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# Process-based investigation of cross-boundary environmental pressure from urban household consumption

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## HIGHLIGHTS

- We propose an urban spatial conceptual framework that includes USR and UFRs.
- A complementary EMA and CFA method is employed in urban household consumption system.
- Process-based cross-boundary environmental pressure of household consumption are evaluated.
- USR exerts pressure on its UFRs by extensive resource extraction and environmental emissions.
- We elucidate the USR–UFR environmental relationships and household energy policy

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ABSTRACT

Sustainability research at the city scale is increasingly focusing on urban household consumption in the context of global climate change. We use a complementary emergy accounting (EMA) and carbon footprint accounting (CFA) method to investigate the environmental pressure generated by household consumption in Xiamen, China. We distinguish between the resource extraction, consumption and disposal stages within an urban spatial conceptual framework, comprising the Urban Footprint Region (UFR) and Urban Sprawl Region (USR), and analyze five environmental footprint categories associated with cross-boundary household emergy and carbon flows. Cross-boundary activities, which link the USR with its UFR, contributed nearly 90% of total emergy and 70% of total GHG emissions in CFA. Transport fuel, building materials and food contribute most to environmental pressure in both EMA and CFA. The results indicate a significant cross-boundary resource burden and environmental footprint associated with household activities. The employed framework, method, and scope challenge the conventional spatial boundary of the urban system, and the results have important policy implications for urban sustainability and cross-boundary environmental management.


## 1. Introduction

Growing awareness of the importance of creating sustainable cities and developing mitigation strategies for resource use and greenhouse gas (GHG) emissions has led to an increasing focus on urban household consumption (Churkina, 2008; Druckman and Jackson, 2008; Lin et al., 2010; Moloney et al., 2010; Wang et al., 2011; Zhao et al., 2010). The consumption of key goods and services by urban households has a direct and indirect environmental footprint (Aguilar and Ward, 2003), and the environmental effects of resource depletion, waste disposal and GHG emissions extend far beyond the city's geographic boundary and conventional boundary-limited methodology (Jones and Kammen, 2011). As a result, identifying the environmental responsibility resulting from household consumption is attracting increasing attention (Druckman and Jackson, 2009; Lenzen and Peters, 2010; Matthews et al., 2008; Wei et al., 2007). Improved understanding of the content, intensity, and modes of household consumption, and of the resulting cross-boundary environmental pressure, will facilitate efforts to reduce footprint size and improve urban sustainability (Batty, 2008; Churkina, 2008; Hillman and Ramaswami, 2010; Yang et al., 2012).

Household consumption activities are a complex process of resource supply, use and by-products output. These processes give rise to materials and embedded energy transfers between the

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city core and its supporting areas (Churkina, 2008). Various approaches and models have been used to carry out multi-dimensional analysis of household consumption, with the goal of tracking the resulting environmental effects in different spatial areas (Matthews et al., 2008). These methods have investigated the economic, technical and environmental characteristics of household activities, and include emergy accounting (EMA), carbon footprint accounting (CFA), input-output analysis (IOA), life cycle assessment (LCA), ecological footprint (EF), exergy analysis, and cost-benefit analysis (Churkina, 2008; Druckman and Jackson, 2009; Gao, 2010; Hau, 2002; Jones and Kammen, 2011; Pulselli et al., 2009; Wiedmann, 2009). Research has tended to focus either on the household consumption structure with a view to providing insights on city sustainability, or on environmental emissions and impacts on local and global ecosystems.

EMA is a widely used method to account for the role of energy flows between ecological and socio-economic systems, and explore the resulting sustainability implications (Huang and Hsu, 2003). Emergy is defined as all the available energy that is used, directly and indirectly, in making a product, expressed in units of one type of energy (Odum, 1996). Several EMA studies have investigated household activities within cities, e.g., domestic food consumption, domestic building emergy, and residential metabolism (Druckman and Jackson, 2009; Gao, 2010; Li and Wang, 2009; Pulselli et al., 2009). However, household consumption studies are difficult to conduct, because while energy flows into households can be partly captured, statistical materials on household expenditure data are often incomplete. Moreover, while local environmental effects of household consumption can easily be estimated, consequent cross-boundary impacts in supporting areas are often neglected.

