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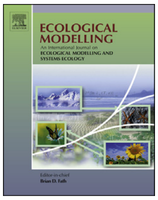

Evaluating spatiotemporal differences and sustainability of Xiamen urban metabolism using emergy synthesis

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ABSTRACT

The need to create sustainable cities has led to increasing concern on achieving healthy spatial metabolic interactions and system sustainability. Based on emergy synthesis and an urban spatial conceptual framework, we employ a set of seven emergy-based indicators to evaluate the sustainability of spatiotemporal metabolism for Xiamen, southeast China, using 1987–2007 land use and socio-economic statistic data. The results show a general improvement in socio-economic performance (emergy intensity, GDP emergy ratio, and emergy turnover ratio), but a steady deterioration in environmental performance (emergy self-support ratio, emergy density, and waste density) during the period 1987–2007. An increasing environmental and socio-economic metabolic gap exists between the built-up urban sprawl region (USR) and urban footprint regions (UFRs) due to resource privation and environmental space occupation, potentially undermining system sustainability. Compared to other Chinese cities and provinces, Xiamen still exhibited relatively weaker sustainability in 2002 due to increasing pressure on ecosystem health. Environment-oriented, society-oriented and cross-boundary-oriented metabolic strategies should be incorporated into future city development to foster urban system sustainability.

1. Introduction

Urban system metabolism has a major influence on the surrounding footprint regions. As supporting spaces providing environmental resources for the built-up urban sprawl region (USR), urban footprint regions (UFRs) play a vital role in the metabolic vitality of cities (Yang et al., 2012). UFRs are surrounding supporting spaces which meet the demands of the urban population in terms of consumption and waste accumulation, and are negatively affected by urban pollution and changes in climate. The USR of a city and the adjacent and exclave UFRs form an urban spatial conceptual framework, which was proposed to identify urban environmental relationships against the backdrop of global environmental change. The metabolic components (e.g. materials, energy, water and nutrients) interact between the USR and UFRs, and the co-evolution of the USR and UFRs makes cities behave as if they were “superorganisms” with their own metabolic processes (Yang et al., 2013; Zhang et al., 2009). The potential for urban spatial components to cooperate as a metabolic system could improve their capacity to respond to the challenge of regional environmental change and sustainability (Brunner, 2007; Kennedy et al., 2011; Seto et al., 2012; Seitzinger et al., 2012; Yang et al., 2011).

Metabolism is a fundamental process in the biological sciences and was first introduced into urban studies by Wolman (1965), who argued that the evolution of the urban system closely resembled a group of related metabolic processes. Following formative work in the 1970s, disappearance in the 1980s, and reemergence in the 1990s, the past decade has witnessed increasing interest in the study of urban metabolism, which has been defined as “the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste” (Kennedy et al., 2007, 2011). The concept of urban metabolism gives insights into the co-evolution of metabolic components, and coexistence with the global web of other cities. Thus, urban metabolism research has provoked widespread interest in a deeper understanding of city sustainability.

Metabolism-related studies have tended to focus on the role that metabolic components and spatial energetic interactions play in the sustainability of urban systems (Geng et al., 2011; Kennedy et al., 2011; Pincetl et al., 2012; Zhang, 2013). As both centers of energy confluence and dissipation, a trend toward increased demand has been observed in most cities for metabolic components from peripheral UFRs. Assessing the potential impacts of economic activities on urban metabolic components can provide a

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Table 1
Basic statistics for Xiamen city, 1987–2007.

Categories	Urban spaces	1987	1992	1997	2002	2007
Population (person)	Xiamen city	1.07E+06	1.15E+06	1.25E+06	1.37E+06	2.43E+06
	USR	4.02E+05	4.83E+05	5.70E+05	8.22E+05	1.14E+06
	UFR	6.65E+05	6.70E+05	6.77E+05	5.50E+05	1.29E+06
Area (m^2)	Xiamen city	1.93E+09	1.93E+09	1.93E+09	1.93E+09	1.93E+09
	USR	3.42E+07	5.27E+07	1.11E+08	1.19E+08	2.49E+08
	UFR	1.90E+09	1.88E+09	1.82E+09	1.81E+09	1.68E+09
GDP (US$)	Xiamen city	3.80E+08	1.27E+09	5.97E+09	6.20E+09	2.24E+10

quantitative estimate of their sustainability performance (González et al., 2013). Increasing urban metabolism also implies more intensive cross-boundary environmental effects (e.g. land occupation, ecological damage, resource privation and pollution transfers), contributing to environmental conflicts between the core and the periphery (Broto et al., 2012). Another difficult question is how to reduce developing imbalances between USR and UFRs to achieve a more sustainable future. A number of methodologies and models have sought to bridge the gap between theoretical and practical knowledge of urban sustainability, including emergy synthesis (Krausmann et al., 2003; Lou and Ulgiati, 2013), life cycle analysis (Rugani and Benetto, 2012), network analysis (Chen and Chen, 2012), set pair analysis (Su et al., 2013) and thermodynamic-based methods (Liu et al., 2013).

