

Urban Metabolism: A review of recent literature on the subject

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Abstract

Urban areas are the primary habitat for a majority of the global population. The development of cities not only entails a fundamental change in human settlement patterns but also a dramatic transformation of the physical environment. Thus, urban areas and their development are at the centre of all discussions on sustainability and/or sustainable development. This review essay introduces the notion of Urban Metabolism (UM), a term that provides a conceptual framework to study how a city functions, and hence, a way to address the sustainability issue of a city. Due to the significance and scope of the subject, the notion of UM is interpreted and thus approached differently across diverse disciplines from both the natural and social science fields. In order to comprehend the commonalities and controversies between them, the present review also briefly introduces the historical roots of the term. This review reveals the increasing significance of a rich and rapidly evolving field of research on the metabolism of urban areas.

Keywords: urban metabolism; city; sustainability; sustainable development; environment; fields of discipline.

Resum. *Metabolisme urbà: una revisió de la literatura recent sobre el tema*

Les àrees urbanes són el principal hàbitat de la majoria de la població mundial. El desenvolupament de les ciutats no sols implica un canvi essencial en els patrons d'assentament humans, sinó també una dramàtica transformació del medi físic. D'aquí que tant les àrees urbanes com el seu desenvolupament esdevinguin el tema central de tots els debats sobre sostenibilitat i desenvolupament sostenible. Aquest assaig introdueix la noció del meta-

bolisme urbà (MU), un terme que proporciona un marc conceptual per a l'estudi del funcionament de les ciutats i, en conseqüència, una aproximació a l'anàlisi de la sostenibilitat d'aquestes. Tant la importància com l'abast del tema deriven cap a formes diverses d'interpretar i, per tant, d'aplicar el concepte del MU a través de les diferents disciplines dels camps de coneixement de les ciències naturals i socials. Amb l'objectiu de comprendre les similituds i controvèrsies entre aquestes, la present revisió també exposa breument les arrels històriques del terme. Aquesta revisió posa de manifest la importància creixent d'un camp de recerca sobre el metabolisme de les àrees urbanes immerses en una abundant, fèrtil i ràpida evolució.

Paraules clau: metabolisme urbà; ciutat; sostenibilitat; desenvolupament sostenible; medi ambient; disciplines del coneixement.

Resumen. *Metabolismo urbano: una revisión de la literatura reciente sobre el tema*

Las áreas urbanas son el principal hábitat de la mayoría de la población mundial. El desarrollo de las ciudades no solo implica un cambio fundamental en los patrones de asentamiento humano, sino también una dramática transformación del entorno físico. Es por ello que tanto las áreas urbanas como su desarrollo se encuentran en el centro de todas las discusiones sobre sostenibilidad y desarrollo sostenible. Este ensayo introduce la noción de metabolismo urbano (MU), un término que proporciona un marco conceptual para el estudio del funcionamiento de las ciudades y, consecuentemente, una aproximación al análisis de la sostenibilidad de las mismas. Tanto la importancia como el alcance del tema derivan en formas distintas de interpretar y, por tanto, de aplicar la noción del MU a través de distintas disciplinas pertenecientes a los campos de las ciencias naturales y sociales. Con el fin de comprender las similitudes y las controversias entre las mismas, la presente revisión también expone brevemente las raíces históricas del término. Esta revisión pone de manifiesto la importancia creciente de un campo de investigación sobre el metabolismo de las zonas urbanas inmerso en una abundante, fértil y rápida evolución.

Palabras clave: metabolismo urbano; ciudad; sostenibilidad; desarrollo sostenible; medio ambiente; disciplinas de conocimiento.

Résumé. *Métabolisme urbain: Un examen de la littérature récente sur le sujet*

Les zones urbaines constituent l'habitat principal de la majorité de la population mondiale. Le développement des villes implique non seulement un changement fondamental dans les schémas d'établissement humain, mais aussi une transformation radicale de l'environnement physique. C'est pourquoi les zones urbaines et leur développement sont au centre de toutes les discussions sur le développement durable. Cet article introduit la notion de métabolisme urbain (MU), un terme qui fournit un cadre conceptuel pour l'étude du fonctionnement des villes et par conséquent, une approche de l'analyse de la viabilité de ce concept. En raison de l'importance et la portée du sujet, la notion de MU est interprété, et donc abordé, différemment selon les disciplines appartenant aussi bien aux domaines des sciences naturelles et qu'à celui des sciences sociales. Afin de comprendre les similitudes et les controverses entre ces dernières, cet article expose également brièvement les racines historiques du terme. Cet examen met en évidence l'importance croissante d'un domaine de recherche portant sur le métabolisme des zones urbaines, plongé dans une évolution rapide, riche et fertile.

Mots-clé: métabolisme urbain; ville; développement durable; environnement; disciplines de la connaissance.

