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A multi-level framework for metabolism in urban energy systems from an ecological perspective

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ABSTRACT

Cities have become the main centres of consumption and transformation of resources. As cities are still growing in terms of physical size, number of inhabitants and total energy consumption, unique challenges present themselves in order to safeguard a healthy urban living environment, while preventing resource shortages and pollution. The concept of urban metabolism may contribute to sustainable growth of cities as it can be used to understand emergent patterns in flows of energy and materials in the urban environment. The concept of urban metabolism draws upon an analogy with the biological meaning of metabolism, as it occurs in organisms and ecosystems. Here we present a review of the interpretation of urban metabolism in the context of urban energy dynamics and assess the validity of the proposed analogy with biology. Based on this analogy, we propose a conceptual framework for the role of urban metabolism in urban energy systems. Our review highlights that urban energy systems show a hierarchical organization comparable to ecological systems. However, the emergent patterns that result from the dynamics within urban systems differ from those occurring within ecological systems. We suggest that, in contrast to biological systems, urban energy systems lack energetic constraints at the lowest level of organisation that could enable the resource-efficient regulation of energy requirements at larger scales. The proposed framework highlights that low-level resource supply regulations may contribute to introduce scale-dependent relationships that increase energy use efficiency as cities grow.

1. Introduction

Cities have become the key centres of consumption and transformation of resources. Nowadays, cities consume approximately 75% of global material resources and 80% of the global energy supply while generating approximately 50% of the world's waste and 75% of total carbon emissions (Gladek and Van Odijk, 2014; Swilling and Annecke, 2012). Urban living is becoming the dominant life style globally: since 2007 more people are living in cities than outside them and their number is still increasing (Swilling and Annecke, 2012). It is expected that 90% of the global population is living in cities by the year 2100 (Fragkias et al., 2013). Owing to the high economic and industrial activity in cities, this development brings about unique challenges to safeguard a healthy urban living environment while preventing resource shortages and pollution. In order to understand which processes regulate this potentially effective resource use, scientific methods and techniques are required to analyse social and economic interactions that occur within cities and relate them to their aggregated impact on the environment. By analogy with biological systems, the concept of Urban Metabolism provides a promising model for analysing and steering these interactions towards sustainability (Kennedy et al., 2011). Here we present a review on urban system dynamics and, based on analogies with ecological systems, propose a conceptual framework for the use of Urban Metabolism to achieve an efficient use of resources in cities.

In the context of our analyses, when discussing energy use, we refer to both direct energy and indirect energy use. Cities are considered complex systems characterized by the interactions between system components. Such interactions are derived from the necessity of cities to fulfil a variety of social and economic functionalities such as provision of habitat, products and services as well as political control (Lane et al., 2009). Social and economic activities in cities are closely supported by energy services (Rutter and Keirstead, 2012). Hence, the link between social and economic activities occurring within cities and energy services exemplified by the definition of urban energy systems proposed by Rutter and Keirstead (2012),[1] provides a potential mechanistic relationship to analyse the environmental impact of the city as a whole. Therefore, dynamics of urban energy systems may

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[1] An urban energy systems is "*.the combined processes of acquiring and using energy to meet the energy services demand of an urban population…*" (Rutter and Keirstead, 2012)".

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explain urban interactions and yield insight in connections between environmental and socio-economic processes that occur in cities.

2. Ecological origin of urban metabolism

Urban metabolism is a widely adopted concept that is used to describe how interactions within cities impact the use of resources and energy (see Kennedy et al., 2011). The idea of urban metabolism as an analogy to the view that ecosystems interact with their environment as a single 'super organism' originated from the field of systems ecology (Odum, 1959; Patten and Odum, 1981). According to this view, ecosystems were analysed as functioning entities by describing the dynamics of energy and nutrient flow (Conan, 2000). More recently, the metabolic theory of ecology postulates that the metabolic rate of individual organisms is a function of an organism's body mass and body temperature and controls ecological processes at all levels of organization from individuals to the biosphere (Brown et al., 2004). Based on this theory, sub linear (allometric) scaling relationships between variables such body mass and metabolic rate at the organism level, were extended to other variables at higher levels such as population growth, population density or standing stock of biomass (Brown et al., 2004) (see Box 1). These relationships indicate that individual energy efficiency increases when organisms and systems become larger. Hence, the natural foundation of this theory provides a potential solution to mitigate the increasing energy use and its effect on the use of energy that sustain other socio economic functionalities of the city in growing cities. In that way, we would be able to characterize aspects of the cities with the potential to shift patterns of energy consumption from linear or super linear models to models describing sub linear relations as it occurs in ecological systems with body size (Fig. 1).

