From local to national metabolism: a review and a scale-up framework

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ABSTRACT

Research background: Countries are likely the most important subjects involved in the environmental control and response to global environmental issues, while the majority of the related metabolic analyses are focused on the metabolism at the city scale.

Objective: Analyzing why and how to scale up the metabolic study from city to country.

Methods: Combining quantitative analysis with a literature review socio-metabolic research, since it is an effective method to study resource and environmental issues and has been applied at different scales.

Results: 1) A single city or a smaller area is hardly self-sufficient, and its sustainability and resilience needs the support of the surrounding environment; 2) At the country scale, systems exhibit a higher level of self-organization and a corresponding higher level of complexity, addressing the need for applying the metabolic theory at the national scale; 3) The emergy analysis methods show its advantages in study metabolic processes for national metabolism; 4) Input-output analysis plays an important role in and region coordination.

Conclusions: The interactions among and within the scales are nested, as well as the goals and methods. Therefore, socio-metabolic research on scales differ in their priority goals, and the methods adopted must be targeted.

Introduction

The world is facing an urgent need for economic, social, and environmental transformation, requiring huge efforts for pursuing a sustainable future (Haberl et al. 2019). In 2015, all 193 United Nations (UN) member States adopted the Agenda 2030 with its 17 Sustainable Development Goals (SDGs) (United Nations 2015) – a comprehensive framework comprising many potentially diverging policy goals and aspiring for transformative change in the economic, social, and environmental challenges (Fuso Nerini et al. 2019). These challenges are strongly interlinked (Haberl et al. 2019), in fact, SDGs are expected to be mutually supportive (Kroll, Warchold, and Pradhan 2019) and need buy-in from all nations (Brito 2012). This means that governance processes across multiple sectors, stakeholders and countries are critical (Fuso Nerini et al. 2019; Kroll, Warchold, and Pradhan 2019) and long-term social and economic improvement will need closer attention to be paid to the environment (Brito 2012). Meanwhile, great efforts must be made to reduce or change human use of geophysical resources (such as energy, materials, or land) to prevent severe ecological degradation and mitigate climate change effects (IPCC 2014; Programme UNE 2016). Climate action is explicitly addressed by SDG13, and is expected to impact almost all aspects of sustainable development, so it is necessary to understand how action to address climate change could reinforce or undermine the other SDGs, and vice versa (Fuso Nerini et al. 2019). A quantitative and comprehensive research is therefore mandatory to link the social, economic, and environmental fields, aiming at guiding and monitoring the progress to sustainable levels (Liu et al. 2015; Hoekstra and Wiedmann 2014).

At the core of sustainable development, science is, therefore, the need to understand the interactions between Society and Nature, how these interactions change over time and how they will be likely affected in the next future (Kates et al. 2001). Socio-metabolic research (SMR) is an effective system approach for analyzing the physical exchange process (material and energy flow) between human society and its natural environment as well as the material and energy flow within human society, and their impacts to the natural environment (Oliver-Solà et al. 2008; Ayres and Simonis 1994). SDGs framework introduced a set of detailed monitoring indicators related to metabolism, such as domestic material consumption (DMC),...
material footprint (MF), resource efficiency, and so on, while scholars from different backgrounds have developed various research strands of socio-metabolic approaches (Haberl et al. 2019). SMR is based on the assumption that social systems and ecosystems are complex systems that can replicate themselves, affect each other, and develop together over time (Weisz 2011). As pointed out by Pincetl et al. (Pincetl, Bunje, and Holmes 2012), system components at different scales tend to act and influence each other by nesting within another. Moreover, scale matters in a wide variety of aspects of driving forces, impacts, and responses to sustainable development challenges, because it is directly related to how and where governance decisions are made. This requires new approaches to multi-scale actions (Wilbanks 2007), as far as cross-scale innovative co-management structures can promote sustainable development (Cash et al. 2006). As a matter of fact, local decision-making is influenced by regional policies, which in turn affects global politics and economy, rising from local to larger scales, and the decisions in turn affect sustainable development: what happens to sustainability at one scale affects sustainability at other scales.

As an increasing number of people and human activities are concentrated in cities, with more than 55.3% of the world population living in urban areas (UN-DESA 2018), thus cities bring significant and increasing economic contribution to their economies (Bai 2003). More and more research is being focused on the urban-scale operation and functioning (Xian and Ouyang 2014; Newell and Cousins 2014). However, the environmental issues of cities extend outside the urban boundaries, not only involving multiple dimensions, but also scales of impacts ranging from local, regional to global (Bai 2003, 2007). This requires larger scales of analyses, taking into account the interaction of urban to national to even global scale. Urban metabolism has been used as a metaphor in multiple fields, indicating that traditional methods may not have fully epistemological tools to face the new challenges (Musango, Currie, and Robinson 2017), including sustainable development ones. Research has now recognized the importance of scale. So far, SMR has been applied to multi-scale research from individual/family (Kalbar et al. 2016; Kenny and Gray 2009), neighborhood (Lausselet et al. 2019) and urban spatial scales (Agudelo-Vera et al. 2012; Wheeler and Beatley 2014) to regional and even global scales (Nuss and Blengini 2018; Kennedy and Hoornweg 2012), as well as from individual sectors to socio-economy (Oliver-Solà et al. 2008; Odum 2007). Several questions raised: (1) being SMR applied to complex systems at different scales, what are the main differences among the research methods at different scales? (2) Both cities and countries are complex socio-economic-ecological systems: in what do the urban metabolism and national metabolism differ? (3) From the perspective of historical development of metabolic theory, what are the focuses at different stages, and which ones should draw more attention in the future?

This paper contributes to the understanding of the differences of SMR applied at different scales. Based on the literature, it outlines the origin and development of metabolic theories and studies at different scales, as well as their analytical methods of metabolism research, and finally puts forward the significance of scale-up framework in SMR. Compared with previous reviews, this paper established the framework of SMR across scales and the methods. The majority of the related metabolic analyses are focused on the metabolism at the city scale or a smaller area. However, a single city or a smaller area is hardly self-sufficient, and its sustainability needs the support of the surrounding environment. In this framework, we argue that countries are more likely the most important subjects involved in the environmental control and response to global environmental issues. At the country scale, systems exhibit a higher level of self-organization and a corresponding higher level of complexity, addressing the need for applying the metabolic theory at the national scale.

Origin and development of metabolic theory

The term “metabolism” was coined in the early 19th century to describe chemical changes in living cells and was widely used by chemists concerned with the use of wastewater and fertilizers in agricultural production (Barles 2010). Later, it was also applied to the field of biochemistry, in which biochemical metabolism refers to the complex biochemical reaction network catalyzed by enzymes, allowing to adjust the concentration of the substrate and the product, as well as the reaction rate. It is used to characterize the organic decomposition process involving organism internal parts (cell level) and the organism itself, along with the external environment (Haberl et al. 2004). The vast majority of creatures share the same basic biochemical process, however, the rate of absorption, transformation, and allocation of resources may vary significantly (Brown et al. 2004). Accordingly, ecosystems can be considered as functional entities and analyzed by describing the dynamics of energy and nutrient flows (Conan 2000). The structural and functional similarities between artificial ecosystems and natural ecosystems were then addressed by H.T. Odum (Odum 1959; Patten 1981). Artificial ecosystems such as cities, like organisms, require energy and resource inputs and produce waste (Pincetl, Bunje, and Holmes 2012; Bettencourt et al. 2007). The concept of metabolism has been therefore gradually introduced into the study of artificial (eco)systems, in particular, cities. The term metabolism applied to the study
of ecosystems addresses all physical and chemical processes, including the supply of substances and energy from the external environment to the metabolic body (system), the transfer and storage in the body, and the whole process of metabolic waste and energy discharged to the external environment (Oliver-Sola et al. 2008; Ayres and Simonis 1994; Fischer-Kowalski 1998). It is worth stressing that talking about metabolism for such systems is not a mere narrative metaphor or analogy. It aims at defining analytically the complex systemic structures as networks of resource flows, in which stationary states are reached by means of the feedback network existing between the system components, just like in a living organism.

In the development process of metabolic research, there are different views in the academic community about who should be considered the pioneer of the introduction of SMR into artificial ecosystem research. Some scholars indicate as the initiator of urban metabolism Wolman (Kennedy, Cuddihy, and Engel-Yan 2007; Kennedy, Pincetl, and Bunje 2011), who in “The Metabolism of Cities” (Wolman 1965) defines “metabolism” as: “All the materials and commodities needed to sustain the city’s inhabitants at home, at work and at play.” Lin et al. (2012) commented that the word “urban metabolism” was first proposed by Ernest Burgess, a sociologist, in 1953, 40 years before Wolman. Although Burgess did not provide a formal definition of urban metabolism, he compared urban growth to catabolism. Urban metabolism research can be anyway traced back to 1894 (Lederer and Kral 2015). At that time, German chemist and physician Theodor Weyl, in his “Essays on the metabolism of Berlin,” studied the nutrients excreted from Berlin, comparing them with those absorbed with food. Following Lederer and Kral (2015), titles, methods and wording in his book are sufficient to address Theodor Weyl as a pioneer of urban metabolism (Nuss and Blengini 2018; Zhang 2013). Contemporary critical urban theorists, such as Sywngedouw, Kaika, and Heynen, studied urban metabolism from the perspective of modern Marxism, applying Marx’s method to “analyze the dynamic internal relationship between man and nature” (Pincetl, Bunje, and Holmes 2012; Heynen, Kaika, and Sywngedouw 2006).