Summary

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Introduction and background¹

Cities are the primary habitat for a fast-increasing majority of the global population. Modern urban growth, beginning in the 19th and early 20th centuries in Europe and America as a result of the spread of industrialization and the associated rapid increase in the use of fossil fuels, is now a common trend all over the world (Girardet, 1996).

Cities have grown dramatically not only in size and density but complexity across the globe. This growing complexity is associated with their social structures, economic systems, geopolitical settings, and the evolution of technology (Decker et al., 2000; Kennedy et al., 2007; Satterthwaite, 2007).

According to the United Nations, over half of the world's population lives today in urban areas (UN-WUP-2011), and by 2030 this figure is estimated to increase to 60% (Decker et al., 2000). Urban areas in low- and middle-income nations will absorb most of the world's population growth between now and 2020 (Satterthwaite, 2007). Moreover, the majority of this urban population is located in coastal zones or in zones with a distinct coastal influence (Glasow et al., 2013). Recent studies show that low elevation coastal zones², although accounting for only about 2% of the world's land area, contain about 10% of the world's population and 13% of the world's urban population. On average, developing countries have a higher share of their population living in coastal lowlands (14%) than OECD countries (10%), with even greater disparities in the urban sphere (21% compared to 11%). Furthermore, urban settlements in coastal lowlands are densely settled and expand very rapidly (McGranahan et al., 2007).

In the Mediterranean region, more than one third of the population lives in coastal administrative entities totalling less than 12% of the surface area of the Mediterranean countries. The concentration of population in the coastal zone is higher in the southern countries than in the northern shores of the basin (UNEP/MAP, 2012).

1. The work carried out by the authors of Broto et al. (2012) and Rapoport (2011) was particularly useful for the writing of this review.
2. According to McGranahan et al. (2007), the Low Elevation Coastal Zone is defined as a contiguous zone along the coast less than 10m above sea level.

The development of cities represents a fundamental change in human settlement patterns and entails a dramatic transformation of the physical environment (Hosier, 1993).

On a global scale, urban settlements occupying 2% of the world's land surface use over three-quarters of the world's resources and discharge similar amounts of wastes to the environment (Baccini, 1997; Barles, 2010; Girardet, 1996). Hence, cities are not only important drivers for socio-economic development, but also sources of human pressures on ecosystems because of the environmental consequences associated with their development (Glasow et al., 2013; Sekovski et al., 2012; UNEP/MAP, 2012). As population density and economic activity increase, so do pressures on the structure and function of ecosystems and on the services provided by them (Bai, 2007; Decker et al., 2000; Huang et al., 2012; Niza et al., 2009). But cities also offer important economies of scale accommodating large numbers of people in a limited space and providing them with jobs, housing, and services (Girardet, 1996; Satterthwaite, 2007). Hence, the effective management of the environment and of the impact of cities on the wider environment is critical for a large proportion of the world's population.

Since cities play a significant role in the world's major environmental agenda, they also need to be part of the global problem-solving process (Girardet, 1996). Accordingly, urban areas and their development are at the centre of all discussions on sustainability and/or sustainable development (Baccini, 1997), the latter understood as development without increase in the throughput of materials and energy beyond the Earth's carrying capacity for regeneration and waste assimilation (Goodland and Daly, 1996). Yet, urban areas remain largely unrecognised as agents in the flow of energy and materials, and therefore remain grossly understudied (Barles, 2010; Decker et al., 2000). Likewise, their local, global and differed impacts in both space and time are also poorly recognised (Barles, 2010). In addition, although at least some urban metabolism (UM) studies at regional-local level exist (e.g. Kennedy et al., 2007; Niza et al., 2009; Browne et al., 2009) the literature is dominated by case studies from developed countries.

For cities to increase compatibility with the surrounding environment, first, a clear understanding of the functioning and processes of the urban system, and the impacts and implications of urban lifestyles (in terms of consumption and discharge patterns) is essential to face the social, environmental, and economic challenges of the near future and to manage the urban environment in a way that is more compatible with its hinterlands (Baccini, 1997; Decker et al., 2000; Girardet, 1996).

Therefore, there is an urgent demand to gain a better understanding of cities' functions, states and needs in order to achieve more circular urban systems. A concept that addresses this claiming demand is urban metabolism. UM provides a conceptual framework to study how a city operates and is constituted and therefore, is a means of assessing the impact performance of a city, a region, or a country.

This review attempts to reveal the increasing significance of UM as a rich and rapidly evolving field of research on urban environments. First, the concept of urban metabolism is introduced in general terms to continue with the concept's historical roots or intellectual antecedents. From here we move on to identify and present the diverse approaches on UM, as applied by different disciplines to study the performance of cities. Finally, the paper ends by focusing on the most widely used approach of UM today, i.e. the biophysical perspective, to briefly expose the diversity of methodologies used when studying the city.

