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Cross-boundary environmental effects of urban household metabolism based on an urban spatial conceptual framework: a comparative case of Xiamen

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ABSTRACT

The cross-boundary environmental effects of urban household metabolism are of increasing interest in the context of global climate change and the sustainability of urban systems. To assess resource exchanges and environmental emissions, urban household metabolism was investigated using an 'emergy synthesis framework', with the city of Xiamen providing case study data. Two data sets, one from the highly urbanized Xiamen Island (XI) and the other from the less urbanized Xiamen Mainland (XM), were collected and analyzed using an 'urban spatial conceptual framework'. Household consumption and its spatial environmental effects are embodied by exchanges of resources, energy, services, and wastes between the urban system's physical footprint ('Urban Sprawl Region', USR), and its ecological footprint ('Urban Footprint Region', UFR). The results show that Xiamen's USR is connected to its UFRs by approximately 98.74% emergy flows. The distinct emergy indicators identified within the results show that the driving forces, processes, influences, efficiency and sustainability of household metabolism vary dramatically between XI and XM, demonstrating that different urban and social contexts significantly affect household metabolism. The Emergy Sustainability Index reveals that USR households need to make lifestyles changes to sustain development. The employed frameworks (urban spatial conceptual framework and emergy synthesis framework) enable the computation of household consumption and cross-boundary environmental effects. The results may help foster alternative household consumption strategies which could result in more equitable resource allocation and effective mitigation of cross-boundary environmental influences.

1. Introduction

With 60% of the world's population predicted to be living in cities by 2030 (UNSD, 2006), efforts to achieve regional sustainability are increasingly focused on the environmental effects of urban metabolism (Hillman and Ramaswami, 2010). Optimizing the allocation of regional resources and promoting low-carbon household consumption strategies requires an understanding of metabolism activities at the city scale, including household consumption of resources, goods, services and resulting waste. Conventionally defined urban systems are confined by a fixed administrative boundary which is much smaller than the environmental footprint area. Overcoming the problem of attributing responsibility for cross-boundary environmental effects is of increasing concern in the context of global climate change and urban system sustainability (Chen et al., 2010; Churkina, 2008; Hillman and Ramaswami, 2010; Jones and Kammen, 2011; Ramaswami et al., 2008; Zhou et al., 2010).

Most environmental impact studies focus on urban metabolism within the contiguous space of a rigid city boundary using boundary-limited methodologies (Hillman and Ramaswami, 2010). This often leads to the cross-boundary environmental effects on supporting regions being neglected. For example, cities consume increasingly large amounts of energy and materials, and discharge significant amounts of waste products into their enclave supporting regions (Churkina, 2008; Jones and Kammen, 2011). However, in the conventional urban system framework, the determination of the corresponding environmental responsibility largely depends on established boundaries of legal responsibility. As a result, cross-boundary environmental responsibility, for example in the context of global climate change, is unclear. A new, more equitable urban system framework should therefore be established to take into account cross-boundary environmental responsibility and relationships.

The concept of urban metabolism was first proposed by Wolman (1965), but the role of households in urban metabolism remained

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neglected for a long time (Churkina, 2008). It has been argued that household metabolism is crucial to regional sustainability and low-carbon strategies (Berg and Nycander, 1997; Churchill and Baetz, 1999; Codoban and Kennedy, 2008; Moles et al., 2008). Household metabolism was addressed by the HOMES (Household Metabolism Effectively Sustainable) project (UNPD, 2008), and an increasing number of studies have discussed the sustainability and related environmental consequences of household activities (Bin and Dowlatabadi, 2005; Druckman and Jackson, 2008, 2009; Matthews et al., 2008; Moloney et al., 2010; Newman, 1999). Although such studies frequently employ sophisticated modeling techniques, the extent of cross-boundary environmental impacts remains unclear. Moreover, such boundary-limited results have not been translated into comprehensive management strategies for cross-boundary environmental issues and household consumption options (Jones and Kammen, 2011; Svirejeva-Hopkins and Schellnhuber, 2006; Tukkerc et al., 2010).

Recently, emergy synthesis and related hybrid methods have been introduced into the analysis of urban household metabolism. The emergy synthesis method has been promoted as a way to bridge the gap between socio-economic development and environmental protection (Huang et al., 2006). Emergy synthesis can account for material, energy, and monetary flows within the urban metabolic system and their respective environmental effects on the surrounding environment (Odum, 1996). The emergy synthesis method generally focuses on urban-level metabolism studies supported by top-down data (Lei and Wang, 2008; Jiang et al., 2009; Zhang et al., 2009), and fewer studies have been conducted on sub-urban scale metabolism using bottom-up data (Liu, 2005; Moll et al., 2005; Li and Wang, 2009). At the sub-urban scale, several settlement scale issues have been investigated, including domestic water and energy metabolism (Liu, 2005), household consumption patterns (Moll et al., 2005), and hybrid Emergy-LCA-based building sector metabolism impacts (Li and Wang, 2009). These studies show that emergy theory can usefully be applied to sub-urban scale metabolism and the resulting environmental effects.

