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Measuring urban ecosystem functions through 'Technomass'—A novel indicator to assess urban metabolism

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ABSTRACT

Cities are complex systems of accumulated matter. The continuous process of matter accumulation in urban systems differs in intensity across the globe according to specific urban features, such as location and age of the urban tissue, and as a physical manifestation of metabolic lineaments, material accumulation should differ amongst cities. In this paper, a new indicator to measure this process of material accumulation is proposed, namely, the Technomass. Emulating ecology, which measures biomass in natural ecosystems, a sample of different urban tissues in a given city – Bogotá – was measured in terms of volume and rates of matter accumulation. Technomass is able to indicate overall asymptotic behaviour, specific spatial profiles and intensification of rates in time. In metabolic terms, the indicator looks into the black box, providing the possibility to link metabolic behaviours with urban form and attempting to fill the gap between urban planning, urban metabolism (UM) and Material Flow Analysis (MFA). This new indicator offers a broad scope of applications. Further possibilities and links to urban research and policy making are explored in the discussion section.

1. Introduction

The idea of cities as artificial or hybrid ecosystems (Alberti and Hutyra, 2013) is increasingly being recognised. However, new conceptual and methodological approaches to understand how cities work (Bettencourt et al., 2007) in combination with better methods to assess and measure urban ecosystem functions (Alberti and Hutyra, 2013) are direly needed.

According to Odum (1969), ecological succession is meaningful in the developmental biology of organisms, as well as in the development of human society. Here, an ecosystem is considered to be a unit of biological organisation interacting with the physical environment characterised by patterns of energy flows and material cycles within the system (Odum, 1969). Biomass is a fundamental ecological indicator at the ecosystem level (Odum, 1969; Pimentel and Pimentel, 1979). Biomass (body weight) is the "central variable determining an organism's dynamic and ecological properties" (Pahl-Wostl, 1997; Bendoricchio and Palmeri, 2005). Biomass calculations are fundamental to understanding ecological functions and to managing natural and agricultural ecosystems (Pimentel and Pimentel, 1979). The underlying principle here is that ecosystems have specific rates and intensities of material accumulation – biomass – where all living organism – animals, plants, insects and microorganisms – are accounted for (Pimentel and Pimentel, 1979). In urban ecosystems, the calculations of such overall ecosystem processes of material accumulation are currently not considered as an important component of urban systems analysis.

This paper attempts to fill this gap in knowledge and research by proposing a new indicator to measure the process of matter accumulation in urban ecosystems – Technomass. The aim is to define, conceptually and operationally, a new urban metabolism indicator. This study is an attempt at understanding the city as an ecosystem, which requires a paradigm shift, a move from studies of the "ecology in cities" to analyses of the "ecology of cities" (Grimm et al., 2000; Broto et al., 2012). However, urban ecology and other related disciplines remain focused on urban natural aspects, such as green spaces, vegetation assembles and biodiversity (Breuste et al., 2013), but that leave understudied the fundamental urban functions and processes (Qureshi et al., 2010), both hybrid, the mix between ecological and technological factors, or purely technologic, such as the dynamics of matter accumulation, but are still deeply interrelated with the city's ecology.

The objective is to explore the laws of material accumulation of urban ecosystems in metabolic terms, looking at rates and dynamics of material accumulation in the urban tissue, in spatial terms

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from the centre to the periphery and in temporal terms as well. The consistency of Technomass as an indicator in a specific city was tested. In the first part, urban metabolism (UM) approaches and Material Flow Analysis (MFA) are discussed in the context of looking at the rationale behind determining the importance of a new indicator, along with where and how this new indicator can play a role in urban research. The city of Bogotá is used as study case, but an adaptable methodology has been developed aimed at further applications to other cases across the globe. The further implications of Technomass are explored in the discussion section. The conclusions explore the relevance of the indicator to understanding certain specific and general facts of Bogotá and linking those with further research needs.

1.1. Urban metabolism

The concept of metabolism has been largely applied to urban and social studies, not as a metaphor but as a central concept highlighting material and energetic processes within the economy and society vis-a- vis various natural systems (Fischer-Kowalski, 1998). In a broader context, UM can be defined as a sum of the total technical – i.e., production – and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste (Kennedy et al., 2007). In metabolic terms, urban systems are defined as the complex organisation of appropriation, transformation, production and emission, energy and information (Antequera, 2005; Decker et al., 2000; Broto et al., 2012; Inostroza, 2013a). The first attempt to describe UM was developed by Wolman in his study "The Metabolism of Cities" (Wolman, 1965), which modelled the metabolism of a hypothetical U.S. city. A key innovation of Wolman's approach was to present the city as an ecosystem (Broto et al., 2012).