What does urban metabolism mean? A historical perspective of the concept

The concept of urban metabolism has been used, in recent years, as a way of enhancing our understanding of the way in which environmental, social and economic factors interact to shape urban phenomena and processes. Thus, UM can be a productive and useful way to conceptualize how urban areas function, and a valuable concept for understanding urban processes and the relations between society and nature in urban areas (Rapoport, 2011).

Concerns about UM are not entirely new and, after having been overlooked for many years, have once again become central in urban environmental matters (Barles, 2010). The term "metabolism", developed in the early 19th century to characterize chemical changes within living cells, was broadly applied in the following fifty years, in the field of biology and in what would become biochemistry, to represent processes of organic breakdown and combination, within individual organisms (at a cellular scale) and between organisms and their environment. Ever since, metabolism has lived a dual existence in the natural sciences, applying both to processes through which bodies change and reproduce themselves and to more holistic conceptions of ecosystem relations (Fischer-Kowalski, 1998; Foster, 1999; Wachsmuth, 2012).

In the 1970s, the ecological approach to UM was largely influenced by H.T. Odum's (1983) conceptualization of energy flows. H.T. Odum, working in the field of systems ecology, pioneered the application of the notion of biological metabolism to describe metabolism in terms of solar energy equivalents (or *eMergy*) (Holmes and Pincetl, 2012). The entire ecosystem was taken as a unit of analysis, in order to study and model an entity, its environment, and the interactions between the two (Rapoport, 2011). H.T. Odum's *eMergy* analysis represents an attempt to apply a biophysical value theory to both ecological and economic systems to study the energetic flows in the metabolism of socio-economic systems (Holmes and Pincetl, 2012), since it recognizes the variation in the quality of different forms of energy (fuels, electricity, solar) that accomplish different amounts of work. This is based on H.T. Odum's (1996) claim that the different types of energy flows are organized in an energy transformation hierarchy, *Transformity*, which measures energy quality. This argument connects with the entropy concept, understood as a measure of

dispersion, determined by the second law of thermodynamics. Hence, solar energy equivalents are used as a universal metric (Kennedy et al., 2011).

However, long before H.T. Odum, urban metabolism in the 19th century, although not using the term at the time, was applied by agricultural chemists to understand the cycle of organic matter and nutrients in order to encourage exchanges between the city and agriculture, that is, by using urban population excreta from cities as a new agricultural fertilization source in the production of food (Barles, 2010). The fertiliser revolution and the mobilization of new raw materials that made urban excreta useless led to the end of this peculiar form of urban chemistry, but at the same time, paved the way for urban metabolism (Barles, 2010). Thus, the biological concept of metabolism has influenced understandings of, and approaches to, urban metabolism in urban ecology, industrial ecology and ecological economics (Rapoport, 2011).

Also in the 19th century, the concept of metabolism entered the social sciences via Karl Marx. Marx had been influenced by Justus von Liebig, a German soil chemist who used the concept of metabolism to describe the material exchanges and interdependent relationships between human society and nature (Fischer-Kowalski, 1998; Martínez-Alier, 1987; Wachsmuth, 2012). It was in this sense that Marx's use of the expression "metabolism between man and earth" referred specifically to the cycles of plant nutrients (Martínez-Alier, 1987: 220-221) in terms of fertility conditions, agricultural production systems and urbanization. By applying the notion of UM, Marx described first the human transformation of nature through the labour process, and secondly the capitalist system of commodity exchange. Marx was also first to use the concept of social metabolism to question the apparent separation between human beings and their environment, the society-nature duality, which Marx coined as "metabolic rift" (Wachsmuth, 2012). The term "metabolic rift" comprises the characterization of the social and environmental implications of industrial agriculture and urbanization, referring to the notion that human beings in capitalist society have become estranged from the natural conditions of their existence (Foster, 1999).

Specifically, Marx regarded urbanization as a key process leading to "metabolic rift" because of the reduced interaction between humans and the Earth resulting from the migration of people from rural to urban areas or because of the growth in long-distance trade in food and clothing (Martínez-Alier, 1987; Wachsmuth, 2012). The implication of this perspective is that environmental crises unfold in relation to historical and spatial patterns of inequality that, in the context of increasing urbanization, manifest themselves within the city (Broto et al., 2012). In short, Marxian conceptions of metabolism have influenced understandings of, and approaches to urban metabolism in the fields of ecological economics, political ecology and urban political ecology (Rapoport, 2011).

With reference to the concept of metabolism applied to the economy, according to Martínez-Alier (2004, 2013) the first precursors appeared at the end of the 19th century. Podolinsky's work on agricultural energy flows and

Marx's and Engels' interest in the interactions between the human economy and the natural environment, both expressed the concept of metabolism. In this sense, the significance of identifying and tracing physical flows of material and energy through the human economy has been recognized for several decades (Ayres and Kneese 1968, 1969; Georgescu-Roegen, 1971; Leontief 1970, 2002; Wolman 1965).