Cross-boundary resource transfers and environmental interplay between urban parts have triggered increasing concern in the context of global climate change (Hillman and Ramaswami, 2010; Jones and Kammen, 2011; Matthews et al., 2008; Wang et al., 2011). Increasing city metabolites implies a larger burden on surrounding environmental buffering areas (Churkina, 2008; Kennedy et al., 2007), and urban household metabolism studies improve understanding of cross-boundary environmental effects by computing material and energy flows. Consequently, urban household metabolism studies provide insights which can be used for cross-boundary environmental management and to develop household consumption strategies. Moreover, it supplies a new perspective from which to understand environmental relationships between urban spaces.

This paper assesses the cross-boundary environmental effects of household metabolism based on a proposed urban spatial conceptual framework. Input–output resources and consumption processes in a typical Xiamen household system are quantitatively analyzed using the emergy synthesis method, based on survey data and statistic materials. Household system metabolism in different urban spaces is compared using emergy indicators, providing quantitative results for our conceptual framework. This allows us to identify household consumption processes and potential spatial differences, determine the inherent driving mechanisms and spatial effects of household metabolism, and provide an alternative reference for regional environmental management and low-carbon-oriented household consumption options.

2. Urban spatial conceptual framework

Recent studies have shown that urban areas have a footprint extending to distant and remote places, arising from their influence on climate, the dispersal of air pollution, and urban demands for energy and material goods (Churkina, 2008). Before the complex relationship between urban centers and their supporting regions can be identified, a clear conceptual framework of the urban spatial components must be established. Thus, we propose the urban spatial conceptual framework shown in Fig. 1, which divides the urban system into the Urban Sprawl Region (USR) and the Urban Footprint Regions (UFRs).

The USR, or urban built-up area, refers to a physical footprint area with a centralized and continuous urban morphology. The UFR, which is derived from the “theoretical footprint space” in ecological footprint theory, is the “actual footprint space”. The UFR concept was first mentioned by Churkina (2008) as a way to model the carbon cycle of urban systems. However, the original definition does not completely reflect the multi-directional environmental linkages between urban spatial components. As an indispensible part of the urban system, the UFR connects with the USR through thousands of functional ties in terms of energy flows, material circulation and wastes disposal (Hillman and Ramaswami, 2010; Svirejeva-Hopkins and Schellnhuber, 2008). Most of the resources and energy used by a city come from the UFRs (Churkina, 2008; Svirejeva-Hopkins and Schellnhuber, 2008), which may be adjacent or exclave to the city center (Folke et al., 1997). From the perspective of functional relationships, we define the UFR as being not only the spaces from which resources are provided to meet the demands of urban consumption and production, but also the spaces affected by urban pollution and changes in climate. UFRs may be either adjacent to the USR or exclave (not contiguous to USR). UFRs are characterized by widespread distribution, multiple roles and multi-directional connections with the USR. This division of urban spaces facilitates the analysis of cross-boundary metabolic activities and environmental responsibility.

A city is a special kind of organism (Zhang et al., 2009), and to some extent its sustainable development depends on a balance of metabolic flows between the USR and UFRs. As shown in Fig. 1, each urban system has only one USR, but many adjacent and exclave UFRs. The USR is a heterotrophic subsystem which extracts “nutrients” from UFRs (semi-autotrophic subsystems). The permeability and dependence of the urban system means that the USR metabolic activities cannot be supported solely by the limited internal urban space (Zhang et al., 2009). The nutrients required to sustain urban metabolism are continuously transported into the USR from UFRs, while UFRs receive wastes and other urban metabolites. These nutrients and metabolites constitute the urban metabolism components.

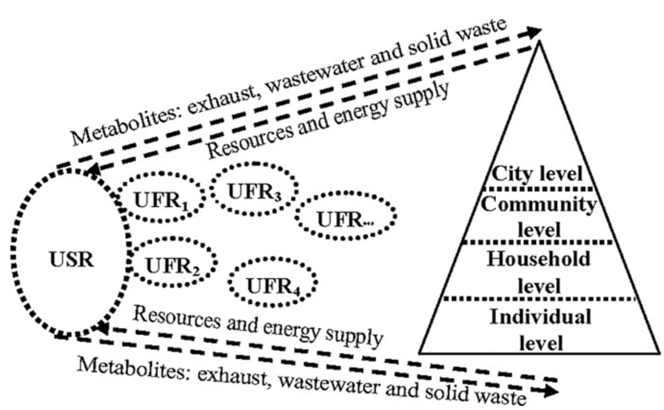

Fig. 1. The urban spatial conceptual framework.