Common approaches to UM are mostly focused on accounting of the flows of materials and energy in a city (Kennedy et al., 2011; Broto et al., 2012). The major methodologies include flows assessment, measurement and/or calculating the inputs to the urban system (Naredo and Frías, 2003). Through systematic recording of all physical flows to and from an urban area, these studies attempt to describe the relationship between urban systems and their environment (Minx et al., 2011). Some earlier studies even included the quantification of urban biomass and organic discharges from cats and dogs (Duvigneaud et al., 1977). However, the same studies ignored direct input of materials and manufactured products. A later effort, e.g., Naredo and Frías (2003), determined the total material and energy flow of Madrid. They concluded that even though economies are changing from primary extractive to tertiary sector based on services, the material and energy demands do o decrease but, instead, increase with no dematerialisation of the economy.

Even though the body of UM research has increased during the last decade, a common approach is to leave the urban tissue as a black box, where inputs and outputs are accounted for, but nothing is said about the direct process of accumulation. The proportion of the material flow that accumulates in the urban tissue as a stock is still an open question. To date, UM studies have not explored the linkages between material and energy flows with respect to locations, activities, or people, as they use highly aggregated data, often at the city or regional level that cannot provide explore resource or energy use. It is nearly impossible to determine the metabolism of a specific city if flows cannot attributed to people, places, and uses. In addition, it is difficult without knowledge of how resources and energy are used in specific localities for specific purposes so as to superimpose the flows on specific locations—places of production and consumption. This is a fundamental limitation of current UM studies (Pincetl et al., 2012).

Other studies assessing UM are conceptual (Antequera, 2005; Kennedy et al., 2011; Inostroza, 2013a) or static approaches and do not include the temporal aspects (Toledo et al., 2002). As metabolism is a process, it has to be assessed in dynamic terms to include temporal dimensions to compliment stereotype spatial studies.

1.2. Materials Flow Analysis (MFA)

Materials Flow Analysis (MFA), developed under the industrial ecology perspective, has received enormous attention during the last decade and is being included in the European Union official statistics (EUROSTAT, 2009).

MFA and Substance Flow Analysis (SFA) are typical analytical tools based on materials balance (Kleijn et al., 2000). MFA has concentrated mostly on flows based on the Law of Mass Preservation (e.g., Kneese et al., 1970; Ayres et al., 1996). The difference with UM lies in the system boundaries' definition: where UM focuses on cities, MFA considers the overall social system (Fischer-Kowalski, 1996; Fischer-kowalski and Rotmans, 2009). MFA accounts for inputs and outputs into the national economy of specific materials, energy and water, and/or looking at the outputs in terms of waste and pollution (Naredo and Frías, 2003). The national economy is treated as a black box, e.g., inter-industry deliveries of products are not described. Natural flows into, within, and out of the natural environment are likewise excluded (EUROSTAT, 2009).

The application of MFA to cities has been limited by methodological difficulties, such as capturing urban areas as well-defined, bounded systems and the lack of data at the city level (e.g., Kennedy et al., 2007; Minx et al., 2011).

In MFA, three types of socio-economic material stocks are distinguished: artefacts, animal livestock, and humans. Artefacts are mainly man-made fixed assets as defined in the national accounts such as infrastructures, buildings, vehicles, and machinery, as well as inventories of finished products. MFA accounts for all material flows between the national economy and natural environment and between economies of different countries. It measures the flows of material inputs, outputs and stock changes within the national economy in the unit of tonnes (= metric tonnes) per year. Materials are grouped into 4 main categories: Biomass, Metal ores, Non-metallic minerals and Fossil energy materials/carriers (EUROSTAT, 2009).

According to the aforementioned criteria, the calculation of net stock changes should also include the changes in human population and animal livestock. However, experience shows that these stock changes are very small compared to, for example, the stock accumulation through buildings, machinery or consumer durables (EUROSTAT, 2009). Therefore, in practice, the changes in the human population and animal livestock can be ignored (EUROSTAT, 2009). This highlights theoretical, methodological and even conceptual shortcomings of the classification used by EUROSTAT.

The distinction between stocks and flows is a fundamental principle of any material flow system. A flow is a variable that measures a quantity per time period, whereas a stock is a variable that measures a quantity per point in time. MFA is merely a flow concept. This means that in MFA stock changes are accounted for but not the quantity of the socio-economic stock itself (EUROSTAT, 2009). Although MFA is a flow concept, it is still important to define carefully what is regarded as a material stock, in addition to stocks and stock depletion as essential parts of the MFA framework (EUROSTAT, 2009). They are accounted for indirectly or via the identification of which material flows should or should not be accounted for as inputs or outputs.