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Dynamic assessment of urban economy-environment-energy system using system dynamics model: A case study in Beijing

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ABSTRACT

Economic development, accompanying with environmental damage and energy depletion, becomes essential nowadays. There is a complicated and comprehensive interaction between economics, environment and energy. Understanding the operating mechanism of Energy-Environment-Economy model (3E) and its key factors is the inherent part in dealing with the issue. In this paper, we combine System Dynamics model and Geographic Information System to analyze the energy-environment-economy (3E) system both temporally and spatially, which explicitly explore the interaction of economics, energy, and environment and effects of the key influencing factors. Beijing is selected as a case study to verify our SD-GIS model. Alternative scenarios, e.g., current, technology, energy and environment scenarios are explored and compared. Simulation results shows that, current scenario is not sustainable; technology scenario is applicable to economic growth; environment scenario maintains a balanced path of development for long term stability. Policy-making insights are given based on our results and analysis.

1. Introduction

Rapid economic development has led to serious environmental issues that significantly affect human health. Government agencies and policy-making institutions have paid increasing attention toward enacting regulations and policies that both protect the environment and promote economic development. However, setting policy priorities to achieve this goal depends on balancing complex relationships between the environment, the economy, and energy consumption.

Many scholars have analyzed complex relationships and interactions between environment, economy and energy, in order to guide authorities to enact policies and regulations that balance sustainable economic development, sustainable energy utilization while protecting environment (Lenzen and Dey, 2002; Oliveira and Antunes, 2004; Simoes et al., 2015; Mundaca et al., 2015).

In this paper, we combine System Dynamics model (SD) and Geographic Information System (GIS) to analyze the energy-environment-economy (3E) system both temporally and spatially. SD has recently been applied to a wide range of problems, such as in the decision-making analysis of enterprises, cities and nations, as well as comprehensive research on society, economy, energy and the environment, and GIS is used to analyze the dynamic outcomes of the simulation on a spatial dimension, it can also quantify spatial analysis by overlaying various spatial variables (Lu et al., 2012; Rahman et al., 2009). Combined, spatial and temporal analysis clearly show the relationship and interaction of economy, energy and environment. For this purpose, we select Beijing as a case study. As the capital of China, Beijing is critical to economic development, generating a large part of gross national product (GDP) of the country, for example, the GDP of Beijing is 2.5 trillion yuan in 2016, contributing 3.3% of China. At the same time environmental problems in Beijing have become serious, especially air pollution, affecting numerous aspects of daily life, including human health. In order to systematically plan alternative policy approaches under these conditions, it is important to simulate and analyze the complex interactions between the environment, economy and energy, and forecast how these factors may change in Beijing. A system dynamics model (SD) is applied to simulate interactions in the 3E system and reflect temporal changes in the economy, environment and energy. We first adjust parameters to simulate different policy priorities, including technology, environment, energy and current priorities, and then compare projected outcomes for these simulated policy priorities. We then use Geographic Information System (GIS) to compare simulated outcomes from the SD model spatially. Every district in Beijing has its own simulated value, which is calculated based on the present

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value. The simulated value is used to analyze the distribution of energy, environment and energy. Simulation results shows that, current scenario is not sustainable; technology scenario is applicable to economic growth; environment scenario maintains a balanced path of development for long term stability. Policy-making insights are given based on our results and analysis. Our findings suggest that simple policy priorities do not favor sustainable development, and that combining policy priorities is the best option for promoting development.

2. Literature review

The 3E system has been widely used to analyze interactions and relationships between environment and economy in an effort to guide sustainable growth and development (Lenzen and Dey, 2002; Lazzaretto and Toffolo, 2004; Oliveira and Antunes, 2004; Hanley et al., 2006; Simoes et al., 2015; Mundaca et al., 2015).

System dynamics models are well-suited for forecasting long-term trends and have been used widely to simulate environmental change and energy utilization. Naill (1992) applies an SD model to simulate energy supply and consumption in the US, providing recommendations for the government, to improve energy utilization efficiency and mitigate global warming. Anand et al. (2006) incorporates factors, such as population growth and energy conservation to estimate CO2 emission from the cement industry in India based on an SD model, and assess the effect of policy on CO2 reduction. Stepp et al. (2009) applies SD tools to identify and understand the role of feedback effects on transportation-related greenhouse gas (GHG) reduction policies, generating a model that could be used to qualitatively analyze the effects of different policies. Lin et al. (2007) and Li et al. (2011) establishe an SD model of Energy Utilization and Greenhouse Gas Emission to study sustainable energy utilization and GHG reduction under uncertain conditions. Rozman et al. (2012) and Li et al. (2012) apply an SD model to revealing environmental, economic, social effects on ecological agriculture, and analyzing various policy scenarios. Walters and Javernick-Will (2015) employes an SD model, which uses feedback mechanisms to understand how dynamic and systemic factors, such as technology, finance, environment and others, to influence long-term water system functionality. Rahmani and Zarghami (2015) uses an SD model to simulate the climate change and uncertainty brought on by the assumption of stationary patterns in hydrologic time series. Mallick et al. (2016) combines global climate forecasts, SD and Monte Carlo simulations to assess the rate of change in climate parameters and analyze the effects of climate change on pavements.