Research has increasingly focused on investigating socio-economic metabolism from the perspective of land use and land cover change during urbanization (Huang et al., 2006; Krausmann et al., 2003; Kuskova et al., 2008; Lee et al., 2009; Seto et al., 2012; Su and Fath, 2012; Zhang et al., 2009). This is because sustainability of the combined environmental-economic system depends not only on the nature of the urban metabolic processes, but also on land-use change (Huang et al., 2006). Land cover is often modified by societies to enhance various types of production, but this tends to accelerate the consumption of energy and may result in negative ecosystem changes (Krausmann, 2001). Emergy synthesis links urban socio-economic metabolic processes with land-use change, and also provides an accounting analysis of material flows using comparable energy units. However, there are at least two aspects of emergy-related research which require further improvement. One is to provide a definition of urban sustainability using a horizontal comparison of different spatial units and a vertical comparison of different time periods. An important deficiency in material and energy flow analysis is that it is unable to directly judge the degree of sustainability (high or low) and assess changes (increase or decrease) in sustainability (Zhang, 2013). The second need for improvement is in interpreting the importance of metabolic differences within the urban space, and in identifying space-related measures capable of sustaining these metabolic processes. This is important because other bio-physical methods, e.g. the ecological footprint method, cannot link measures with actual spaces. In the literature, there are only a few cross-sectional studies of multiple cities and few time series studies of urban metabolism.

In this paper, we employ emergy synthesis within an urban spatial conceptual framework to investigate socio-economic metabolic processes within different urban spaces, and to compare metabolic sustainability in different cities. We also interpret the relationship between socio-economic metabolic activities and land-use change by developing an emergy indicator system which can quantify metabolic structure, pressures, intensity and efficiency. The results can assist in the development of urban planning alternatives and the understanding of urban sustainability performance.

2. Case study

Xiamen is located on China's southeast coast facing the Taiwan Strait, and was one of China's first four national-level Special Economic Zones. Sustained and rapid economic growth has resulted in Xiamen's official population increasing from 1.07 million in 1987 to 2.43 million in 2007, while GDP increased from US$ 0.38 billion to US$ 22.4 billion (Table 1). The Xiamen landscape has been radically changed by the expansion of the economic center and built-up areas. Most city residents live on Xiamen Island, where special economic policies have been in effect since 1980, but in recent years the urban built-up area has expanded rapidly on the mainland due to space constraints. During the period 1987–2007, the Xiamen built-up area increased from 3.42E+07 m^2 to 2.49E+08 m^2 (Table 2) as agricultural land has been continually converted to built-up area (Tang et al., 2013). As one of China's first low carbon pilot cities, Xiamen has made significant efforts to improve environmental protection while promoting socio-economic development (Zhao et al., 2011).

3. Methods

3.1. Emergy synthesis

Emergy was proposed in the 1970s to highlight the biophysical value of resources to the economic system, and thus link the natural and socio-economic systems. Based on general system principles and laws of thermodynamics, Odum (1971, 1988, 1996) described

Table 2
Land-uses in Xiamen city, 1987–2007.

Urban spaces	Land-use types	Area (m^2)				
		1987	1992	1997	2002	2007
UFR	Saltwater bodies	3.31E+08	4.25E+08	3.35E+08	3.70E+08	3.24E+08
	Freshwater bodies	2.71E+07	2.19E+07	3.28E+07	3.37E+07	3.22E+07
	Rural built-up land	4.40E+07	5.85E+07	7.21E+07	7.52E+07	1.22E+08
	Farmland	7.29E+08	8.57E+08	7.29E+08	6.59E+08	4.43E+08
	Woodland	6.58E+08	5.07E+08	5.42E+08	6.00E+08	6.67E+08
	Tidal flats	1.10E+08	1.10E+07	1.12E+08	7.53E+07	9.70E+07
USR	Unused land	1.07E+07	1.64E+07	4.97E+07	2.39E+07	8.63E+07
	Urban built-up land	2.35E+07	3.64E+07	6.15E+07	9.52E+07	1.62E+08