In 1965, the engineer and geographer Abel Wolman published the first explicit application of the metabolism concept to the urban sphere. Wolman modelled the metabolism of a hypothetical American city of one million people in response to deteriorating air and water quality, and used metabolism as a method of analysing cities and communities through the quantification of inputs –water, food, and fuel, and outputs –sewage, solid refuse and air pollutants, while tracking their respective transformations and flows. Wolman defined metabolic needs as “all the materials and commodities needed to sustain the city's inhabitants at home, at work and at play” (Wolman, 1965:179; Decker et al., 2000; Kennedy et al., 2007).

A wave of empirical studies of the metabolism of various cities ensued (Boyden et al., 1981; Duvigneaus and Denaeyer-De Smet, 1977; Hanya and Ambe, 1976; Newcombe et al., 1978). After this initial popularity, several decades elapsed before a renewed interest in urban metabolism was expressed, in the late 1990s, within the context of two emerging concerns: first, the capacity of the planet to feed and maintain a growing population and, second, the destructive power of humans due to the Earth's finite, limited and unique characteristics (Barles, 2010; Kennedy et al., 2007; Rapoport, 2011). The study by Kennedy et al. (2011) presents a chronological review of some 15-20 comprehensive studies on UM, in addition to numerous related studies, from the first study by Wolman in 1965 to the current period. Likewise, Zhang (2013) presents a review of UM studies applied to cities, and introduces studies on UM approached from different perspectives such as the expanding field of household or community metabolism (Moll et al., 2005; Liu et al., 2011).

Therefore, contemporary work employing the concept of UM tends to draw on either biophysical or political economy sciences. Additionally, different disciplines in their diverse approaches to UM, draw on various branches of systems theory (Gandy, 2004; Rapoport, 2011). While UM studies in the fields of ecological economics and industrial ecology rely on thermodynamics, world system analysis, initially developed by Immanuel Wallerstein (1974), is the basis for ecological economics and to a lesser degree for political ecology. Likewise, urban ecologists draw on complex systems theory (Rapoport, 2011).

Contemporary understandings of urban metabolism

As introduced in the previous section, the notion of UM is understood and employed differently across the disciplines of urban ecology, industrial ecology, ecological economics, political ecology and urban political ecology. It

must be emphasized that the writing of this section has been fundamentally based on Broto et al. (2012) and Rapoport (2011). Thus, this section briefly introduces the most prominent interpretations of UM by the five disciplines (see also table 1 as a summary).

As Broto et al. (2012) and Rapoport (2011) state, urban ecology understands *the city as an ecosystem* in the biological sense, seeing the city as both a 'system' and a 'natural' entity. The concept of UM is loosely based on an analogy with the metabolism of organisms. Cities are similar to organisms in that they consume resources from their surroundings and excrete wastes outwards (Decker et al., 2000; Kennedy et al., 2011). The city is seen as an ecosystem embedded in a larger system, and the metabolism notion is used to describe the interactions between the numerous subsystems of an urban region, in an attempt to understand how cities process energy or matter in relation to their surroundings. Hence, the application of a systemic approach to the analysis of human-environment relations enables the full complexity of urban systems to be effectively captured and interpreted (Broto et al., 2012).

Accordingly, urban ecologist proponents argue that by emulating the cyclical and efficient nature of natural ecosystems, that is, by shifting from a linear to a circular metabolism, in which outputs are recycled back into the system to become inputs, urban settlements will become viable and sustainable in the long term (Rapoport, 2011).

However, it is important to note Golubiewski's (2012) observation questioning the suitability of the UM framework in applying the concept of the city as a biophysical system. By underlining the essentials of both foundational ecology and biology disciplines, she unveils "a weakness of UM as the tendency to conflate organism and ecosystem, often using the terms interchangeably" (Golubiewski, 2012:757). Hence, by drawing parallels with the biology of individual organisms, UM inconsistently applies the analogy that "has the effect at times of conflating concepts, limiting analyses, or fostering misleading interpretations" (Golubiewski, 2012:757).

In this vein, a group of scholars working in the subdiscipline of systems ecology have developed research to understand *cities as socio-ecological systems*, i.e. urban ecosystems (Golubiewski, 2012). According to these scholars, working from complex system theory, "urban ecosystems are complex, dynamic biological-physical-social entities, in which spatial heterogeneity and spatially localized feedbacks play a large role" (Pickett et al., 2008:148). There is an attempt, therefore, to understand complex systems approaching system dynamics from different perspectives, such as eMergy or solar energy equivalents (H.T. Odum, 1996), Network theory (Fath et al., 2007; Ulanowicz, 1987), Hierarchy Theory (Allen and Starr, 1982; Zellmer et al., 2006) and complexity and Thermodynamics (Schneider and Kay, 1994). Likewise, the work by Giampietro et al. (2009) has contributed to the metabolic studies from the perspective of complex systems theory.

