overall, cities appear to develop more consumptive metabolisms as they become wealthy and spread out. These findings agree with previous studies, which established that when reporting metabolic energy and carbon flows from cities, one should carefully normalize by the appropriate metrics, namely economic metrics such as GDP for production-based flows, and population metrics for

Table 3.1 Simple univariate correlation matrix between per capita parameters for 27 of the world's megacities as of 2010

Correlations								
	Electricity cons.	Heating and indust. fuel	Transp. fuel	Water cons.	Solid waste	Heating degree days	Area per pers.	GDP
Electricity consumption (MWh)	–							
Heating and industrial fuel (GJ)	0.40	–						
Transportation fuel (GJ)	0.61	0.70	–					
Water consumption (kL)	0.51	0.51	0.69	–				
Solid waste production (t)	0.44	0.23	0.57	0.45	–			
Heating degree days	0.45	0.59	0.50	0.17	0.27	–		
Area (km^2) per person	0.78	0.60	0.79	0.72	0.68	0.42	–	
GDP ($)	0.68	0.41	0.68	0.46	0.55	0.58	0.80	–

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consumption-based flows (Ramaswami and Chávez 2013). Additional studies observe changing patterns of metabolic flows across the income axis. For example, in a study looking at phosphorus metabolism through food consumption in Chinese cities, Li et al. (2012) observed an increasing trend of overall phosphorus flow in and out of cities, while an inverted U shape described the share of phosphorus remaining within the urban boundaries. Taking a longitudinal perspective, Cui et al. (2015) conclude that the quantity, configuration, and efficiency of phosphorus metabolism through cities can change drastically in response to changes in consumer and producer behavior, as well as in socioeconomic structure. All of the drivers, trends, and outcomes discussed in this section have directional impact on urban metabolism.

3.4 Theory for Measuring Urban Material and Energy Flows

This chapter has introduced a number of urban metabolism frameworks and models to assist with measuring urban-scale material and energy flows. Baynes and Wiedmann (2012) present a robust set of approaches often used in urban metabolism, such as transboundary footprinting, input-output consumption-based approaches, and complex systems science. One additional approach is a network-oriented method termed “ecological network analysis,” or ENA, which presents a set of strong tools for examining structure and function of ecosystem flows (Patten 1978; Finn 1976; Fath and Patten 1999). ENA is a variant of economic input-output analysis (Leontief 1951). ENA has been used to model various metabolic flows, including energy, carbon, water, and others, in a range of cities (Zhang et al. 2010; Liu et al. 2011; Chen et al. 2015). The most notable benefit of the network approach is that it can provide information about relationships between urban sectors in a holistic way, in which both direct and indirect (remote) interactions can be captured.

Increasingly, current research has been striving for urban metabolism data that includes both in-boundary activities and out-of-boundary (or life cycle) impacts (Chen et al. 2014). Input-output models (Smith and Morrison 2006) and life cycle analysis (Pincetl et al. 2012) have been utilized to include activities that occur “upstream” and “downstream” of the city in the framework of urban metabolism. With their embodied material and energy inputs for urban growth, they are both capable of assessing the footprints of cities. Recent work integrating input-output and life cycle data with ENA is promising for assessing and regulating urban sectors to mitigate resource overuse and unintended emissions (Chen and Chen 2015, 2016). Novel integrations could assist metabolic understanding of cities.

Future theoretical frameworks can consider integrating multiple metabolic lenses into understanding the complexities of cities. For example, considering the multiple possibilities for parceling cities into territorial, production, and consumption footprints (see Chávez and Ramaswami 2013) can help us gain a stronger appreciation for the metabolisms of cities and the relevant approaches for maximizing their respective material and energy flows.

3.4.1 Efficient, Sustainable, and Resilient Metabolisms

Creating efficient, sustainable, and resilient metabolism models, while challenging, is imperative in our rapidly expanding and urbanized world. Resource use is increasing, many production systems are peaking, and the consumption and demand for goods and services are at unprecedented highs. Methods and principles of industrial ecology, such as those mentioned in Section 3.3 (material and energy flow analysis and life cycle footprinting), as well as others (dematerialization, recyclability, urban industrial symbiosis, and so forth) (Chertow et al. 2016), can become the cornerstones for assisting the range of stakeholders who are integrating and implementing three vital characteristics – efficiency, sustainability, and resilience – into community metabolisms. While sometimes perceived as interchangeable, these three attributes are unique in the following ways:.

Efficiency concerns the quantity of inputs to produce an output. Typically, an efficient metabolism is characterized by relatively low levels of material use and energy flows to achieve a standard level of output. Examples of key indicators for measuring and tracking efficiency in community metabolisms are electricity per economic or sector output, energy per sector output, or material inputs per waste generation.

