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Accessing on the sustainability of urban ecological-economic systems by means of a coupled emergy and system dynamics model: A case study of Beijing

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HIGHLIGHTS

- A Systems Dynamics model simulating urban emergy flows is set up.
- Current economic development of Beijing depends on high consumption of resources.
- Beijing has extreme and increasing dependence on external resources.
- Beijing relies heavily on nonrenewable resources and its development is unsustainable.
- Low GDP growth is better than high GDP growth with increased environmental investment.

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ABSTRACT

Due to high population densities and rapid economic development, great number of cities worldwide rely heavily on external resources, and many are experiencing serious environmental pollution. Municipal governments are facing the issue of balancing the relationship between economic growth and environmental preservation. An urban system is an open, complex, dynamic ecological-economic system with different types of materials and resources. This paper combines emergy theory and System Dynamics (SD) and establishes an emergy-flow SD model of an urban eco-economic system that includes economic, population, waste and emergy sub-models. Three scenarios with different economic growth rates and investments in environmental preservation are designed to analyze the sustainable development capacity of Beijing under different scenarios. The results of the analysis show that current economic development in Beijing highly depends on resources consumption, especially the consumption of imported resources. Based on the current growth rate, development in Beijing will heavily depend on external resources that may make the system being more fragile in the future. A lower economic growth rate and a small increase in environmental preservation investment are more suitable for in Beijing than area higher economic growth rate and a large increase in environmental preservation investment.

1. Introduction

Most cities worldwide are experiencing serious problems caused by resource shortages and environmental pollution including water shortages, land shortages, ecological damage, air pollution, and traffic jams. The essence of these problems is the demand associated with urban residential consumption and economic development, which outweigh the resources supplies and carrying capacities of the urban environment. Globally, 54 per cent of the world population lived in urban areas in 2014 (United Nations, 2015). The urban population of the world has grown rapidly since 1950, increasing from 746 million to 3.9 billion in 2014. By the year 2045, the number of people living in cities is projected to increase by 1.5 times to 6 billion according to predictions by the United Nation (United Nations, 2015). Accounting for more than 80% of the global GDP, cities also play important roles in global economic development. As developing countries become more

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eager to develop their economies, these problems will become even more severe in such countries. In 2013, cities in China contributed to 57% of the GDP and 54% of the national population but only 2% of the national land area (National Bureau of Statistics, 2014). Due to the relative compactness of the cities and under the pressures caused by economic growth. Population growth and consumption, local resources could not meet the demands of urban development; therefore, numerous external resources were imported into cities for use and consumption. Meanwhile, substantial waste was generated because of resource consumption, surpassing the urban ecological carrying capacity; therefore, the urban environment has been degraded. Researching the impact of economic development and resident consumption on resources and the environment in urban ecological-economic systems will contribute to producing effective policies for sustainable urban development.

Currently, many researchers are interested in solving these problems and developing relevant measures and policies. These measures and policies can be divided into three categories. The first category reduces economic growth rates or adjusts economic structures. Some scholars believe that the ecological environment and resources of a city cannot sustain such rapid economic growth. The most effective method of achieving these goals is to reduce the economic growth rate or change the urban industrial structure (Stewart, 2002; Guan et al., 2011; Chiesa et al., 2014; Zhang et al., 2014; Donaghy and Hopkins, 2015; Xie and Wang, 2015). The second category controls the population. Urban residents also consume considerable resources daily and have extensive impacts on the environment; therefore, controlling population growth can help solve these problems (Timlett and Williams, 2009; Eyo and Ogo, 2013; Mendes et al., 2013; Rothwell et al., 2015). The third category strengthens environmental management, such as by increasing investments in environmental preservation, garbage classification, recycling, reducing industrial emissions, and using clean energy instead of fossil fuels, which can directly improve the urban ecological environment (Yeboah, 2010; Carvalho et al., 2011; La Gennusa et al., 2011; Liang and Zhang, 2012; Valdivia-Alcala et al., 2012; Li, 2013; Yeo et al., 2013; Linzner and Salhofer, 2014; Zhou et al., 2015). However, using only one particular policy to protect the urban environment and promote sustainable urban development, is often ineffective, and a policy portfolio approach generally provides increased effectiveness. Since the ecological consequences of gross economic activities and population growth far outweigh the restoration ability of an ecological system, in some cities, decreased economic growth successfully decreases rates of pollution generation but fails to control the total pollution volume, which increases. Therefore, some scholars have attempted to design various policy portfolios based on the three above mentioned policies to abate the total pollution generations of cities and achieve the sustainable development (Pearce, 2001; Capello and Faggian, 2002; Pihlak, 2009; Song et al., 2011; Gasper et al., 2011; Liu et al., 2011;Ji, 2011, 2015).