Broto et al. (2012) and Rapoport (2011) associate the notion of UM developed in industrial ecology with the analysis of *material and energy flows*

in the city. UM studies in this field focus on quantifying the flow of particular materials and/or energy in an urban system. The goal is to optimize metabolism with the final aim of making cities less dependent on their wider hinterlands, since being self-sufficient, in terms of resource generation and waste disposal, is considered the hallmark of a sustainable UM (Barles, 2010; Baccini, 1997; Brunner, 2007). Though the aim is similar to that pursued by urban ecologists, the rationale behind the approach of industrial ecologists is that, through the systematic recording of all physical flows to and from an urban area, it becomes possible to describe the relationship between the environment and an urban system (Rapoport, 2011). The lack and the imperative need to systematically account for physical flows through the economy have also been advocated by ecological economists (Murray et al., 2005; Naredo, 2006; Carpintero, 2005).

By optimizing economy-environment relations, or their metabolism, industrial ecologists attempt to identify and reduce the loss of materials in order to lessen environmental impacts, and to develop symbioses by shifting from a linear to a circular metabolism. In other words, the discipline seeks to develop methods that improve metabolic efficiency or to reduce the amount of resources used per unit of economic output. This is a process usually referred to as *dematerialization or decoupling* (Carpintero, 2005). At this point, industrial ecologists and ecological economists share the interest in the relationship between economic growth and resource consumption, by applying the same notion as *the material basis of the economy* (Adriaanse et al., 1997; Carpintero, 2005; Broto et al., 2012; Naredo, 2006).

In this regard, ecological economists use UM to analyse potential existing measures to break the links between urbanisation, economic growth and resource consumption with the focus of concern on depletion of natural resources and environmental damage (Carpintero, 2005; Naredo, 2006; Rapoport, 2011).

However, ecological economics differs significantly from the industrial ecology discipline in the way in which it draws on the use of systems theory. Here, the notion of metabolism is applied to a view of an economic sector that is subject to the laws of thermodynamics (Rapoport, 2011). In other words, the metabolism idea is related to the hegemony of the laws of thermodynamics on economic flows (Broto et al., 2012). Quoting Daly and Farley (2004:70) the economy is seen as embedded in an “ordered system for transforming low-entropy raw materials and energy into high-entropy waste and unavailable energy. The urban is presented as a key form of organization of the current economic system”.

In the research debate on how to break the link between urbanization, economic growth and resource consumption, a group of ecological economic scholars who regard the unending capital accumulation as the main cause of continued resource depletion and environmental damage, advocate for alternative models to dematerialization theories: the steady-state economy (Czech and Daly, 2004) and de-growth theory (Martínez-Alier et al., 2010b; Schneider et al., 2010).

The steady-state economy as presented in Czech and Daly (2004) entails an economy that undergoes neither growth nor recession, but finds a stable size at a stable level of throughput, consistent with the ecological principle of carrying capacity, and dependent on technological progress to increase the efficiency ratio of production throughput.

De-growth theories according to Schneider et al. (2010:512) propose “an equitable downscaling of production and consumption that increases human well-being and enhances ecological conditions at the local and global level, in the short and long term”, or actually limiting the scale of production and consumption.

The ecological economics and political ecology disciplines share a common interest in the unequal social and ecological distributional flows and structural inequalities that unfold with the functioning of cities. However, their particular focus of concern differs, creating and applying different conceptions of UM. These scholars relate urban agglomeration resource demands to the structural inequalities and ecological conflicts occurring in the world regions supplying these resources (Hornborg, 1998; Martínez-Alier, 2009).

Within ecological economics there is some interest in studying *the economic drivers of rural-urban relationships*, as named by Broto et al. (2012). However, when building on world systems theory, two slightly different perspectives appear.

The first perspective seeks to explain the connections between urban flows and inequality by supporting the idea that cities are both centres of capital accumulation and dissipative structures or systems sustained through increasing resource exchanges with their peripheral environments (usually corresponding to rural underdeveloped regions). This ever-increasing exchange process reveals in itself the main cause of the creation of continual structural inequalities between urban areas and their periphery in the world system (Broto et al., 2012). As Broto et al. (2012) explain, in this approach UM is applied to analyse the way in which urban areas impact upon and are impacted by broader global systems. Therefore, the underlying ecological conditions of human economies determine this unequal distribution of resources. This relates to and builds on Harvey’s proposals of the “uneven geographical development” of capitalism (1982:373), which emphasizes the significance of the politics of space and the role of space in social reproduction, mainly in the urban context, as well as the property rights in land markets shaping the physical landscape of spatial accumulation driven by the capitalist mode of production.

