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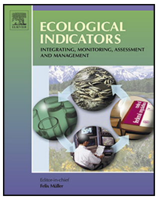

Urban material flow analysis: An approach for Bogotá, Colombia

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ABSTRACT

The urbanisation process has exceeded the traditional pace of human settlement and is moving towards the formation of large urban regions in response to an increasing demand for services and environmental goods, combined with increasing production of waste and emissions. Therefore, it is fundamental to determine resource flows into cities, especially in developing countries, as well as the transformations that occur and the outputs that are produced, such as products, services and wastes. In this study, we apply urban material flow analysis, which determines the flows of inputs (water, energy, food and others) and outputs (wastewater, air pollution, wastes and others) to the city of Bogotá, Colombia to determine the relationship between demand for resources and the environmental impact of outputs. Quantitative and qualitative data for Bogotá are used to assess and compare the material and energy flow trends for this city. The results indicate that in this city, inputs and outputs are directly and linearly related. Consumption of energy and construction materials has increased, whereas food and water consumption have remained steady. Levels of recycling and sewage treatment are low, and emissions such as particulate matter have decreased. The findings from this study can be used to formulate and apply policies and strategies to improve the sustainability of resources, decrease the reliance on physical resources, increase the efficiency of resource and energy use in urban areas, and enhance sustainable production and consumption in cities.

1. Introduction

Urban areas are home to more than 50% of the world's population. This imbalance has generated asymmetric patterns of resource utilisation in recent decades that has resulted in environmental degradation and accompanying problems, such as higher population growth rates, often due to migration; a disproportionate increase in the use of resources; high levels of congestion and pollution due to inadequate road infrastructure (the delivery of transportation), especially in cities in developing countries; problems related to land and ecosystems; and environmental problems, such as water and air pollution and improper disposal of wastes (WWF, 2012; Marcotullio and McGranahan, 2007; Bartone et al., 1994).

Urbanisation generally occurs in parallel with increasing income, which in turn leads to an increasing ecological footprint, particularly in increased carbon emissions. This over-exploitation affects the functioning capability of urban areas, and urban sprawl contributes to ecological fragmentation (Poumanyvong and Kaneko, 2010).

The behaviour of cities can be compared to the metabolism of living organisms in an analysis approach that seeks to explain the relationship between a human community and its geographic base of support in terms of the construction of a landscape as a territorial expression of the metabolism by which a society maintains and supports natural systems. This approach helps to identify the main factors affecting the environment and determine when and why changes in territory configuration occur. This method is based on an analysis of energy and material flows and takes into account a broad view of reality from social, economic, geographic and environmental perspectives (Tello et al., 2002).

Territorial development depends on the energy and material flows that are the result of patterns of consumption, land use, the configuration of the landscape, and the features of the population, among other characteristics. The changes in these characteristics determine the magnitudes of the problems and the environmental impacts on human settlements (Fischer-Kowalski, 1998; Fischer-Kowalski and Hüttler, 1999).

In recent years, research related to the problems and environmental impacts of urban areas has used the concept of urban metabolism to explore cities and communities through the quantification of inputs (water, food, and fuel, among others) and

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outputs (sewage, solid refuse and air pollutants) while also tracking their respective transformations and flows. In this model, the city itself, from a biological perspective, serves as an ecosystem that encompasses the interactions among the numerous subsystems of an urban region (Wolman, 1965; Grimm et al., 2000; Marcotullio and Boyle, 2003).

The urban metabolism analysis approach involves studying how cities convert raw materials, fuel and water into the urban-built environment, human biomass, and waste. The application of this approach has the following advantages in urban contexts. First, urban metabolism analysis generates results regarding the magnitudes of resource exploitation or use and waste production, which makes it possible to analyse urban sustainability. Second, urban metabolism analysis establishes measures of resource efficiency and identifies opportunities for improvement. Third, urban metabolism analysis produces a comprehensive accounting of the stocks and flows through cities that pertain to critical processes for the environment, such as the accumulation of waste, depletion of groundwater resources and the impacts of chemicals and hazardous materials (Kennedy et al., 2011).

Urban metabolism has mainly been studied from three perspectives. These include the city as an ecosystem, the city with respect to material and energy flows, and the city with respect to the optimisation of economic–environmental relations.