It is worth mentioning that the idea of comparing artificial ecosystems such as cities to organisms predates the application of SMR to socio-ecological systems. A recent study (Céspedes Restrepo and Morales-Pinzón 2018) pointed out how the human organization in communities was metaphorized for the first time as a biological organism several centuries ago (Sennett 1996), on the basis of the development of medicine during the seventeenth century. Thomas Willis and Albrecht von Haller studied the neural systems using the connections and circulation of electrical impulses and blood as the basis for the health and development of individual tissues (Céspedes Restrepo and Morales-Pinzón 2018). The transformation of the health paradigm brought about by new discoveries led to a new perspective rooted on the concepts of flows, health, and personality to address the human body and society (Sennett 1996). Based on the city-human body metaphor, terms like “vein” and “artery” were used to denote one-way roads, while other expressions such as “urban heart” were used to differentiate the functional center of the cities. The history of the metaphor of artificial ecosystems such as cities as organisms indicates that the theory of metabolism has anyway a body of theoretical basis. The emergence of the concept of metabolism reinforced the organic city-human body metaphor, giving an isomorphic character to what until the eighteenth century represented only an analogy between the spatial configuration of the city and how living beings operate (Céspedes Restrepo and Morales-Pinzón 2018).

In general, SMR research in social sciences and artificial ecosystems has gone through a process of conceptual step-wise growth (Barles 2010). In the 1860s, the concept of metabolism arose in the field of biology, and soon it was found somewhat connected with many classic theories on social science (Fischer-Kowalski and Hüttler 1988), and the SMR research on artificial ecosystems become an emerging field of study. Later, with the further development of biology and ecology, the use of SMR in social sciences was somewhat limited (Fischer-Kowalski and Hüttler 1988), until in the late 1990s the interest in the artificial ecosystems metabolism started increasing, following the growth of environmental issues and related laws and regulations (Davoudi and Sturzaker 2017). Changes in scale from cells to the human body even to the city may be however required by SMR, whose development is summarized in Table 1.

SMR regards the research object as an “organism,” and each “organism” is in contact with its surroundings in space or time, as Figure 1 shows. The “organisms” of the same scale are interconnected and influence each other, and at the same time, the “organisms” of different scales also interact and influence each other. These interactions with the surroundings are nested, as Figure 1 shows. When we regard a research object as an organism, then it is composed of “cell-tissue-organ-system-human body.” Where “cell” is the basic structural and functional units of living organisms, and “tissue” is group of “cells” and “cell” stroma with similar morphology and function, “organ” operates specific function, system is composed of multiple “organs” that can perform one or several functions in a certain order. The
| History | Description | Reference |
|---------|-------------|-----------|
| **Organism metaphor (back to 1614)** | | |
| Human communities are considered in relation to biological systems. Medical advances led to a new view of the body and the society based on flow, health and individuality. The metaphor generated from the comparison between city and human body is not only the analogy between the spatial configuration of city system and human anatomy, but also the functional and structural elements of the city (Céspedes Restrepo and Morales-Pinzón 2018). | | |
| **1614, Santorio Santorio** | Published “De Medicina Statica Aphorismi” on the flow of materials in the human body, which is the first investigation into the metabolism of humans. | (Céspedes Restrepo and Morales-Pinzón 2018) |
| **1628, William Harvey** | Published “De motu cordis” on breathing and circulation. | |
| **1757, Albrecht von Haller** | Showed that nerve impulses travel the body through “pathways” in a similar way to the circulation of blood. | |
| **1776, Adam Smith** | Published “The wealth of nations” where he described flows of goods and money between societies and nature; labor market and goods are seen to work in a similar manner to blood circulation. | (Sennett 1996) |
| **1800s, urban planners** | Urban planners incorporated the medical discoveries into the design of the eighteenth century city with the objective that it “worked like a healthy body, flowing freely and enjoying a clean skin.” | |
| **1941, E.L. Thorndike** | Pointed the description of “A nation may very well be a natural bio-social entity, quite comparable, in fact, to that of a colony of ants, or of bees, or of termites.” | |
| **The emergence of the metabolism (back to 1815)** | | |
| **1815, G. C. Sigwart** | The concept of “Stoffwechsel” was first put forwards by chemist G. C. Sigwart in 1815. In German, “Stoff” means substance, material and fodder, and “wechsel” means interchange and transform. From the literal perspective, “Stoffwechsel” means the interchanging and transforming process of substance, material and fodder between two things. If we apply Aristotles’s “matter-form” framework to illustrate this concept, “Stoffwechsel” is the “matter interchange” compared to the “form interchange,” and we can call the connotation of “matter interchanging” as philosophical “Stoffwechsel.” | (Céspedes Restrepo and Morales-Pinzón 2018) |
| **1839, Theodor Schwann** | Proposed the neologism “metabolism.” | |
| **1859, Karl Marx** | Published “Capital” and used the term “Stoffwechsel,” i.e. Metabolism. | (Zhang 2013) |
| **1884, Karl Marx** | Described the exchange of materials and energy between society and environment in his Economic & Philosophical Manuscripts of 1844. | (Lederer and Kral 2015) |
| **1894, Theodor Weyl** | Essays on the metabolism of Berlin, investigated nutrient flows discharged from Berlin, comparing these values to nutrient consumption through food intake. | |
| **1925, Burgess** | A sociologist, first utilized the term with no formal definition to set up analogy between urban growth and the anabolic and catabolic processes. | |
| **1959, E.P. Odum** | Developed a model of an urban system heterotrophic characteristics. | |
| **Initial Period (1965 to 1980)** | | |
| **1965, Wolman** | Published “The Metabolism of Cities,” examined the process of supplying material, energy and food to a hypothetical city, as well as its respective output products; wrote “All the materials and commodities needed to sustain the city’s inhabitants at home, at work and at play.” | (Wolman 1965) |
| **1969, Ayres and Kneese** | Conducted research on a national level using EW-MFA, analyzing material flow in the United States from 1963 to 1965. | |
| **1970s** | The first applied research on urban metabolism began in the early 1970s. UNESCO 1971 Man and the Biosphere Programme led researchers to analyze the status of Rome, Barcelona, and Hong Kong in 1970. | |
| **1973, H.T. Odum** | Used metabolic energy to represent the production of organic matter (photosynthesis) and its consumption (respiration) by the metabolic processes of ecological systems and analyzed the relationship between humans and their environment from an energy perspective. He proposed the concept of embodied energy (“emergy”). | (Odum 2007; Huang 1998; Odum 1973; Zucchetto 1975; Stanhill 1976; Zhang, Yang, and Yu 2009) |
| **1975, Zucchetto** | Following H.T. Odum study, conducted studies with the emergy analysis method combining the system of man and nature. | (Kennedy, Pincetl, and Bunje 2011; Zucchetto 1975; Gaggioli and Wepfer 1980) |
| **Growth Period (1981 to 2000)** | | |
| **1980, Gaggioli and Wepfer** | Improved emergy analysis by separating products to avoid double counting, identifying associated and symbiotic products, and improved transformity values (using the rules of “emergy algebra”), and this has led to expanded use of emergy analysis. | (Kennedy, Pincetl, and Bunje 2011; Gaggioli and Wepfer 1980; Odum 1981) |
| **1981, H.T. Odum** | Introduced the concept of hierarchies among the components of a system. | |
| **1983, H.T. Odum** | Began to develop research on Paris since 1850 using the emergy method and data provided by Stanhill. | (Odum 1983; Zhang, Yang, and Yu 2015; Stanhill 1976) |
| **1989, E.P. Odum** | Introduced the concept of urban parasitism to account for nonreciprocal relationships within an urban system. | (Zhang, Yang, and Yu 2015; Odum 1989) |

(Continued)
“system” is coordinated to enable various complex life activities in the “human body” to proceed normally functions. “human body” is able to make decision and self-organize.

Main methods of metabolism research

Several metrological approaches are used for understanding the socio-economic and socio-ecological systems, such as Material Flow Analysis (MFA), Ecological Footprint Analysis (EFA), Emerge Accounting Method (EMA), Life Cycle Assessment (LCA) and Input-Output Analysis (IOA). These methods use thermodynamic laws of conservation of mass and conservation of energy (Mostafavi, Farzinmoghdam, and Hoque 2014), in which flows entering and leaving the system are deemed as equivalent (Musango, Currie, and Robinson 2017) (stationary states). Hence, they are also called accounting approaches. Material Footprint (MF) and Domestic Material Consumption (DMC) are the monitoring indicator related to metabolism. Another approach using multiscale integrated analysis of the societal and ecosystem metabolism (MuSIASEM) is based on Georgescu-Roegen’s flow-fund model, where funds have to be maintained but are not consumed (Giampietro, Mayumi, and Ramos-Martín 2009;
Gerber and Scheidel (2018) and refer to entities such as labor, land, or technological capital that provide services to the social system (Haberl et al. 2019).

**Main definition and aim**

MFA studies the flow of resources used and transformed as they flow through an area, and investigate resource or human problems related to the relationship between individual activities and their external environmental impact (Loiseau et al. 2012). This approach focuses on three main issues: system definition, quantification of stocks and flows, and interpretation of results (Kennedy, Cuddihy, and Engel-Yan 2007). The MFA system boundary includes resource inputs, production, consumption, waste management, and disused stocks (Li and Kwan 2018).

Ecological footprint refers to the land area required by a country, a region, a city, or a census tract to meet the metabolic needs of its inputs and outputs (Li and Kwan 2018). EFA matches the physical resources and energy needed to support the city and the biocapacity required to absorb waste generated by the city itself (Li and Kwan 2018), and can also compare urban demand and supply (Moore, Kissing, and Rees 2013).