The second perspective departs from the idea that the fast increasing metabolism of cities, that is, their enlarging constant demand for resources and generation of waste, is related to the proliferating number of ecological conflicts in “commodity frontiers”, commonly situated far from cities (Martínez-Alier et al., 2010a). Since urban metabolic processes rely on areas beyond their boundaries, these processes produce and reproduce inequality through conflicts around the social and environmental costs of resource extraction (Broto et al., 2012). Therefore, as suggested by Martínez-Alier (2010a:153), the metabolism

analysis should focus on “the manner in which human societies organize their growing exchanges of energy and materials with the environment”.

An alternative debate, —by proponents from the urban ecology and ecological economic disciplines— which follows the ecology argumentation and builds on complex systems theory, seeks to understand *cities as socio-ecological systems*, whose processes are influenced by human agents and socio-economic factors (Golubiewski, 2012). This approach advocates for metabolism studies that not only elucidate the magnitude of the heterotrophy of the city, but contextualize the city’s consumption of resources within the analysis of the structures (agents or funds) using these flows, and the functions performed by the consumption of these flows, i.e. the purpose of this consumption (Sorman and Giampietro, 2012). Therefore, these approaches not only analyse the external constraints, namely supply and sink side limits, but also “study the internal relation of structures and functions associated with the metabolic pattern of society” (Sorman and Giampietro, 2012: 4).

Furthermore, political ecologists and political geographers interested in social and distribution impacts in cities, analyse the urban inequality of material and nonmaterial flows, and the role that infrastructure networks and spatial patterns of urbanization have in creating and reproducing patterns of urban inequality within the city (Broto et al., 2012; Monstadt, 2009).

An inferred suggestion from these types of studies is that different parallel metabolisms for the same resource might coexist in the same city. For example, water may be supplied by networked infrastructure to the urban elite but also by water vendors to poor urban citizens with limited access to water supply networks (Bakker, 2003a). Thus, infrastructure networks are central to the understanding of metabolic circulation in cities, since through their analysis, socioeconomic inequalities may be disclosed (Broto et al., 2012).

In association with studying the impact of urban flows on inequality the analysis of their governance, and/or control also becomes relevant. That is, understanding how power relationships shape urban flows and how urban flows are influenced by broader social power relationships (March, 2013; Rapoport, 2011). In this sense, the control of metabolic flows is essential for the reproduction of structures of power (Broto et al., 2012).

Urban political ecologists focus on understanding the way in which urban metabolic flows and the networks that mediate them are controlled by and socially mobilized to serve particular purposes, usually in the interest of the elite to achieve or maintain social power positions, and often at the expense of marginalised populations (Otero et al., 2011; Swyngedouw and Heynen, 2003). This work has displayed the role of politics, the urban elite, neoliberal reforms and international finance institutions in governing urban resource flows (Bakker, 2003b; Broto et al., 2012; March and Saurí, 2013; Otero et al., 2011). In addition, governance that commands individuals and institutions on urban flows may be contested or subverted by daily practices of individuals and groups and local political economies of cities, and hence also requires an analysis (Bulkeley et al., 2011 in Broto et al., 2012; Monstadt, 2007). Nevertheless,

Table 1. Contemporary interpretations and current debates on the concept of urban metabolism across different disciplines from biophysical and political economy sciences

Interpretations/ current debates	Discipline				
	Urban Ecology	Industrial Ecology	Ecological Economics	Political Ecology	Political Geography
The city as an ecosystem	X				
The city as material and energy flow or material and energy flows in the city		X			
The material basis of the economy, or breaking the links between urbanization, economic growth and resource consumption		X	X		
The city as a socio-ecological system	X		X		
Economic drivers of rural-urban relationships, and the production and reproduction of inequality			X	X	
The reproduction of urban inequality and the governance of urban flows			X	X	
Resignifying the city: urban metabolism and social, technical and ecological relationships				X	X

Source: author's elaboration mainly from Broto et al. (2012) and Rapoport (2011).

understanding the way in which these infrastructure networks reproduce power structures is particularly complex since in modern cities many networks are out of sight and therefore invisible to citizens (Kaika and Swyngedouw, 2000).

Political ecologists and urban political ecology scholars, assuming the notion of the interdependence between ecosystem function and human activity, particularly in urban areas, build on the idea that resource flows interact reflexively with the social world to reimagine relations between social, technical, economic, and ecological forces in urban areas to hence create new conceptions of UM (Heynen et al., 2006; Swyngedouw, 2006). In doing so, they contribute to the idea of *resignifying the city* (Broto et al., 2012).