A city is a large, open, complex ecological-economic system, with interactions among economic factors, social factors, population factors, resources and environmental factors, etc. It is hard for conventional econometric approaches to conduct comprehensive and consistent analyses on the interactions among economic factors, social factors, and environmental factors of a city from a system perspective. Since the Emergy approach was proposed by Odum in 1996, researchers have used the new theory and methodology to investigate ecological-economic systems (Brown and Ulgiati, 2001; Campbell et al., 2005; Chen et al., 2009b; Zhang et al., 2009). Emergy is the total available energy of one type that is required to form a resource, product, or service (Odum, 1996; Brown et al., 2004). The emergy method accounts for the direct and indirect efforts of nature in generating resources and supporting production and human labor activities that promote economic performance. In so doing, it provides a link between ecology and the economy in studies of urban ecological-economic systems (Hardin, 1986; Daily and Ehrlich, 1992; Meyer and Ausubel, 1999). It can be used to transform different types of materials, resources, labors, and capitals with different units into a unified unit, the solar emjoule (sej), which is called "emergy synthesis" (Brown and Ulgiati, 2004; Chen and Chen, 2009a). Then, a quantitative analysis of the ecological-economic system can be conducted based on the unified units. With the assessment of the utilization value of natural resources in an ecological system, the real wealth of nature and society can be accurately evaluated (Odum, 2000). Some scholars have stated that the emergy analysis theory is based on natural values, and ecological flows and economic flows can be converted into emergy flows to uniformly assess the natural environment and human economic activities and to quantitatively analyze the structure, functions and ecological-economic benefits of the system.

However, it is difficult to study the dynamic interactions in cities and the policies that affect various factors using only the emergy method in a static manner. Any small change in one factor may lead to a huge change in the whole system; therefore, it is necessary to dynamically analyze the relationship between the internal structure of the system and the different subsystems. System dynamics (SD) can be used to properly analyze the causal relationships among various factors and to simulate urban ecological-economic systems. SD is a system simulation methodology for addressing complex dynamic feedback (Zhang et al., 2011; Zhao et al., 2011). Due to the systemic thinking and visualization characteristics of the method, it has been extensively applied in many research fields in which system analysis methods are generally used, including in social, economic, ecological, and resource and policy assessment systems (Forrester, 1969, 1971; Saysel and Barlas, 2001; Dyson and Chang, 2005). SD models have been applied to simulate urban systems to study urban water management (Bagheri and Hjorth, 2007; Winz et al.., 2009), urban energy consumption and environmental pollution (Feng et al.., 2013; Vafa-Arani et al.., 2014). However, significant attention has not been paid to the study of urban emergy flows in an urban ecological-economic system from the perspective of SD. Using computer simulations, SD can also show future trends of the related factors in the systems. The SD approach has significant advantages in terms of addressing complex systemic problems (Berling-Wolff and Wu, 2004; Arquitt and Johnstone, 2008).

This paper uses the SD approach to simulate the emergy flows in urban ecological-economic systems by constructing a SD model. Then, this model was used to analyze the dependence of urban economic development on external resources and nonrenewable resources, as well as future trends in resource consumption for different economic development levels. The innovation of this paper is the use of the SD model to simulate urban emergy flow systems, resulting in the establishment of an emergy-flow dynamics model.

2. Data and methods

2.1. Study area and data

Beijing is an international metropolis with a large population and high population density that has experienced rapid economic development. Common problems facing cities, such as overcrowding, substantial traffic, and air pollution, also exist in Beijing. Beijing is located at 115 °7′–117 °4′ E and 39 °4′–41°6′ N, and it covers an area of 16,410.5 Km^2, which includes six central districts (Dongcheng, Xicheng, Haidian, Chaoyang, Fengtai and

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