EMA was first proposed by H.T. Odum, the American systems thinker and ecologist (Odum 1971) who defined “emergy” as a common measure of the available energy used directly or indirectly to produce a product or service, expressed in solar energy units (Odum 1983). All the contributions involved in the production are therefore measured in the same unit, and the resulting quantity is called emergy (from “embodied energy”). Sustainability-oriented indicators can be then calculated to derive suitable and holistic assertions about the use of energy and material flows from local renewable, nonrenewable, and imported resources (Beloin-Saint-Pierre et al. 2017). These emergy indicators address different sustainability issues, among which the system efficiency in using resources, the criticality of its dependence on purchased resources or on nonrenewable sources and its environmental load and sustainability (Liu, Brown, and Casazza 2017).

Input-Output analysis was originally proposed for commodities related to the various production and consumption sectors of the national economy. The analysis assesses material flows between economic sectors by tracking product and sector-specific resource flows (Musango, Currie, and Robinson 2017), that are empirically analyzed (Leontief 1936; Miller and Blair 1985; Duchin and Lange 1998). The economic model based on IO analysis reveals how the industry interacts to generate GDP by purchase tracking of resources and products.

LCA is a systematic method for evaluating the environmental burdens associated with a product, process, or activity, by identifying and quantifying energy and materials consumed and the downstream impact on the environment (Curran 1997; Tan and Khoo 2005). LCA is a method of cradle-to-grave accounting for specific production processes, assessing the effects of resource conversion and utilization, which requires consideration of environmental impact of products,
services and systems throughout the supply chain, as well as waste treatment (Beloin-Saint-Pierre et al. 2017).

MF refer to the total materials in the entire production process to meet the final consumption demands (Wiesen and Wirges 2017). It allows deriving indicators of material extraction, trade, and consumption, indicating the pressures on the environment while supporting economic growth and satisfying the material needs of people (Lutter, Giljum, and Bruckner 2016). MF is highly correlated with the carbon footprint and the ecological footprint, and it is worth mentioning that IOA and LCA are two main calculating approaches for MF (Giljum et al. 2019).

MuSIASEM, originally proposed as MSIASM (Giampietro, Mayumi, and Ramos-Martin 2009), was developed by Giampietro and Mayumi (Smit et al. 2018) as an open framework that takes into account economic, environmental, and social aspects, differentiating flows of water, energy, food, and money (Giampietro and Mayumi 2000a, 2000b). MuSIASEM is a method that can study economy, society, and ecology both qualitatively and quantitatively (Geng et al. 2011). The proponents of MuSIASEM argue that since socioecological systems are self-organized, the study of metabolism requires considering their hierarchically organized structural and functional compartments operating at different space dimensions and multiple scales (Gerber and Scheidel 2018).

**Main applications**

Pincetl et al. divided the methods to study urban metabolism into UM 1.0 and UM 2.0 (Pincetl, Bunje, and Holmes 2012). In UM 1.0, the methods are mainly accounting methods, including MFA and EMA. In UM 2.0, the applied methods come from multiple fields, involve accounting methods (e.g., LCA), ecological methods (Ecological Network Analysis), geographical methods, ecosystem service methods, political ecology methods, and political-economic methods. Concerning LCA-based analysis, there are two fundamental approaches, i.e. process-based LCA and economic input-output LCA (EIO-LCA), which are often combined for related research, the latter more focused on the calculation, evaluation, and prediction of urban inputs and outputs in various economic sectors related to economic activity. LCA can be applied to single-year and time-series to assess all flows and effects of the entire product, from cradle to grave (Beloin-Saint-Pierre et al. 2017).

MFA can be performed to investigate metabolic processes and offers a wide range of details about metabolic flows on multiple scales (Barles 2010), covering regional, national, and global scales as well as households, industries, or other units, using stationary or dynamic approaches (Baccini and Bader 1996). When applying material-based analytical methods, this is often one of the biggest obstacles to integrating different data sets (Li and Kwan 2018). It is worth mentioning that Substance Flow Analysis (SFA) can compensate for some of these problems of MFA, which can be used to track specific paths of matter or group of substances from origin to destination, so determining where they accumulate (Baccini and Brunner 2012). A concern about the materials, the most widely studied are still mainly at the national level, including steel, copper, zinc, chromium, phosphorus or a combination of nitrogen and phosphorus (Yuan et al. 2011). Since the SFA produces very detailed information, it may be used to provide targeted material flow management strategies.

IOA provides similar information for the material-flow accounting across the economy, by opening up “black boxes” to show internal flows (Daniels 2002) and how resources interact with urban activities. It fills therefore some gaps when applied to the urban environment and a detailed distinction is made between the various actors of the urban system. This is necessary to simulate the function of urban metabolism (Zhang 2013): the participants are divided into different sectors and the metabolic flow between these sectors is clearly expressed in the form of a physical input-output table. Therefore, IO analysis tracks products and sector-specific productivity as well as resource flows to assess the material flows between the sectors of the economy (Giljum and Hubacek 2009). IOA can be also extended to include more explicitly environmental issues, in particular, to analyze (inter) national supply chains in order to quantify footprints of urban areas. In this case, it is often referred to as Environmentally extended input–output analysis (EE-IO).

MF can precisely measure the pressure on natural resources and demand of material, and it is a measure to examine the sustainability across countries (Arshad Ansari, Haider, and Khan 2020). A country’s MF is usually computed by combining input-output data with trade (Lutter, Giljum, and Bruckner 2016), MF is an advantageous indicator to inform decision-makers about material use, and it is also known as raw material consumption (RMC).

While MuSIASEM is commonly used to analyze the societal metabolism of countries (Velasco-Fernández, Ramos-Martin, and Giampietro 2015), sectors (Velasco-Fernández, Giampietro, and Bukkens 2018), and energy systems (Diaz-Maurin and Giampietro 2013; Sorman and Giampietro 2011; González-López and Giampietro 2017; Di Felice, Ripa, and Giampietro 2018, 2019), its application to urban metabolic system is still limited (Qi et al. 2017; Perez-Sanchez et al. 2019). In MuSIASEM framework, the urban system is analyzed at different levels, taking into account how the changes in a level act on the other ones depending on the feedbacks between the various departments (Wang, Wu, and Li 2017). MuSIASEM may be regarded as a general ecological efficiency evaluation of
regional development, helping national and regional governance to address the main problems, to formulate appropriate policies and to balance the various departments and regions. Especially in the energy consumption of different departments and regions of the system, policy-makers can address pros and cons of development, as well as the challenges and opportunities (Geng et al. 2011). MuSIASEM can be used to characterize energy and matter necessary for the further development of a society (Geng et al. 2011), in turn necessary for the sustainability of the entire world (Fischer-Kowalski 1998; Giampietro, Mayumi, and Ramos-Martin 2009), as well as a decision support tool for the analysis of different scenarios, including current trends and preferred scenarios that remain within system boundaries (Rodríguez-Huerta, Rosas-Casals, and Hernández-Terrones 2019).

**Limitations of these methods**

LCA and IOA are currently the most used (Beloin-Saint-Pierre et al. 2017), but other approaches exhibit advantages under different perspectives. In order to better face problems of artificial ecosystems (such as cities and countries), it is necessary to combine different evaluation methods (Beloin-Saint-Pierre et al. 2017). As concerns MFA methods, the main differences between local and national MFA are data sources (Hammer et al. 2003). On the other hand, local metabolic studies often lack uniform data classification. Research at the national level is often based on national information (e.g. statistics and indicators), depending on different backgrounds and perspectives (Rosado, Kalmykova, and Patricio 2016). Eurostat developed a set of standardized economy-wide material flow analysis (EW-MFA) method, mainly intended for the national level, while also applicable to the city level (Eurostat 2001; Barles 2009). Generally speaking, material flow analysis of the entire economy can in principle describe the flow for each sector, the resource input and output flows, yet neglecting some of the mutual role of sectors, and blurring potential intervention levers (Hammer et al. 2003). In fact, MFA studies only consider the direct exchanges of materials and energy, so neglecting the embedded upstream and downstream processes required to provide urban residents with unit resource consumption (Goldstein et al. 2013) (Kalbar et al. 2016), and it cannot be used for integrated systems of different materials (Qi et al. 2017).

Concerning LCA-based methods, there are four different iterative phases of life cycle assessment: goal and scope definition, inventory analysis, impact assessment, interpretation (Chau, Leung, and Ng 2015). As artificial ecosystems (e.g. cities and countries) are complex systems, it is quite challenging to define their life cycle, which often requires long-term data collection from the cradle to the grave. Beloin-Saint-Pierre et al. (2017) pointed out that although life cycle is an important modeling perspective for assessing sustainability, most urban metabolic studies do not even clearly define the life cycle of complex systems like cities (Beloin-Saint-Pierre et al. 2017).

MF is defined as the sum of all materials extracted to produce the final demand along the supply chain, irrespectively of where the materials have been used. Domestic material consumption (DMC), the indicators of direct material use, it records domestically extracted plus imported minus exported materials, the MF does not falsely indicate dematerialization if a country offshores material-intensive production (Pothen and Tovar Reaños 2018).

Urban ecological footprint refers to urban development and natural resources and the area of biological production required to treat waste generated by urban systems (Li and Kwan 2018). The sustainability of urban metabolism can be also assessed by ecological footprint. Indeed, the equivalent land area of ecosystems for sustainable urban development is about two orders of magnitude larger than the relevant urban area (Kennedy, Cuddihy, and Engel-Yan 2007). This means that the city relies on large amounts of land to provide input resources and process waste output (Decker et al. 2000).

EMA ensures that the energy that makes up the creation and flow of all materials is considered together with the material, addressing the difference in material and energy quality. It may link ecological and economic systems, overcoming the lack of the traditional economic statistical analysis methods, which cannot compare scales (Qi et al. 2017). Emery-based analyses may be flawed by the lack of available data, as well as by the difficulty of combining different energy sources measured in different units. In fact, the complexity of emery-based analysis and the resulting limited application are sometimes due to the solar joule metric conversion (Huang 1998). Within the city, data must be obtained from provinces and countries that communicate with urban areas to quantify the differences in inputs or imported products or technologies included in the service.