Geographic Information System is used to collect, store, manage, and analyze the spatial and geographical data based on computer systems (Li et al., 2007; Guan et al., 2008). Over the last 30 years, GIS has developed into a powerful and efficient way to investigate spatial patterns (Mollalo et al., 2015). Geography is critical to environmental research, and, GIS has provided an important tool for analyzing environmental changes from a spatial perspective. Cinderby (1999) uses a new participatory approach developed by the GIS community, involving the integrations of spatial data and mental maps and how they use energy in environmental management. Lahmer et al. (1999) presentes a hydrological modeling approach based on the use of GIS, to provide new insight into the regional problems. Basso et al. (2000) integrates spatial data, to evaluate the environmental sensitivity of the Agri basin in Southern Italy, based on GIS. Wu et al. (2008) employes GIS to explore the relationship between esophageal cancer and climatic and geographic factors in China. Bai et al. (2014) characterizes a database management tool for developing a GIS, to observe and project data for decision-making. Rosenzweig et al. (2014) provide a globally consistent, protocol-based, multimodel climate change assessment for major crops, based on GIS. Song et al. (2015) combines Delphi survey, GIS and Monte Carlo simulation to assess regional ecological vulnerable areas and to quantify the uncertainty of assessing results. Tahri et al. (2015) combines GIS and Multi-Criteria Decision-making to evaluate the suitability of locations to carry out a renewable energy project. Ranjan et al. (2016) presentes an overview of the latest technology of GIS, and also the importance of GIS in practical use. Khan and Jhariya (2016) employes GIS to analyze the land use land cover (LULC) changed in Raipur and India and to assess the dynamic process taking place on the surface.

3. Methodology

We use a system dynamics model and geographic information systems to examine how various factors influence interactions between environment, economy and energy. The basic assumptions and settings on production function, technology function and energy function and their explanations are given in Appendix A. SD model is used to predict how the change of regulation and policy affect economic development, energy consumption and environmental disruption temporally. All codes of the SD model are provided in Appendix B. We selected Beijing as a case study. As the capital of China, Beijing is a large urban area undergoing rapid economic development, and thus exemplifies the complex interactions under investigation. Data is collected from the China and Beijing Statistics Yearbook, and relevant government websites, from 2000 to 2015.

Our aim is to use an SD model to forecast changes in trends related to economic development, environmental protection and energy consumption. Our SD model is composed of eight sub-systems, e.g., GDP, technology input, capital input, renewable resources, nonrenewable resource, SO2 emissions, chemical oxygen demand (COD) emissions, and solid waste emissions. The production function, which is based on the Cobb-Douglas production function, is one of the most important parts of our model. We consider three main types of environmental pollution in practice: air pollution, water pollution and solid waste pollution. We use SO2 emissions, COD emissions and solid waste emissions as proxies for air pollution, water pollution and solid waste pollution, respectively. We choose the year 2000 as a starting point, time period of the collected data is from year 2000 to 2015, and we establishe the model in VENSIM with the time step of 1 year, and the time span of 50 years from 2000 to 2050. Fig. 1 shows the stock-flow diagram of our model.

Thus, we adjust key parameters to compare outcomes under four scenarios, each representing different policy priorities: technology input (technology scenario), environmental protection input (environment scenario), and consumption elasticity of resources (energy scenario). We adjust these three parameters and compare how the changes of these parameters affect the outcomes. Table 1 gives initial parameters setting in current scenario, which are in accordance with consumption rate of energy resources, investment of environment conservation and technology of Beijing in practice (see Beijing Statistics Yearbook, and relevant government websites). For alternative scenarios, we adjust the value of corresponding parameters. For example, in energy scenario, for fixing other parameters, the value of consumption renewable and nonrenewable energy resources reduce to 0.3 and 0.15, respectively.

GIS model is used to analyze the dynamic outcomes of the simulation on a spatial dimension, it can also quantify spatial analysis by overlaying various spatial variables (Lu et al., 2012; Rahman et al., 2009). Combined, spatial and temporal analysis clearly show economy, energy and environment.

Beijing is composed of 16 districts and 328 streets or towns, each with its own present value. Thus, the simulation outcomes and changing trend of every street or town are possible to be calculate based on their present value. GIS software is applied to exhibits maps of projected spatial distribution for every street and town.