In the urban context, the concept of metabolism was adopted to develop theory on networks and material flows within cities by analogy with the way organisms use resources and energy in order to survive (Camaren and Swilling, 2012; Rapoport, 2011; Swilling and Annecke, 2012). Seminal studies focused on accounting material inputs and outputs of cities such as energy, water, food and nutrients (Newcombe et al., 1978; Wolman, 1965). According to Kennedy et al. (2011), there are two different accounting methods that have been implemented for urban metabolism studies: solar energy equivalents (recently termed as emergy) and Material Flow Analysis (MFA).

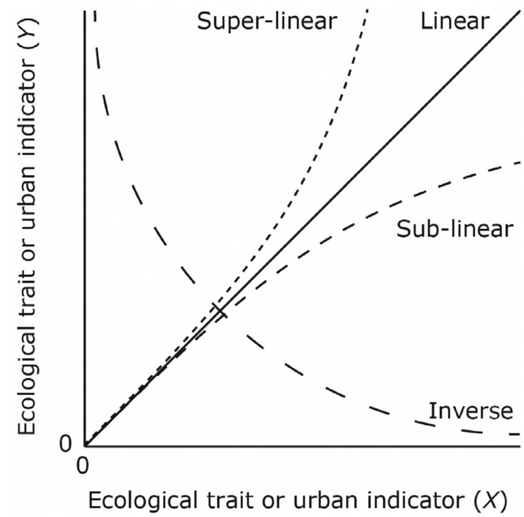

Fig. 1. Examples of Allometric scaling relationships between ecological traits or urban indicators X (e.g. body size, the number of inhabitants, number of firms, physical size of the city) and the subsequent energy consumption Y, generalized to depict the allometric scaling relationship $Y \propto X^{\beta}$. A linear scaling relationship implies no economy of scale, while sub-linear scaling implies economies of scale that allow for more efficient energy use with an increase in the body size of an organism, or the city size. Super linear scaling implies the presence of diseconomies of scale in terms of energy consumption. Inverse relationships depict a decline of the trait of indicator Y with an increase of the trait or indicator X.

Application of the concept of urban metabolism based on these accounting methods conceives the city as a single ecosystem that should emulate the cyclical and the efficient nature of biological processes envisioned by system ecologists (Rapoport, 2011). Owing to the implied cyclicity of resource use in ecological ecosystems, these methods challenge the linearity of consumption patterns and waste production of cities (Golubiewski, 2012; Rapoport, 2011). However, the applicability of urban metabolism is limited to urban and industrial ecology with the main purpose of describing flows of materials and energy as an accounting method with no practical implications in the way resources should be used or distributed across the city. Yet, expansion of the concept of urban metabolism into the social and political realm, as proposed by (Rapoport, 2011), may help to intervene in politics, power

Box 1
Examples of scaling relationships shown in Fig. 1.

Inverse scaling: $\beta < 0$

Ecological scaling relationships between the average population density (Y) and the average body size of a species (X) exhibit inverse scaling (with the exponent $\beta < 0$), for example for mammal primary consumers ($\beta = -0.75$) (Damuth, 1981) and an Amazonian bird community ($\beta = -0.22$) (Russo et al., 2003). In a similar way, the equilibrium number of individuals or carrying capacity is predicted to vary inversely to body size (Brown et al., 2004).

Sub linear scaling: $0 < \beta < 1$

A classic sub linear ecological scaling relationship (with $0 < \beta < 1$) is identified between the energy use (or metabolic rate) of an organism (Y) and its body mass (X), which typically reveals an scaling exponent $\beta = 3/4$ (Kleiber, 1947; West and Brown, 2005). A similar sub linear scaling relationship exists between the total biomass and body size (Brown et al., 2004).

Linear scaling: $\beta = 1$

Individual-based human development indicators (Y) typically scale linearly with city size (X) (with $\beta = 1$), for example the total housing in the US ($\beta = 1.00$), household electrical consumption in Germany ($\beta = 1.00$) and household water consumption in China ($\beta = 1.01$) (see Bettencourt et al., 2007 for details).

Super linear scaling: $\beta > 1$

Wages, income, growth domestic product, bank deposits as innovation-based development indicators (i.e. new patents) (Y) show super linear scaling relationships with city size (X) (with $\beta > 1$), for example the number of new patents in the US ($\beta = 1.27$), R&D employment in China ($\beta = 1.26$) and EU GDP ($\beta = 1.26$) (see Bettencourt et al., 2007 for details). Such super linear scaling is not expected to hold across wider ranges of organisms sizes owing to the fundamental constraints of body size on the energy supply network (West and Brown, 2005).