In general, combining economic factors with material and energy flow analysis can build an environmental input-output table that helps to better understand the participants in urban metabolic processes. While the combination of material and energy flows and input-output tables is difficult, since the data on material and energy flows may be limited (it must be calculated using the economic – capital – matrix), exchanges between departments can be considered, yet the results can remain a rough simulation. Based on EW-MFA and the raw material equivalent (RME) of the input-output table, other attempts have been made to describe the upstream raw material consumption of MFA (Kalbar et al. 2016; Barles 2009). Unlike Odum’s consideration on energy, MFA reports stock and resource flows by quality (Kennedy, Pinceti, and Bunje 2011). Emery assessment method takes a more comprehensive approach than MFA,
considering the embodied energy of metabolic flows across urban system boundaries (Liu et al. 2011). It is worth noticing that common sources of data to analyze sustainable development (such as SDG reporting) are mainly collected by national statistical offices (NSOs), government ministries, and international organizations (Espey et al. 2015). These sources of data are anyway valuable and necessary, yet sometimes costly to obtain (Fritz et al. 2019).

For national metabolism studies, national statistics have more international standards and are more complete. For example, when using the energy method applied to a country, the import and export data are relatively complete and the statistics are detailed; on the contrary, for the provinces data are less reliable or incomplete, while the import and export data of cities may be even lacking, making quite challenging to carry out a detailed analysis. Therefore, the existing inventory method results more accurate at the national scale, while cities need to further supplement such data in accordance with national statistical thinking. Indeed, the links between cities may be not consistent with the links between countries, as shown in Table 2.

### Metabolic studies at different scales

With the development of SMR at different scales, many studies have extended the connotation of metabolic theory, including Personal Metabolism (PM), Household Metabolism (HM), Service Sector Metabolism (Service Sector), Industrial Metabolism (IM), Urban Metabolism (UM), Social Metabolism (SM), Regional Metabolism (RM) and even Anthroposphere Metabolism (AM). Table 3 shows the corresponding fundamental references, but the differences among the different scales remain to be explored, especially at the national metabolism level.

#### Urban metabolism

Similar to an ecosystem, the city, acting as a “superorganism,” interacts with its environment. The physical, chemical, and biological processes in cities that transform resources/materials into usable products and wastes resemble that of human bodies or ecosystems (Newman 1999). Based on this idea, in the late 20th century the Urban Metabolism (UM) developed into a creative method for studying urban resource use, energy conversion, emissions (such as greenhouse gases) and impacts on environment. At present, many scholars have defined urban metabolism. The widely accepted definition of urban metabolism is “sum of the technical and socio-economic processes that occur within the cities, resulting in growth, production of energy, and elimination of waste” (Kennedy, Cudilliy, and Engel-Yan 2007). Some scholars address the urban metabolism as a “collection of complex socio-technical and socio-ecological processes by which flows of materials, energy, people, and information shape the city, service

### Table 2. Urban and National Metabolism under Sustainable Development.

| Target System boundary | Urban metabolism | National metabolism |
|------------------------|------------------|---------------------|
| Best local sustainability | Optimal sustainability of the country as a whole | Not fully open; Boundary stability; |
| Dynamic. As urbanization progresses, urban built-up areas continue to expand; Inconsistent. For example, in China, the boundaries of cities are the administrative boundaries and often including rural and sub-urban area. While in the USA, the boundary of a city is usually the boundary of a built-up area. | Boundary recognition. |
| Industrial Network Larger differences in industrial network structure in different cities | Urban and Industrial Networks | Little difference in industrial networks between different countries |
| Innovation and focus | Resource availability | Intra-city industrial networks and inter-city nesting |
| Develop and adapt larger-scale actions with smaller stakeholders | Without this bottom-up encouragement, larger and effective actions are often limited to democratic government systems. | |
| The data is more detailed, but the data types and calibers of different cities are difficult to be consistent | High availability and little difference in data types between countries | |
| Provides the potential for participation, flexibility and innovation | Provides potential for resource mobilization and cost sharing. Can solve some cross-scale, watershed problems | |
| Less complex and easier to track all the richness of the relationship | More complexity, but can only be solved by simplifying relationships for analysis and understanding | |
| Low probability of threat, but low resilience | Threats are more likely to occur, but the resilience to threats is higher and a wider range of resources are available for damage response and cost sharing | |
| Strong sensitivity to the local environment | Weak local environment, lack of information on local and scale linkages, and lack of resources to support effective action | |
| Micro-level assessments focus on the use of resources by products and organizations, and may be related to monetary values, such as the price of a product or the cost of materials and energy spent by a company. | Economic-wide studies measure resource utilization and resource productivity (macro level) across countries, three countries, or regions within the world’s regions. | |
| More attention is paid to the technical choice of departments and the identification of key units. | Studies at the national scales usually take more account of the final policy implementation recommendations. | |

Source: adapted from (Wilbanks 2007; Sala, Ciullo, and Nijkamp 2015).
the needs of its population, and impact the surrounding hinterland” (Currie and Musango 2017). As the urban metabolic research further developed, the concept of urban metabolism used to describe how interactions within cities affect the use of resources and energy has been widely accepted (Musango, Currie, and Robinson 2017).

Similarly, metabolic studies of artificial ecosystems at different scales have been proposed and explored, such as regional metabolism (Baccini 1996; Baccini and Bader 1996), social metabolism (Pastore, Giampietro, and Mayumi 2000; Baynes 2016), and industrial metabolism (Ayres and Simonis 1994; Wassenaar 2015). Lu and Chen (2015) address a narrow perspective, in which urban metabolism only refers to the metabolism within the urban system. From a broader perspective, other scales of metabolic research can represent an expansion and extension of urban metabolism. Decker and colleagues argue that industrial metabolism, industrial ecology, and regional metabolism may be regarded as further nomenclatures for human activity that differ from urban metabolism.

**Social metabolism**

In the nineteenth century, Marx and Engels applied the word “metabolism” to the Society (Fischer-Kowalski 1998). Societal metabolism was first introduced in Marx’s “Capital” (Foster 1999; Martinez-Alier 2009; Broto,
Allen, and Rapoport 2012), which puts the foundations for the development of a strong environmental sociology (Foster 1999). The term societal metabolism was then taken up by ecological economists and combined with political ecology (Martinez-Alier et al. 2010). The concept of “social metabolism” (or “economic,” “socio-economic” or “societal” metabolism) grew from the observation that biological systems – e.g. organisms and ecosystems – and socio-economic systems – e.g. households, firms, and economies – (Gerber and Scheidel 2018), can be addressed to describe how human societies organize their growing energy and materials and their interactions with the environment (Giampietro and Mayumi 2000a; Fischer-Kowalski 1998). In other words, social metabolism can be used to measure the process by which a society transforms energy and matter to ensure its continued existence (Giampietro, Mayumi, and Ramos-Martin 2009; Fischer-Kowalski 1998). More specifically, the “social metabolism” refers to all the energy and material transformations that are taking place within an open social system such as an economy, and between this system and its environment (Gerber and Scheidel 2018). These complex processes determine the functional structure of the system, ensure its reproduction, maintain and repair its parts, and exhibit specific dynamics according to different contexts (Giampietro, Mayumi, and Şorman 2012).

Social metabolism starts with appropriate materials and energy inputs in human societies and ends with them being stored as outputs in natural areas as waste, smoke, or resides. In fact, there is also a cycle of transformation and consumption of materials between inputs and outputs (Rodríguez-Huerta, Rosas-Casals, and Hernández-Terrones 2019). Societal metabolism puts its emphasis on the relationship between flows and the agents that transform input flows into output flows, while maintaining and preserving their own identity (Rodríguez-Huerta, Rosas-Casals, and Hernández-Terrones 2019). It focuses on material flow and the exchange of energy, material, and information between nature and society (Dombi et al. 2018). Hence, it connects funds and flows of the used and dissipated elements, addressing indicators characterizing specific features of the system (Rodríguez-Huerta, Rosas-Casals, and Hernández-Terrones 2019). The analysis of a complex system using a social metabolic approach provides an overview of the multiple flows in the system, as well as an understanding of their interactions and impact on the environment (Rodríguez-Huerta, Rosas-Casals, and Hernández-Terrones 2019), therefore addressing possible causes and solutions of the environmental problems of a society (Fischer-Kowalski and Haberl 1998).

**National metabolism**

The city acts as a complex system, in which itself, its various components, and its external environment interact and exchange materials with each other (Pulido Barrera, Rosales Carreón, and de Boer 2018). The country is a larger system than the city, exhibiting a higher degree of self-organization which makes it more complex than the urban system. From a spatial perspective, the theory of metabolism has been applied in the individual, family, urban, and regional scales, but as to national scale, no comprehensive descriptions of metabolism have been addressed so far (Musango, Currie, and Robinson 2017). On the other hand, social metabolism studies are often mostly based on a national scale. But social metabolism is different from national metabolism. The country exhibits multidimensional characteristics including society, economy, and nature dimensions altogether. In other words, its intensity and extension are broader than the social metabolism. We claim that within the artificial ecosystems at different scales, the interaction mechanisms of its different components with the external environment are in turn different. Thus, the methods of studying artificial ecosystems at different scales should also be different. Therefore, defining different artificial ecosystems and choosing related research methods may actually play a significant role in multi-scale research.