EMA reveals hidden environmental costs and the inherent sustainability of the system, but does not indicate the environmental effects of polluting emissions (Brown and Buranakarn, 2003). CFA tracks total carbon emissions across the material flow process within a given geographic region, but ignores the contributions of ecological products and services (Druckman and Jackson., 2009; Wiedmann, 2009). Therefore, some researchers have made efforts to link EMA with CFA through process-based material flow analysis, which enables levels of natural resource exploitation and pollutant emissions throughout the entire life cycle to be estimated (Barala and Bakshi, 2010; Li and Wang, 2009; Pizzigallo et al., 2008). In this paper we define an indicator system to measure urban sustainability and determine the size of the environmental footprint using a combined EMA–CFA method.

In addition to the practical difficulties of conducting household consumption studies, identification of the urban spatial boundary is a difficult task. While cities have a fixed geographic location, GHG emissions resulting from household consumption spread far beyond the city boundary. Another challenge is presented by upstream GHG emissions associated with the production of key household materials, including foods, fuel and concrete, which have often been ignored when produced outside city boundaries (Matthews et al., 2008; Ramaswami et al., 2008). Nevertheless, a hinterland approach (Aguilar and Ward, 2003) or Scope 1+2+3 GHG accounting (WRI, 2009) provide insights into the energy flows across the city boundary, and thus foster a further understanding of cross-boundary environmental effects.

In this paper, we combine EMA with CFA to investigate household consumption and resulting environmental footprint within a proposed urban spatial conceptual framework. Process-based analysis of urban household resources flows, direct wastes and GHG emissions is conducted for Xiamen, a coastal city in southeast China. Our objective was to investigate cross-boundary environmental links between the USR and UFR, conduct process-based assessment of the environmental footprint associated with household consumption during the resource extraction, consumption and waste disposal stages, and establish metrics for the cross-boundary environmental effects of urban household consumption.

Analysis of household consumption improves understanding of the overall role and responsibility distribution of households, enabling the design of appropriate and effective policies for cooperation in urban sustainability and environmental footprint reduction.

## 2. Urban spatial conceptual framework and case study

Urban demands for energy and generation of wastes including GHG emissions have an environmental footprint which extends far beyond the city boundary, especially in a globalized economy (Churkina, 2008). The conventional conception of a city with fixed legal boundaries is increasingly being challenged by cross-boundary environmental responsibilities and the struggle to achieve regional sustainability. Churkina (2008), for example, emphasized that an urban system includes both the urban sprawl area and its footprint area, and provided a preliminary definition without elaboration.

To identify the dependent relationship between the city core and its surrounding impact areas, we propose an urban spatial conceptual framework to depict the urban system structure. An urban system consists of an Urban Sprawl Region (USR), i.e., the "physical footprint space" of a built-up area with a contiguous urban morphology from city core to periphery, and Urban Footprint Region (UFR), the "supporting footprint space" required to meet the demands of the urban population in terms of consumption and waste accumulation, as well as the space negatively affected by urban pollution and changes in climate (Fig. 1). The UFR of a city, an extended city physical space, is linked to its USR by transfers of materials, energy and services across a flexible boundary. The framework and its related concepts are an extension of Churkina's urban framework and an environmental form of hinterland theory.

USR households not only pour waste products into the UFR, but also depend on these same areas to provide almost all of their life-supporting resources (Churkina, 2008; Svirejeva-Hopkins and Schellnhuber, 2006). Because cross-boundary transfers of materials, energy and information are partly driven by urban household consumption, these transfers reflect consumer awareness of resource and environmental issues, and can therefore be the target of consumer-oriented environmental management policies. City policymakers should consider the extent of the environmental effects of resource extraction and waste emission in the UFR, and adopt appropriate alleviating strategies.

Xiamen Island (XI) (118°04′04″E, 24°26′46″N), with an area of 141.09 $km^2$ and a population of 830,444 in 2009, is the original

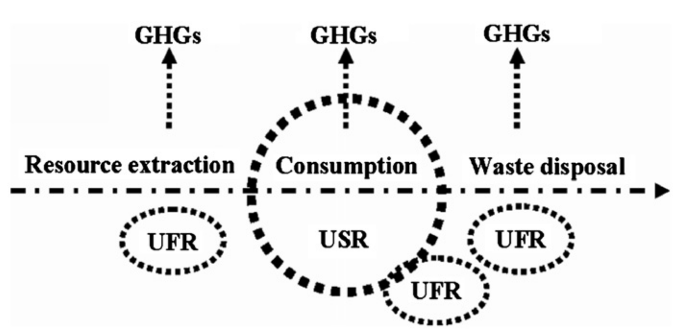


**Fig. 1.** The urban spatial conceptual framework.