For political ecologists UM is conceived as consisting of a number of dynamic, interconnected, and mutually transformative physical and social processes (Heynen et al., 2006) whose flows are shaped by the historical context in which they emerge and the urban practices around them (Gandy, 2004). This conception of UM, built on Marx's idea of metabolism, explores the complex interweaving of social and biophysical processes occurring in cities that transform nature into commodities, and which produce new forms of nature (Gandy, 2004), emphasizing the conception of urbanization as the outcome of historical change by political contestation (Broto et al., 2012; Gandy, 2006).

From this perspective finally, urbanization is seen as “a process by which new and more complex relationships of society and nature are created” (Keil, 2003:729); or as defined by Swyngedouw (2006:35) “urbanization is conceived as a social process of transforming and reconfiguring nature”. Hence, a scientist model is replaced by a historically driven conception of urban nature which is rooted in the political dynamics of capitalist urbanization as a contested and multi-dimensional process of urban change (Gandy, 2004).

From this approach, the characterization of metabolism also adopts a critical political stance, since, despite being a process of exchanging resources, humans can control their input into this exchange. In this regard, a key remark is that metabolisms have the potential to express people’s drives, desires, and imaginations, but they do so in a dialectic way, that is, through the interplay of structure and agency (Swyngedouw, 2006). This reveals a large diversity in the mechanisms shaping these flows, which are seen as being shaped by a wide array of policies, designs, and management styles alongside forms of cultural production, routine interactions and everyday practices (Broto et al., 2012).

Yet, due to their inherent critical emphasis, the normative and practical applications of this approach are not as obvious as urban ecology and industrial ecology methods. The emphasis of these critical perspectives on UM is raising new questions, which require further theoretical development and methodological innovation through enhanced interdisciplinary dialogue on the future of sustainable cities (Broto et al., 2012).

Commonalities and controversies on urban metabolism

The notion that urban areas operate as metabolic systems has not only already made a significant impact on urban scholarship, but has also led to expanded conceptions and reconceptualizations of UM across different disciplinary fields (Rapoport, 2011).

Each disciplinary approach adds and contributes to the understanding of the relations and interactions between environmental, social and economic factors in shaping urban phenomenon (Rapoport, 2011). Actually, the analysis of the scholars’ work on UM, across the diverse range of disciplines, discloses shared common concerns, such as the relationships between social and natural systems, cities and their hinterlands (both immediate and global) and sustainability and social justice in urban areas (Rapoport, 2011).

Yet, the different disciplinary conceptions of UM introduce a set of analytical dilemmas about the crossing points between the sociopolitical and the biophysical dimensions of urban space (Gandy, 2004). Likewise, in an attempt to seek interdisciplinary approaches, confusion about or misuse of jargon and theory within multidisciplinary research, by making connections across disciplines, may foster misleading interpretations and prevent interdisciplinary problem-solving and knowledge-building research (Golubiewski, 2012:760). Besides, significant variation exists in the extent to which these different disciplinary perspectives proceed from theory into practice (Rapoport, 2011).

The prevailing interpretation of UM today is the biophysical quantitative and accounting perspective (Kennedy et al., 2011) measuring the exchange and transformation of energy and matter between a city and its environment (Moles et al., 2008). This interpretation draws mostly on approaches from the field of urban and industrial ecology which are seen as tools both for identifying environmental problems and designing more efficient urban planning policies (Baccini, 1997; Barles, 2009; Niza et al., 2009).

According to Holmes and Pincetl (2012), UM is defined as a multi-disciplinary and integrated platform that examines material and energy flow in cities, as they are shaped by various social, economic and environmental forces. Factors such as urban structure, form, climate, quality and age of building stock, urban vegetation and transportation technology can influence the rate of a city's metabolism. These studies contradict works that interpret UM in a political or qualitative historical context (Kennedy et al., 2011).

Major criticisms of urban and industrial ecology interpretation claim that though necessary, these quantitative and technological approaches are not sufficient. It is argued that these predominant conceptions of UM depoliticize the urban sphere, since they are unrelated to social and historical contexts, paying little attention to political changes as well (Gandy, 2004; Monstadt, 2009; Rapoport, 2011; Swynghedouw, 2006). In this regard, they fail to explain the changing nature of the contemporary city within an increasingly globalized urban system (Gandy, 2004) based on the underlying capitalist economy. Another objection insists on the shallowness of the analysis to provide the fundamentals for effective urban policy and planning interventions (Fischer-Kowalski and Hüttler, 1999). Yet another criticism observes the shortcomings in better integrating the spatial characteristics and their influence, and the lack of methods to perform long-term analyses (Rapoport, 2011). Therefore, criticisms of biophysical approaches primarily target the integration of sociopolitical and historical factors and spatial characteristics into urban metabolism analysis.