**Why should we focus on the national metabolism, even for the urban metabolism?**

**Can one city be sustainable?**

Sustainability is often misinterpreted as equivalent to self-sufficiency, while in a globalized world self-sufficiency at a local scale actually does not exist (Elmqvist et al. 2013). Like the organism supporting the cells, cities depend on the outside world to provide resources and ecosystem services, which range from energy, food, water, and construction materials to waste assimilation to sustain their function (Bai 2007). Such resource and ecosystem services input often originate from far rural regions, supporting the cities that host more than half of the world population (Seitzinger et al. 2012). Reciprocally, almost all rural systems are affected by the urbanization process, as evidenced by the fact that more than 90% of global gross-added value is generated by urban economies (United Nations 2011). Production and consumption are concentrated in urban areas (Vergragt et al. 2016) and cities government are committed to achieve self-improvement by optimizing the resource use and the efficiency and minimizing waste (Grove 2009), while the economic complexity and dynamic interrelations among local, regional, and global processes and commodities flow address the significant connections between urban and nonurban areas (Hayter, Barnes, and Bradshaw 2003).
For example, a recent study shows that Guangzhou, in China, is increasingly dependent on the external economy (Cui, Wang, and Feng 2019). When facing external events such as fluctuations in the supply of some resources, its resilience will result in quite weak, with a slow recovery capacity. Guangzhou has a close connection with the surrounding environment, as well as with other regions. The metabolic profile of Guangzhou reveals the difficulty of achieving self-sufficient urban metabolism, a situation similar to that of other industrial cities (Conke and Ferreira 2015).

It can never be possible for cities to become fully self-sufficient. Without taking into account the remote dependence and influence on resources and populations in other regions all over the world (Folke al. 1997), individual cities cannot be regarded as “sustainable” (Seto et al. 2012). In other words, we cannot consider the sustainability of a city as isolated from the sustainability of human and natural resources, from both close or distant regions, or the combined resource use and impacts of cities globally (Seitzinger et al. 2012).

To improve global sustainability requires to explore and figure out how cities can be responsible for natural biodiversity and ecosystem services within and beyond the city boundaries (Elmqvist et al. 2013).

Can we build resilience in a single city?

Resilience theory has a long history in engineering science, but the most influential ecological interpretation was developed by the Canadian ecologist C.S. “Buzz” Holling in 1973. Resilience builds on two radical premises (Peterson 2011). The first is that humans and nature are strongly coupled and co-evolving and should therefore be conceived of as one “social-ecological” system; the second is that the long-held assumption that systems respond to change in a linear, predictable fashion is just wrong.

Resilience is now used widely in discussing urban development. The concept of urban resilience has been related so far mainly to climate change adaptation and disaster management perspectives (Chelleri et al. 2015). On the other hand, even the concept of resilience has not a universally accepted interpretation and definition for divergent urban contexts (Pendall, Foster, and Cowell 2010). Currently, most urban resilience research focuses on the societal capacity to respond and adapt to natural disaster events (Wallace and Wallace 2008). Urban resilience is considered as the capacity of a city and its urban systems to absorb the first damage, to reduce the impacts from a disturbance, to adapt to changes that limit current or future adaptive capacity (Ribeiro and Goncalves 2019). Therefore, cities must respond more quickly and more effectively to anticipate and minimize the associated consequences and dangers (Ribeiro and Goncalves 2019).

The key move of urban resilience research is to consider both spatial and temporal interactions, in order to shift from the mainstreaming of the resilience-building paradigm toward a critical understanding and management of resilience trade-offs (Chelleri et al. 2015). However, applying the resilience concept at the local city scale is not particularly useful. Focusing on just one city is counterproductive, as building resilience in one city can often erode cities elsewhere, with multiple negative effects globally (Tainter 2003).

How a single city can improve resource efficiency

Resource efficiency, referring to “using the Earth’s limited resources in a sustainable manner while minimizing impacts on the environment,” is one important link to achieve sustainable development goals (OREP 2015). An increasing number of national and international strategies focussing on resource efficiency (Lutter, Giljum, and Bruckner 2016). When organizations want to achieve energy sustainability, they consider two main issues: the shortage of energy resources and the adverse effects of energy use (Woo et al. 2015), which require all sectors of the economy to improve resource efficiency. Cities are central to support the technological and socio-cultural shift toward sustainable growth via a resource-efficient (Salvia et al. 2015). Since the lifestyle of households is an important driver of overconsumption of natural resources, households play a vital role in reducing resource use to a sustainable level (Laakso and Lettenmeier 2016). Suited measures should be promoted to use resources more efficiently from the household to the national level (Laakso and Lettenmeier 2016), and the governance on resource efficiency should be joined the effort of urban governments, companies, and individual citizens (Salvia et al. 2015).

It requires massive transformations to scale-up

Scales are “the levels at which phenomena occur both in space and time” (Young 2002). Appreciating the role of geographical scale for sustainability is profoundly complicated by constant changes in the world around us, especially as technologies reshape the meaning of proximity and increase interconnections over what were once long distances (Wilbanks 2007). Smaller scales exhibit less complexity but, as a result, are more tractable in tracing out relationships in all their richness, while larger scales include more complexity but can only be addressed by simplifying the relationships in order to make analysis and understanding manageable (Kates et al. 2001).

Scale is a crucial aspect of sustainability, since sustainable development involves differences between scales in systems and processes and thus in how we understand the single issues and are able to act;
relationships between scales in systems and processes shape each other’s perceived realities, and one’s ability to act (Wilbanks 2007). Sustainable research requires mutual methodological integration across natural sciences, engineering and social sciences/humanities, in order to both understand the complex social-ecological dynamics at play and to develop solutions that are based on a sound understanding of both physical and social systems (Fuso Nerini et al. 2019). However, due to the scale effect, a single country’s program may produce negative externalities for other countries (Independent Group of Scientists Appointed by the Secretary-General 2019). To avoid this risk, a comprehensive and systematic framework is needed to promote joint action by countries, thus enabling SDGs to advance on a regional, national, and global scale (Fu et al. 2020).

Resilience thinking involves exploring interacting hierarchies of nested systems: higher-level systems are driven by slow variables and lower-level systems are driven by fast-changing ones (Ostrom 2004). In resilience thinking, complex systems are rarely static and linear. They are often described as constantly flowing, highly unpredictable, and self-organizing, with feedbacks across multiple scales in time and space. From an urban perspective, general resilience thus only makes sense on a much larger scale than individual cities (although specified resilience may be explored at a smaller scale). What happens in the upper and lower scales affects the resilience of the whole system, while the connections to the different scales, if appropriately oriented, may increase the overall resilience of the system (Magoni 2017). The concept of general resilience and scale lead us to another quite radical idea: change and transformation at the city level is necessary for maintaining resilience at the larger scale. Conventional urban responses to disturbances (such as coping and adaptive strategies) may not only, over time, be insufficient at the city-scale, but also counterproductive when addressed to the resilience at the global scale.

When the existing system becomes untenable under the previous ecological, economic, or social structure, the ability of a system to become a fundamentally new system is called transformability (Folke et al. 2010). Although at a first glance, transformations often seem counterintuitive for building resilience, multiple transformations at lower scales may be necessary to maintain resilience at a larger scale (Wu and Loucks 1995). Some attempts have been made to scale up for achieving urban environmental stewardship (Salvia et al. 2015), such as regional or watershed environmental impact assessment or indirect ecological footprint to account for the ecosystem pressures within and outside city boundaries (Elmqvist, Barnett, and Wilkinson 2013). Thus, the sustainability should depend on the boundary and treat resilience as non-normative at these scales. A resilient, self-sufficient city can also be easily a non-sustainable one, in as much it may rely on the (unsustainable) support of the outer regions at larger scales.

A scale-up framework of SMR

For both sustainability and resilience concepts, the local city scale is too narrow. Urban sustainability and resilience thinking and policies must address scales and consider urban dependence and impacts on distant populations and ecosystems (Elmqvist et al. 2013). Collaboration across a global system of cities could manage resource chains for sustainability through resilience (Elmqvist et al. 2013). To build resilience, urban regions must take into account their profound connections with, and impacts on, the rest of the planet. Otherwise, urban resilience may fail to find meaning, or it may create oversimplified goals in a too narrow sense. As the scale of the global challenge associated with rapid urbanization and climate change grows, traditional conceptualizations of sustainability need to be extended through engagement with resilience (Elmqvist et al. 2013), meaning that there are many challenges associated with sustainability and resilience.

The complex economic interactions in the metabolism process make it difficult to determine whether a city is sustainable. This is related to the required resources and environmental costs inside and outside the local geographic area, which are related to production, consumption, waste discharge, and the well-being of residents (Cui, Wang, and Feng 2019). SMR can form a backbone of sustainability science by delivering consistent analyses of social metabolism that helps to better understand the interdependencies between societal well-being and the physical services provided by society metabolism (Haberl et al. 2019). Metabolism is an aspect of the sustainability challenge from resilience. It concerns inefficient and unsustainable resource use, both in cities – as a consequence of consumption rates and the generation of waste/pollution – and at the planetary level, as driven by cities, because of teleconnections (Seto et al. 2012; Newman 2016). SMR is the approach to analyze the input (resource use) and output (waste) and the flow within and outside the system boundaries. Addressing this challenge of system metabolism requires a resilience perspective related to the long-term socio-technical transition toward sustainability (Loorbach 2010). Thus, the integration of resilience thinking and urban metabolism principles in decision-making aims at improving the quality and effectiveness of environmental, social, and economic sustainable development strategies and actions (Magoni 2017).

Nowadays, at city scale, research, and application of sustainability have long been limited to either single or
narrowly defined issues within the city boundaries (e.g. water, energy, population, etc.) (Marcotullio and McGranahan 2007). Therefore, to make metabolic research and application meaningful, the constitution of urban sustainability needs to be re-thought and reconstructed. There is an urgent need for much more proper and larger scales than the individual city to be introduced and analyzed.