The perspective of the city as an ecosystem is a biological emphasis: the city is regarded as a "system" and a "natural" entity (Marcotullio and Boyle, 2003). In this sense, the city is analogous to an ecosystem in which urban structure is stored until the maintenance costs are equal to the maximum local energy input. Throughout history, cities have overcome limits on local energy availability, with connections to remote sources of food, water, fuel and materials being a key feature of urbanisation (Decker et al., 2000). Several studies have taken this approach (e.g., Folke et al., 1997) to analyse and calculate the ecological footprint of cities in Baltic Europe, and these studies have concluded that on a global level, the capacity of an ecosystem to support city development is becoming increasingly scarce as a result of the rapid increase in the population, the intensified emphasis on human activities and depletion of the natural resource base. Alberti (2005) evaluated the effects that patterns of urban development have on the functioning of ecosystems using empirical methods and determined that the interactions between urban development patterns and ecosystem dynamics and functions are controlled by multiple stressors. She further concluded that more research is required due to the complexity of urban economic, social, and ecological processes. Berrini and Bono (2007) applied the urban ecosystem concept to the assessment of the sustainability of 32 European cities and identified several measures that can be implemented to formulate adequate environmental policies that contribute to the sustainability and welfare of cities.

The second approach, analysis of urban material and energy flows, applies industrial ecology to the quantification and assessment of the flows of particular materials (e.g., raw materials, nutrients and food) and energy in standard mass units (e.g., kilograms, tonnes, and joules) as they enter, accumulate and exit the urban system and thereby contribute to environmental problems (Brunner, 2008; Barles, 2009). Several studies have used this approach. For example, Barles (2009) applied this concept to Paris and found that the interactions between urban and regional planning and development and material flows are of significant importance. Browne et al. (2012) studied an urban area in Ireland using the energy flow metabolism ratio analysis approach and determined that to assess sustainability, it is necessary to apply several methods and types of analyses. Sahely et al. (2003) assessed the urban metabolism of an urban region in Canada to analyse energy efficiency, material cycling, waste management and infrastructure in urban systems. Moore et al. (2013) presented a detailed assessment of the urban metabolism, in terms of residential consumption and ecological footprint, of the Vancouver metropolitan area in the year 2006.

The third approach seeks to increase the metabolic efficiency or decrease the amount of resources used per unit of economic output, thus achieving dematerialisation or decoupling between production and the resources used (Dunn and Steinemann, 1998). This approach was used to assess the urban metabolism of Suzhou, China and showed that to achieve long-term sustainability, it is necessary to reduce the city's resource demands and waste generation. The researchers further concluded that the dematerialisation of resources should centre on agriculture, industry and construction, whereas the dematerialisation of wastes should centre on services and domestic consumption (Liang and Zhang, 2011). In Los Angeles County, California, USA, this approach was used to demonstrate decreases in resource inputs and pollution outputs on a per capita basis from 1990 to 2000, for all materials except food imports and wastewater outputs. These decreases resulted primarily from improvements in local efficiency and management policies (Ngo & Pataki, 2008). This approach can be applied to identifying targets for both dematerialisation and progress in the ecological performance of cities, as in the cases of Stockholm and Geneva (Barles, 2010).

Following the introduction of the concept of urban metabolism, the concept of societal metabolism was introduced in studies of the interactions between human societies and their natural environments, in terms of flows of energy and materials. The societal metabolism concept involves viewing socioeconomic systems as subsystems of a larger physical system in determining the relationships between socioeconomic development and the ecological environment (Zhang et al., 2012; Zhang, 2013; Siciliano et al., 2012). This approach has been applied to the analysis of the metabolism of regions such as the European Union (Steurer, 2003), for which economy-wide material flow accounts and main indicators were determined by material categories; the Czech Republic (Kovanda and Hak, 2007), for which decoupling was analysed using economy-wide material flow indicators; the United Kingdom (Krausmann et al., 2008), for which the biophysical causes and consequences of industrialisation were evaluated to determine the need for a new, sustainable, industrial socio-ecological regime with lower per capita material and energy consumption; the Philippines (Kastner, 2009), for which human appropriation of net primary production was assessed to determine how to meet the challenge of increasing biomass demand without putting even greater strain on ecosystems; and Taiwan (Ferng, 2009), for which the effects of changes in food consumption patterns, which have implications for sustainable development, were examined.

This concept has also been applied to the analysis of the flows of materials through socioeconomic systems (Fischer-Kowalski, 1998; Matthews et al., 2000; Kestemont and Kerkhove, 2010). Several methods have been used for this purpose, such as emergy analysis (Odum, 1996; Kuskova et al., 2008; Hossaini and Hewage, 2013) and multi-scale integrated analysis of societal metabolism (Ramos-Martin et al., 2007; Lorgulescu and Polimeni, 2009; Giampietro et al., 2011).

Societal metabolism analysis assesses sustainability from the perspective of the material and energy relationships between society and nature (Fischer-Kowalski, 1998), and material flow analysis (MFA) accounts for the flows of materials through space and time. The indicators derived are consistent compilations of the overall material inputs into economies, the changes in material stocks within the economic system, and the material outputs to other economies or to the environment (Eurostat, 2007, 2009).

In the Latin American context, urban metabolism has been studied by several researchers. Vallejo (2006, 2010) studied resource