Sustainability in urban metabolism addresses the impacts associated with the material and energy flows of a particular system. Sustainability can be measured via environmental (such as CO_2 per sector or CO_2 per GDP), economic (such as income, energy use, and energy-use intensity), and social (such as education and public health) indicators (see Katehi et al. 2016).

Resilience of metabolism relates to the capacity of a particular flow, or to the entire metabolism, for recovery after a disruption. While linkages between metabolism and resilience are ripe for new lines of inquiry, their coupling with disciplinary extensions can yield a practical suite of options for metabolisms to absorb or mitigate against shocks. Industrial ecology – and, specifically, supply-chain analysis – has the potential to reveal key areas of material substitutability, helping inform alternate material uses should system disruptions occur. Example of key indicators of resilience may include metrics for diversity, alternatives among inputs, and measuring impacts from shocks (see Chapter 7).

3.4.2 Gaps in Current Understanding

To embark on and successfully complete effective metabolism assessments requires a wide array of local- and community-level data. It is true that many communities have rich data collection and processing teams. Cities such as New York City, Tokyo, Berlin, and Mexico City have robust data caches, which facilitate metabolism assessments. Many data-rich cities have, coupled with rich secondary data found in the literature. Anecdotally, we note that cities with rich data are often megacities or larger urban centers located in Annex 1 countries (see UNFCCC 2014 for country classifications). Meanwhile, cities in non-Annex 1 countries and/or smaller communities do not display these benefits; in most instances, they are data poor.

Beyond larger urban areas in Annex 1 countries and/or megacities, most communities do not have easily or publicly accessible data to complete vital metabolism assessments that would enhance community and infrastructure planning. As we illustrate using Figure 3.1, much of the world's projected population growth will occur in communities under 500,000 habitants – all of which require substantial and effective planning in order to achieve efficient, sustainable, and resilient metabolisms. Understanding the intricacies of metabolic demands is necessary and imperative – it is also a gap that reasonable data can help close. As an example of this problem, completing coupled and detailed production and consumption footprints that compare cities in the Global North (Annex 1) and in the Global South (non-Annex 1) has proven to be impossible with the current state of data (UCCRN 2016). Should data limitations prevent a community from actively embarking on and a creating efficient, sustainable, and resilient metabolisms?

Given the vast differences in data availability and community development stages, understanding the material needs of communities in relation to their development may yield novel understandings for a sustainable and resilient future. Thus, classifying communities into three broad types may provide new lines of inquiry for the research community. Communities that are unbuilt (*rapidly growing*), built (*mostly stable*), and unbuilding (*shrinking*) each have distinctive attributes in terms of their metabolic flows. We posit that Type A, unbuilt communities, include many of the small(er) communities throughout the Global South that are currently experiencing rapid rates of population and GDP growth. These communities have a very high demand for materials and are poised for styles of planning that can avoid a negative infrastructural and material legacy. Type B, built communities, are the *mostly stable* communities of North America, Europe, Japan, and Australia, where rates of growth (as indicated by GDP) are not bulging as those elsewhere are. These economies are experiencing an increased level of efficiency in material use per GDP, an outcome likely driven by their primarily service-based economic structure. Type C – unbuilding communities that are shrinking and depopulating – are a phenomenon currently observed in the United States' Rust Belt (see Schilling and Logan 2008)) and Europe's east (see Bontje 2004). As shrinking communities transition from materials-intense outputs towards tertiary sector production, they may well be poised for exemplary green infrastructure development.

Box 3.1 Beijing case study

Innovative Policies and Levers: Exemplary Case Studies

Beijing, the capital of China, has one of the largest gross domestic products, or GDPs of Chinese cities (350 billion USD in 2014) and is home to more than 20 million people. Beijing is also the leading city of the Jing-Jin-Ji economic region, the development of which has a substantial impact across the entire country. With a fast-growing population and expanding urban areas, Beijing has an increasingly high demand for energy and resources from Jing-Jin-Ji and the rest of city operations, raising a significant challenge to supplying energy for the city sustainably.

Taking Beijing's 2012 energy use as an example, the three major sources are reported as coal (37 percent), diesel oil (16 percent) and gasoline (14 percent) (Chen and Chen 2015). Meanwhile, energy flow analysis shows that the most energy-consuming components of Beijing at this time were manufacturing (45 percent of total direct energy consumption), services (29 percent), and transportation (16 percent). Using input-output analysis, researchers found that the total energy embodied in Beijing's supply chains associated with urban sectors was almost seven times higher than its direct energy use within the urban boundary. Since Beijing is also in a severe water shortage, it is important that we take both energy use and water consumption into consideration, together.