Since the interactions among and within the scales are nested (see Figure 2). Under different scales, due to the different primary goals, the applicable methods are different and the indicators considered are different. In fact, the primary goals and methods used at different scales are also nested with each other, and it is difficult to define their boundaries. In order to achieve the ultimate goal of sustainable development, the goals at different scales, including social, economic, and ecological goals, are also embedded with each other. It is true that sustainability, resilience, and resource efficiency are important to each scale, but depending on the scale, their goals are focused. For example, between regions, more emphasis is placed on regional coordination and balance, while in cities and smaller scales, more resource efficiency is pursued. At the national level, although it also pays attention to regional balance, resource utilization efficiency, and resilience, its goal is to give priority to national security while pursuing the country’s long-term development. SMR is goal-oriented, studying the process of the substances enter into and flow out at the different scales, with more detailed metabolic theories are derived, from personal metabolism (PM) to Anthroposphere Metabolism (AM). Although IOA is more widely used at urban and regional scales, it can reflect regional trade-offs and coordination. And EMA has shown its advantages in national-scale research, especially in the ability to evaluate natural and human contributions at the same time. SMR is not limited to one method, and multiple methods should be combined, both in one scale and across-scale. Since the goals and interactions are nested, one simple method is hardly to realize the target.

Countries are more likely the most important subjects involved in the environmental control and response to global environmental issues. At the country scale, systems exhibit a higher level of self-organization and a corresponding higher level of complexity, addressing the need for applying the metabolic theory at the national scale. Global challenges, such as climate change, are becoming more and more serious and threaten the survival of mankind, requiring the country to take actions. In this era, the entire mankind is a whole, we can regard the earth as a "human body"- which is of high self-organization, and each country is a "cell." This requires us to first study and understand metabolism on a national scale. Facing with the global challenges, today and in the future, and to achieve SGD, we need to pay more attention on the national level. The development of metabolic theory, as the scale-up, requires method reconstruction and goal-oriented.

Conclusion
As the pressure of climate change increases, people’s concerns about resources and environmental issues are growing. How can a socio-economic (ecosystem (city, region, country, supranational entity, such as the EU or the entire human race) become more or less sustainable at a particular time? Given the current political commitment to sustainable development, this issue has extremely important practical implications. SMR is a resource for environmental efficiency analysis approach which has been applied in various fields to assess cities, sustainability relationship, resource consumption, and waste generation. The gap in environmental efficiency between countries at different stages of development is an issue of international concern, as well as whether the gap is expanding or shrinking. Indeed, the differences among countries such as economic development, input

Figure 2. Priority goals, and methods at different scales metabolic research.
utilization, and pollution abatement, inevitably lead to differences in environmental performances (Li and Wang 2014). If implemented correctly, resource efficiency initiatives can increase competitiveness, ensure growth and employment, promote innovation, reduce resource requirements, and allow improved access to resources, also taking into account that if developing countries should consume at the same level of the richest countries, the Earth will be destined to a collapse (Santana 2014).

Research on metabolism at the national scale helps to understand the local and global impacts of national and global production. Effective actions at the national level help to solve global environmental problems and achieve the goal of sustainable development, requiring better understanding of the impacts of production, living, and ecological activities within the countries. The concept of metabolism promotes a quantitative approach to the assessment of system resource flows and stimulates the idea of designing sustainable cities to identify the leverage points for efficiency interventions. The view of the system as a metabolic superorganism has led to a rethinking of how environmental, social, and economic factors interact to shape urban phenomena. In general, the analyzed research showed that the metabolism of the cities does not have the same characteristics of national metabolism, which is not a replica of large-scale urban metabolism. Accounting for multi-geographical and temporal scales ranging from local to global issues appears therefore mandatory for the development of backcasting and forecasting scenarios.

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References
Agudelo-Vera, C. M., A. Mels, K. Keesman, and H. Rijnaarts. 2012. “The Urban Harvest Approach as an Aid for Sustainable Urban Resource Planning.” Journal of Industrial Ecology 16 (6): 839–850.

Akiyama, T. Urban Metabolism and Sustainability. AUICK Newsletter, No. 17, Japan. 1994.

Arshad Ansari, M., S. Haider, and N. A. Khan. 2020. “Environmental Kuznets Curve Revisited: An Analysis Using Ecological and Material Footprint.” Ecological Indicators 115: 106416.

Ayres, R. U., and U. E. Simonis. 1994. Industrial Metabolism: Restructuring for Sustainable Development Tokyo. Tokyo: United Nations University Press.

Baccini, P. 1996. “Understanding Regional Metabolism for a Sustainable Development of Urban Systems.” Environmental Science and Pollution Research 3 (2): 108–111.

Baccini, P., and H.-P. Bader. 1996. Regionaler Stoffhaushalt: Erfassung, Bewertung, Steuerung [Regional Materials Management: Analysis, Evaluation, Control]. Heidelberg, Germany: Spektrum Akademischer Verlag.

Baccini, P., and P. H. Brunner Metabolism of the Anthroposphere: Analysis, Evaluation, Design. 2012.

Baccini, P., and H. P. Bader Regionaler Stoffhaushalt (Regional Material Management). Spektrum Akademischer Verlag, Heidelberg. 1996.

Bai, X. 2003. “The Process and Mechanism of Urban Environmental Change: An Evolutionary View.” International Journal of Environment and Pollution 19 (5): 528.

Bai, X. 2007. “Industrial Ecology and the Global Impacts of Cities.” Journal of Industrial Ecology 11 (2): 1–6.

Barles, S. 2009. “Urban Metabolism of Paris and Its Region.” Journal of Industrial Ecology 13 (6): 898–913.

Barles, S. 2010. “Society, Energy and Materials: The Contribution of Urban Metabolism Studies to Sustainable Urban Development Issues.” Journal of Environmental Planning and Management 53 (4): 439–455.

Barracó, H., M. Parés, A. Prat, and J. Terradas. 1999. Barcelona 1985-1999. Ecologia D’una Ciutat. Barcelona: Ajuntament de Barcelona.

Baynes, T. M. 2016. MD8. A Socio-economic Metabolism Approach to Sustainable Development and Climate Change Mitigation. Cham: Springer.

Beloin-Saint-Pierre, D., B. Rugani, S. Lasvau, A. Mailhac, E. Popovici, G. Sibiude, E. Benetto, and N. Schiopu. 2017. “A Review of Urban Metabolism Studies to Identify Key Methodological Choices for Future Harmonization and Implementation.” Journal of Cleaner Production 163:S223–S40.

Bettencourt, L. M. A., J. Lobo, D. Helbing, C. Kühnert, and G. B. West. 2007. “Growth, Innovation, Scaling, and the Pace of Life in Cities.” Proceedings of the National Academy of Sciences of the United States of America 104: 7301–7310.

BRIDGE. 2008. About BRIDGE project.

Britto, L. 2012. “Analyzing Sustainable Development Goals.” Science 336 (6087): 1396.

Broto, V. C., A. Allen, and E. Rapoport. 2012. “Interdisciplinary Perspectives on Urban Metabolism.” Journal of Industrial Ecology 16 (6): 851–861.

Brown, J. H., J. F. Gillooly, A. P. Allen, V. M. Savage, and G. B. West. 2004. “Toward A Metabolic Theory of Ecology.” Ecology 85 (7): 1771–1789.

Cash, D. W., W. N. Adger, F. Berkes, P. Garden, L. Lebel, P. Olsson, L. Pritchard, and O. Young. 2006. “Scale and Cross-scale Dynamics: Governance and information in a Multi-level World.” Ecology and Society 11 (2); 12.

Céspedes Restrepo, J. D., and T. Morales-Pinzón. 2018. “Urban Metabolism and Sustainability: Precedents, Genesis and Research Perspectives.” Resources, Conservation and Recycling 131: 216–224.
Chau, K., T. M. Leung, and W. Y. Ng. 2015. “A Review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on Buildings.” Applied Energy 143: 395–413.

Chelleri, L., J. J. Waters, M. Olazabal, and G. Minucci. 2015. “Resilience Trade-offs: Addressing Multiple Scales and Temporal Aspects of Urban Resilience.” Environment and Urbanization 27 (1): 181–198.

ConAccount 2008: Urban metabolism-measuring the ecological city. 1st edition ed. Charles University Environment Centre, Prague, Czech Republic. 2009.

Conan, M. Environmentalism in Landscape Architecture. 2000.

Conke, L. S., and T. L. Ferreira. 2015. “Urban Metabolism: Measuring the City’s Contribution to Sustainable Development.” Environmental Pollution 202: 146–152.

Cui, X. Z., X. T. Wang, and Y. Y. Feng. 2019. “Examining Urban Metabolism: A Material Flow Perspective on Cities and Their Sustainability.” Journal of Cleaner Production 214: 767–781.

Curran, M. A. 1997. Environmental Life Cycle Assessment. New York: McGraw-Hill.

Currie, P. K., and J. K. Musango. 2017. “African Urbanization: Assimilating Urban Metabolism into Sustainability Discourse and Practice.” Journal of Industrial Ecology 21 (5): 1262–1276.

Daniels, P. L. 2002. “Approaches for Quantifying the Metabolism of Physical Economies: A Comparative Survey: Part II: Review of Individual Approaches.” Journal of Industrial Ecology 6 (1): 65–88.

Daniels, P. L., and S. Moore. 2001. “Approaches for Quantifying the Metabolism of Physical Economies: Part I.” Methodological Overview 4 (69-92): 5.

Davoudi, S., and J. Sturzaker. 2017. “Urban Form, Policy Packaging and Sustainable Urban Metabolism.” Resources, Conservation and Recycling 120: 55–64.