Alternatives to overcome the observed shortcomings comprise extending the metabolism model to consider the links between urban and environmental quality, urban drivers, patterns and lifestyles and metabolic flows (Minx et al., 2011 in Rapoport, 2011; Newman, 1999). Likewise, attempts are also made to better integrate the social aspects of and influences on material and energy flows, as well as to understand how spatial characteristics influence the relationship between the built environment and ecosystems (Barles, 2010; Rapoport, 2011).

Methodological approaches toward the biophysical notion of urban metabolism

Urban metabolism, involving 'big picture' quantification of the inputs, outputs and storage of energy, water, nutrients, materials and wastes for an urban region (Kennedy et al., 2011), can be a productive and useful way to concep-

tualise how urban areas function and to determine their spatial relationships with surrounding hinterlands and global resource webs (Rapoport, 2011; Kennedy et al., 2007). At the same time, UM studies can elucidate basic trends in human resource use (Decker et al., 2000), by analysing relevant energy and material pathways at different scales, which might lead to the design of adequate and more efficient urban planning policies towards a more circular pattern of UM, vital to sustainable development (Holmes and Pincetl, 2012; Moles et al., 2008; Niza et al., 2009).

Different methodological approaches are used to account for and analyse urban metabolic processes (Barles, 2010). The studies of Daniels (2002), Daniels and Moore (2002), Hammer et al. (2003), Loiseau et al. (2012), Huang et al. (2012) and Zhang (2013), provide a comprehensive review and a classification of both research methodologies and UM studies conducted through these different methods. Material Flow Analysis -MFA- (Brunner and Rechberger, 2004; Niza et al., 2009; Zhang et al., 2013), Substance Flow Analysis -SFA-(Antikainen et al., 2005), Input-Output analysis (and PIOT-physical input-output tables) (Liang et al., 2012), eMergy (energy flow) analysis (Huang et Hsu, 2003; Liu et al., 2011); Ecological footprint analysis (Holden, 2004; Muñiz and Galindo, 2005), Ecological network analysis (Li et al., 2012), MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism) (D'Alisa et al., 2012) and LCA -Life Cycle Analysis- (Chester et al, 2012), are among the main tools used to conduct physical environmental accounting, based on the study, in variable depths, of material and energy flows (Eurostat, 2001; Loiseau et al., 2012). The substantive use made of the organicist “analogies” of the human-environment relation, as well as the metabolic viewpoint closely linked to the acceptance of “material balance” principles, in which the modelling of material and energy flows is governed by the laws of conservation of matter and energy, are major features shared by most of these studies (Daniels and Moore, 2002; Barles, 2010). Yet, the significant internal variation across the above-mentioned metabolism techniques, from methodological to conceptual variations, makes integration difficult, and justifies the reason behind why a unique, clearly defined methodology with standard criteria and a consistent set of operational tools to conduct UM is still lacking (Daniels and Moore, 2002; Loiseau et al., 2012). Moreover, as Huang et al. (2012) observe, M/SFA applications continue to grow, and are increasingly combined with other research methods to analyse the increasingly complex material/substance flows resulting from socioeconomic development. Hence, in general terms, MFA provides the methodological groundwork, mostly because it is the primary methodological framework that offers great scope for the generic application and the harmonization, integration, and advancement of environmental accounting and systems analysis (Daniels and Moore, 2002). In most of these cases, the UM approach is primarily used as the basis of an accounting framework. Nevertheless, part of the methods introduced move beyond classic MFA-style analyses.

Furthermore, at a regional-local scale, a uniform and standardised methodology does not exist yet either (Hammer et al., 2003; Loiseau et al., 2012; Niza et al., 2009). Therefore, studies on a regional scale use previously published methods for assessing cities' circular metabolism patterns which necessarily required modifications and further improvements (Moles et al., 2008).

Conclusions

Urban areas sustain over half of the world's population today, and all future scenarios point towards an increase in this trend. The concentration of population and socioeconomic activities within a reduced geographic space not only entails important economies of scale but also pressure on the structure and function of ecosystems and on the services provided by them, potentially producing ecosystem impacts from the local to the global scale but varying both in space and time.

Therefore, for cities to alleviate their ecological and environmental impacts, the interactions between societies (i.e., their living patterns in terms of resource consumption and waste discharges) and the biosphere, considered two interdependent systems in co-evolution, need to reach a certain balance. Accordingly, the fundamental previous step is to create a better understanding of the processes, structures and functions of urban systems and the impacts and implications of urban lifestyles.

The notion of urban metabolism provides a conceptual framework to study how a city functions, and hence, a way to assess a city's compatibility with the surrounding environment. Nevertheless, different field disciplines from the social and natural sciences interpret and approach the concept differently, revealing the complexity and multiple dimensions of the same urban phenomenon, and point to the need for interdisciplinary dialogue to develop theoretical and practical approaches to urban metabolism with the aim of making progress in urban sustainability research.

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