The resilience and sustainability (or lack thereof) of coupled energy and water metabolism has been a central problem for fast-growing cities such as Beijing. By applying network resilience metrics to urban systems, some scholars hope to show efficiency gains and how stable an urban system can be while facing both energy and water challenges. The resilience of energy-water coupled systems in Beijing is lower than that of natural ecosystems in general (Chen and Chen 2016). The relationships among urban sectors are altered by the competition of energy and water flows. It is clear that coordinated regulation of different metabolic flows in cities, particularly in megacities (for example, Beijing), is essential for more sustainable and rational development.

3.5 Conclusions

Throughout this chapter, we have presented several motivations for the increased use of urban metabolism as a governing framework for understanding the materials and energy flows associated with cities. While the methodological foundations for adopting urban metabolism may have matured through research, development of a typological framework could greatly benefit its scalability and cross-city applicability. Having an urban metabolism typology can help uncover nuanced city details that, in turn, can lead to inquiry and understanding for metabolic flows as they relate to various types of cities. Typological development has seen some momentum recently.

A typology can simply be described as a form of classification, separation, or presentation that segments groups based on a number of key features. For example, a rudimentary typology for cities can adopt a scale based on affluence from less affluent to more affluent. Alternatively, a typology can examine city growth and adopt a scale from rapidly growing to no growth, or even to shrinking. While these are only some of the several typological options, the few early urban metabolism typologies have accounted for added complexities. For example, Chávez and Ramaswami (2013) propose a typology based on a city's import and export of GHG emissions to classify three types of cities – net consumer, balanced, and net producer. Another effort, rooted in Saldivar-Sali (2010), is led by Massachusetts Institute of Technology's Urban Metabolism team, which has developed a typology that uses four independent variables (climate, GDP, population, and density) to reveal clusters (or groups) of cities in terms of eight dependent variables (energy, electricity, fossil fuel, industrial and construction minerals, biomass, water, and domestic material). The opportunities to build on the early work to bring added understanding to urban metabolic flows continues.

3.5.1 Future of and Opportunities Surrounding Urban Material and Energy Flows

Tools based on urban metabolism have witnessed several iterations and many transitions since early research in the 1960s. Analysis that was initially boundary limited by bulk mass flows has transitioned to robust life cycle assessment approaches with the ability to examine from the jurisdictional boundary across the complete supply chain into a city's hinterland(s) – which often include multiple economies in multiple countries (Pichler et al. 2017). Additionally, the early studies quantified the total physical flows for a limited number of sectors, such as energy or waste. Over time, however, urban metabolism studies have expanded in sectors to include transportation, buildings, materials, and others – as well as economic, social, and environmental indicators. Moreover, recent studies including a full*er* set of metabolic flows can provide estimates beyond non-visual material uses, such as those associated with underground infrastructures in cities. The latest estimates of urbanization and urban resource (material and energy) demands increase the need for deeper understanding across communities and their metabolisms.

The creation and use of typologies can help establish more robust understanding of urban metabolisms. Although some attempts have been made in the recent past which can serve as foundations for future typological frameworks, there are additional research opportunities for developing an overarching typology for urban metabolism. Completing such a typology could help drive efficiency, sustainability, and resilience for communities of all sizes everywhere, while merging urban metabolism typologies with global community standards that are being developed in parallel. Such products can also help reduce the knowledge gaps related to sharing best practice and forging partnerships across communities of similar clusters (or types).

Several unknowns and opportunities for new lines of inquiry remain within the analytical field of urban metabolism. For example, it is understood that we are becoming more material inefficient at the global level; in other words, the global economy now requires more material inputs per unit GDP than it once did. Our continuing global shift to materially inefficient economies, which are experiencing unprecedented transformations, contributes to this worldwide trend of increasing resource use and inefficiency. However, due to data limitations, we are still uncertain how these global trends transpire at local, community scales. Are there significant and important differences between the material requirements in subnational economies, for example? The emerging opportunities for integrating material efficiencies, especially in rapidly growing communities, may be many.

As we consider the future of urban metabolism, we can look back at its origins, appreciate its present, and innovate towards the future. From urban global population projections and the strength of GDP emerging from cities, to the expansive opportunities for efficiency resulting from natural resource use and waste and emissions output, communities face plenty of opportunities and challenges. Considering that the bulk of future urban growth is projected to occur in cities of less than 500,000 inhabitants, the questions surrounding material and energy needs for developing high-quality livelihoods will continue to evolve. Many data gaps remain, inhibiting our nuanced understanding of urban metabolism, and these gaps slow the channelling of necessary resources to their required uses in cities. As researchers, practitioners, policy-makers, and interested citizens, it is up to us to continue employing, deploying, and innovating urban metabolism approaches to increase our understanding of resource flows across the urban boundary – and to implement genuinely resilient systems.

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