Decker, E. H., S. Elliott, F. A. Smith, D. R. Blake, and F. S. Rowland. 2000. “Energy and Material Flow through the Urban Ecosystem.” Energy & Environmental Science 25: 685–740.

Di Felice, L., M. Ripa, and M. Giampietro. 2018. “Deep Decarbonisation from a Biophysical Perspective: GHG Emissions of a Renewable Electricity Transformation in the EU.” Sustainability 10: 10.

Di Felice, L. J., M. Ripa, and M. Giampietro. 2019. “An Alternative to Market-oriented Energy Models: Nexus Patterns across Hierarchical Levels.” Energy Policy 126: 431–443.

Diaz-Maurin, F., and M. Giampietro. 2013. “A Grammar for Assessing the Performance of Power-supply Systems: Comparing Nuclear Energy to Fossil Energy.” Energy 49: 162–177.

Dombi, M., A. Karcagi-Kováts, K. Tóth-Szita, and I. Kuti. 2018. “The Structure of Socio-economic Metabolism and Its Drivers on Household Level in Hungary.” Journal of Cleaner Production 172: 758–767.

Duchin, F., and G. M. Lange. 1998. “Prospects for the Recycling of Plastics in the United States.” Structural Change and Economic Dynamics 9 (3): 307–331.

Elmqvist, T., G. Barnett, and C. Wilkinson. 2013. “Exploring Urban Sustainability and Resilience.” In Resilient Sustainable Cities, edited by L. Pearson, 19–28. New York: Routledge.

Elmqvist, T., M. Fragiokas, J. Goodness, B. Güneralp, P. J. Marcotullio, R. I. McDonald, S. Parmel, M. Schewenius, M. Sendstad, K. C. Seto, et al. 2013. “Stewardship of the Biosphere in the Urban Era.” In Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Global Assessment, edited by T. Elmqvist, M. Fragiokas, J. Goodness, B. Güneralp, P. J. Marcotullio, R. I. McDonald, S. Parmel, M. Schewenius, M. Sendstad, K. C. Seto, et al., 719–746. Dordrecht: Springer Netherlands.

Ermak, S. 1997. “Industrial Ecology: An Historical View.” Journal of Cleaner Production 5 (1): 1–10

Espesy, J., E. Swanson, S. Badiie, Z. Christensen, A. Fischer, M. Levy, G. Yetman, A. de Sherbinin, R. Chen, Y. Qiu, et al. 2015. Data for Development: A Needs Assessment for SDG Monitoring and Statistical Capacity Development. UNSDSN.

Eurostat. “Economy-wide Material-flow Accounts and Derived Indicators: A Methodological Guide”. Eurostat, European Commission, Luxembourg. 2001.

Fischer-Kowalski, M. 1998. “Society’s Metabolism: The Intellectual History of Materials Flow Analysis, Part 1, 1860-1970.” Journal of Industrial Ecology 2 (1): 61–78.

Fischer-Kowalski, M., and H. Haberl. 1998. “Sustainable Development: Socio-economic Metabolism and Colonization of Nature.” International Social Science Journal 50 (158): 573–587.

Fischer-Kowalski, M., and W. Huttler. 1988. “Society’s Metabolism: The Intellectual History of Material Flow Analysis, Part II, 1970-1988.” Journal of Industrial Ecology 2 (4): 106–136.

Folke, C., Å. Jansson, J. Larsson, and R. Costanza. 1997. “Ecosystem Appropriation by Cities.” Ambio 26: 167–172.

Folke, C., S. R. Carpenter, B. Walker, M. Scheffer, T. Chapin, and J. Rockström. 2010. “Resilience Thinking: Integrating Resilience, Adaptability and Transformability.” Ecology and Society 15 (4): 20.

Foster, J. B. 1999. Marx’s Theory of Metabolic Rift Classical Foundations for Environmental Sociology.” American Journal of Sociology 105 (2): 366–405.

Fritz, S., L. See, T. Carlson, M. Haklay, J. L. Oliver, D. Fraisl, R. Mondardini, M. Brocklehurst, L. A. Shanley, S. Schade, et al. 2019. “Citizen Science and the United Nations Sustainable Development Goals.” Nature Sustainability 2 (10): 922–930.

Fu, B., J. Zhang, S. Wang, and W. Zhao. 2018. Classification–coordination–collaboration: a systems approach for advancing sustainable development goals 2020.

Fuso Nerini, F., B. Sovacool, N. Hughes, L. Cozzi, E. Cosgrave, M. Howells, M. Tavoni, J. Tomei, H. Zerriffi, and B. Milligan. 2019. “Connecting Climate Action with Other Sustainable Development Goals.” Nature Sustainability 2 (8): 674–680.

Gaggioli, R. A., and W. J. Wepfer. 1980. “Exergy Economics.” Energy 5 (8–9): 823–837.

Geng, Y., Y. Liu, D. Liu, H. Zhao, and B. Xue. 2011. “Regional Societal and Ecosystem Metabolism Analysis in China: A Multi-scale Integrated Analysis of Societal metabolism (MSIASM) Approach.” Energy 36 (8): 4799–4808.

Gerber, J. F., and S. A. Scheidel. 2018. “In Search of Substantive Economics: Comparing Today’s Two Major Socio-metabolic Approaches to the Economy – MEFA and MuSIASEM.” Ecological Economics 144: 186–194.

Giampietro, M., and K. Mayumi. 2000a. “Multiple-Scale Integrated Assessment of Societal Metabolism: Introducing the Approach.” Population and Environment 22 (2): 109–153.

Giampietro, M., and K. Mayumi. 2000b. “Multiple-scale Integrated Assessments of Societal Metabolism Integrating Biophysical and Economic Representations across Scales.” Population and Environment 22: 155–210.

Giampietro, M., K. Mayumi, and A. Şorman. 2012. The Metabolic Pattern of Societies: Where Economists Fall Short. London: Routledge.

Giampietro, M., K. Mayumi, and J. Ramos-Martin. 2009. “Multi-scale Integrated Analysis of Societal and Ecosystem
Magoni, M. 2017. “Resilience Thinking and Urban Metabolism in Spatial Planning: Which Possible Integrations.” *City, Territory and Architecture* 4 (1): 19.

Marcotullio, P., and G. McGranahan. 2007. *Scaling the Urban Environmental Transition, from Local to Global and Back*. London: Earthscan.

Martinez-Alier, J. 2009. “Social Metabolism, Ecological Distribution Conflicts, and Languages of Valuation.” *Capitalism Nature Socialism* 20 (1): 58–87.

Martinez-Alier, J., G. Kallis, S. Veuthey, M. Walter, and L. Tempere. 2010. “Social Metabolism, Ecological Distribution Conflicts, and Valuation Languages.” *Ecological Economics* 70 (2): 153–158.

Miller, R. E., and P. D. Blair. 1985. *Input-Output Analysis: Foundations and Extensions*. Englewood Cliffs, NJ: Prentice-Hall.

Moore, J., M. Kissing, and W. E. Rees. 2013. “An Urban Metabolism and Ecological Footprint Assessment of Metro Vancouver.” *Journal of Environmental Management* 124: 51–61.

Mostafavi, N., M. Farzinmoghadam, and S. Hoque. 2014. “A Framework for Integrated Urban Metabolism Analysis Tool (IUMAT).” *Building and Environment* 82: 702–712.

Musango, J. K., P. Currie, and B. Robinson. 2017. *Urban Metabolism for Resource Efficient Cities: From Theory to Implementation*. Paris: UN Environment.

Newell, J. P., and J. J. Cousins. 2014. “The Boundaries of Urban Metabolism.” *Progress in Human Geography* 39 (6): 702–728.

Newman, P. 2016. “The Environmental Impact of Cities.” *Environmental and Urbanization* 18 (2): 275–295.

Newman, P. W. G. 1999. “Sustainability and Cities: Extending the Metabolism Model.” *Landscape and Urban Planning* 44: 210–226.

Nuss, P., and G. A. Blengini. 2018. “Towards Better Monitoring of Technology Critical Elements in Europe: Coupling of Natural and Anthropogenic Cycles.” *The Science of the Total Environment* 613-614: 569–578.

Odum, E. P. 1959. *Fundamentals of ecology*. Missouri: Saunders College Publishing/Harcourt Brace.

Odum, E. P. 1989. *Ecology and Our Endangered Life-Support Systems*. Sinauer: Sunderland, MA.

Odum, H. T. 1971. *Environment, Power, and Society*. New York: Wiley-Interscience.

Odum, H. T. 1973. “Energy, Ecology, and Economics.” *Ambio* 2 (6): 220–227.

Odum, H. T. 1981. *Energy Basis for Man and Nature*. New York: McGraw-Hill.

Odum, H. T. 2007. *Environment, Power, and Society for the Twenty-first Century the Hierarchy of Energy*. New York: Chichester: Columbia University Press.

Odum HT. 1983. *Systems Ecology: An Introduction*. New York: Wiley-Interscience.

Oliver-Solá, J., M. Núñez, X. Gabarrell, M. Boada, and J. Rieradevall. 2008. “Service Sector Metabolism: Accounting for Energy Impacts of the Montjuïc Urban Park in Barcelona.” *Journal of Industrial Ecology* 11 (2): 83–98.

(OREP) OREP. 2015.

Ostrom, E. 2004. “Panarchy: Understanding Transformations in Human and Natural Systems.” *Ecological Economics* 49 (4): 488–491.

Pares, M., G. Pou, and J. Terradas. 1985. *Descobrir El Medi Úrb: 2. Ecològia D’una Ciutat*. Barcelona: Ajuntament de Barcelona-Publicacions.

Pastore, G., M. Giampietro, and K. Mayumi. 2000. “Societal Metabolism and Multiple-Scale Integrated Assessment: Empirical Validation and Examples of Application.” *Population and Environment* 22 (2): 211–254.

Patten, O. 1981. “The Cybernetic Nature of Ecosystems.” *American Naturalist* 118: 886–895.

Pendall, R. K., A. Foster, and M. Cowell. 2010. “Resilience and Regions: Building Understanding of the Metaphor.” *Cambridge Journal of Regions, Economy and Society* 3 (1): 71–84.

Perez-Sanchez, L., M. Giampietro, R. Velasco-Fernandez, and M. Ripa. 2019. “Characterizing the Metabolic Pattern of Urban Systems Using MuSIASEM: The Case of Barcelona.” *Energy Policy* 124: 13–22.

Peterson, G. Green Art – from Collapse to Resilience? 2011.

Pincett, S., P. M. E. Bunje, and T. Holmes. 2012. “An Expanded Urban Metabolism Method: Toward a Systems Approach for Assessing Urban Energy Processes and Causes.” *Landscape and Urban Planning* 107: 193–202.

Pothen, F., and M. A. Tovar Reaños. 2018. “The Distribution of Material Footprints in Germany.” *Ecological Economics* 153: 237–251.

Programme UNE. Global Material Flows and Resource Productivity. 2016.

Pulido Barrera, P., J. Rosales Carreón, and H. J. de Boer. 2018. “A Multi-level Framework for Metabolism in Urban Energy Systems from an Ecological Perspective.” *Resources, Conservation and Recycling* 132: 230–238.

Qi, W., X. Deng, X. Chu, C. Zhao, and F. Zhang. 2017. “Emergy Analysis on Urban Metabolism by Counties in Beijing.” *Physics and Chemistry of the Earth, Parts A/B/C* 101: 157–165.

Ribeiro, P. J. G., and L. Goncalves. 2019. “Urban Resilience: A Conceptual Framework.” *Sustainable Cities and Society* 50: 11.

Rodríguez-Huerta, E., M. Rosas-Casals, and L. M. Hernández-Terrones. 2019. “Water Societal Metabolism in the Yucatan Peninsula. The Impact of Climate Change on the Recharge of groundwater by 2030.” *Journal of Cleaner Production* 235: 272–287.

Rosado, L., Y. Kalmykova, and J. Patricio. 2016. “Urban Metabolism Profiles. An Empirical Analysis of the Material Flow Characteristics of Three Metropolitan Areas in Sweden.” *Journal of Cleaner Production* 126: 206–217.

Rueda, S., J. M. Alier, A. Sanz, A. Oliveres, F. Magrinjá, F. Cárdenas, P. Cabrera, X. Monclús, J. Figueras, and M. Olivella. 1999. *La ciutat sostenible: un procés de transformació*. Universitat de Girona.

Sala, S., B. Cluloff, and P. Nijkamp. 2015. “A Systemic Framework for Sustainability Assessment.” *Ecological Economics* 119: 314–325.

Salvia, M., S. D. Leo, C. Nakos, H. Maras, S. Panevski, O. Fülöp, S. Papagianni, Z. Tarevska, D. Čeh, E. Szabó, et al. 2015. “Creating a Sustainable and Resource Efficient Future: A Methodological Toolkit for Municipalities.” *Renewable and Sustainable Energy Reviews* 50:480–496.

Santana, N. B. 2014. “Aparecida Do Nascimento Rebelato D, Périco AE, Mariano EB. Sustainable Development in the BRICS Countries: An Efficiency Analysis by Data Envelopment.” *International Journal of Sustainable Development & World Ecology* 21 (3): 259–272.

Seitzinger, S. P., U. Svedin, C. L. Crumley, W. Steffen, S. A. Abdullah, C. Alfsen, W. J. Broadgate, F. Biermann, N. R. Bondre, J. A. Dearing, et al. 2012. “Planetary Stewardship in an Urbanizing World: Beyond City Limits.” *Ambio* 41 (8): 787–794.

Sennett, R. 1996. *Flesh and Stone: The Body and the City in Western Civilization*. Revised ed. New York, NY: W. W. Norton & Company.

Setto, K. C., A. Reenberg, C. G. Boone, M. Fragkiadis, D. Haase, T. Langanke, P. Marcutullio, D. K. Munroe, B. Olah, and D.
Wassenaar, 2012. “Urban Land Teleconnections and Sustainability.” Proceedings of the National Academy of Sciences 109 (20): 7687–7692.
Smit, S., J. K. Musango, Z. Kovacic, and A. C. Brent. 2018. “Towards Measuring the Informal City: A Societal Metabolism Approach.” Journal of Industrial Ecology 23 (3): 674–685.
Sorman, A. H., and M. Giampietro. 2011. “Generating Better Energy Indicators: Addressing the Existence of Multiple Scales and Multiple Dimensions.” Ecological Modelling 223 (1): 41–53.
Stanhill, G. 1976. “An Urban Agro-ecosystem: The Example of Nineteenth-century Paris.” Agro-Ecosystems 3: 269–284.
Tainter, J. A. 2003. The Collapse of Complex Societies. New York: Cambridge University Press.
Tan, R. B. H., and H. H. Khoo. 2005. “An LCA Study of a Primary Aluminum Supply Chain.” Journal of Cleaner Production 13 (6): 607–618.
Tello, E., and J. R. Ostos. 2012. “Water Consumption in Barcelona and Its Regional Environmental Imprint: A Long-term History (1717–2008).” Regional Environmental Change 12 (2): 347–361.
UN-DESA. 2018. Population Division: World Urbanization Prospects 2018.
United Nations. 2009. System of national accounts 2008. New York: United Nations.
United Nations. 2011. National Accounts Main Aggregates Database (United Nations Statistics Division, New York).
United Nations U. 2015. Transforming our world: the 2030 Agenda for Sustainable Development.
Velasco-Fernández, R., J. Ramos-Martin, and M. Giampietro. 2015. “The Energy Metabolism of China and India between 1971 and 2010: Studying the bifurcation.” Renewable and Sustainable Energy Reviews 41: 1052–1066.
Velasco-Fernández, R., M. Giampietro, and S. G. F. Bukkens. 2018. “Analyzing the Energy Performance of Manufacturing across Levels Using the End-use Matrix.” Energy 161: 559–572.
Vergragt, P. J., L. Dendler, M. de Jong, and K. Matus. 2016. “Transitions to Sustainable Consumption and Production in Cities.” Journal of Cleaner Production 134: 1–12.
Wallace, D., and R. Wallace. 2008. “Urban Systems during Disasters: Factors for Resilience.” Ecology and Society 13 (1): 18.
Wang, X., S. Wu, and S. Li. 2017. “Urban Metabolism of Three Cities in Jing-Jin-Ji Urban Agglomeration, China: Using the MuSIASEM Approach.” Sustainability 9 (8): 1481.
Wassenaar, T. 2015. “Reconsidering Industrial Metabolism: From Analogy to Denoting Actuality.” Journal of Industrial Ecology 19 (5): 715–727.
Weisz, H. 2011. “The Probability of the Improbable: Society–nature Coevolution.” Geografiska Annaler. Series B, Human Geography 93 (4): 325–336.
Wheeler, S. M., and T. Beatley. 2014. Sustainable Urban Development Reader. New York, NY: Routledge.
Wiesen, K., and M. Wirges. 2017. “From Cumulated Energy Demand to Cumulated Raw Material Demand: The Material Footprint as a Sum Parameter in Life Cycle Assessment.” Energy, Sustainability and Society 7: 13.
Wilbanks, T. J. 2007. “Scale and Sustainability.” Climate Policy 7 (4): 278–287.
Wolman, A. 1965. “The Metabolism of Cities.” Scientific American 213 (3): 179–190.
Woo, C., Y. Chung, D. Chun, H. Seo, and S. Hong. 2015. “The Static and Dynamic Environmental Efficiency of Renewable Energy: A Malmquist Index Analysis of OECD Countries.” Renewable and Sustainable Energy Reviews 47: 367–376.
Wu, J., and O. L. Loucks. 1995. “From Balance of Nature to Hierarchical Patch Dynamics: A Paradigm Shift in Ecology.” Quarterly Review of Biology 70: 439–466.
Xian, C. F., and Z. Y. Ouyang. 2014. “Urban Ecosystem Nitrogen Metabolism: Research Progress.” Shengtaixue Zazhi 33 (9): 2548–2557.
Young, O.R. 2002. The Institutional Dimensions of Environmental Change: Fit, Interplay, Scale. Cambridge, MA: MIT Press.
Yuan, Z., J. Shi, H. Wu, L. Zhang, and J. Bi. 2011. “Understanding the Anthropogenic Phosphorus Pathway with Substance Flow Analysis at the City Level.” Journal of Environmental Management 92 (8): 2021–2028.
Zhang, Y. 2013. “Urban Metabolism: A Review of Research Methodologies.” Environmental Pollution 178: 463–473.
Zhang, Y., Z. Yang, and W. Li. 2006. “Analyses of Urban Ecosystem Based on Information Entropy.” Ecological Modelling 197 (1): 1–12.
Zhang, Y., Z. Yang, and X. Yu. 2009. “Ecological Network and Emergy Analysis of Urban Metallic Systems: Model Development, and a Case Study of Four Chinese Cities.” Ecological Modelling 220 (11): 1431–1442.
Zhang, Y., Z. Yang, and X. Yu. 2015. “Urban Metabolism: A Review of Current Knowledge and Directions for Future Study.” Environmental Science & Technology 49 (19): 11247–11263.
Zucchetto, J. 1975. “Energy-economic Theory and Mathematical Models for Combining the Systems of Man and Nature, Case Study: The Urban Region of Miami, Florida.” Ecological Modelling 1: 241–268.