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An integrated data envelopment analysis and emergy-based ecological footprint methodology in evaluating sustainable development, a case study of Jiangsu Province, China

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ABSTRACT

Many cities are experiencing rapid urbanization and ecological degradation, which has resulted in unsustainable development. It is essential to conduct a scientifically rigorous method to assess the regional sustainability. Among many indicators, eco-efficiency could be an effective instrument to promote a transformation towards sustainability. This study applied the emergy ecological footprint analysis and data envelopment analysis to evaluate the eco-efficiency using data collected from 1993 to 2012 for Jiangsu Province, China. The results showed that Jiangsu's emergy ecological footprint and ecological deficit experienced an ascending trend in general during the period 1993–2012, indicating that the regional development of Jiangsu has been moving away from sustainability for a long time. In six types of biologically productive areas, fossil land and arable were the major parts of emergy ecological footprint. Furthermore, the growth of green gross domestic product was only about 52% of the conventional gross domestic product, and the pollutants emission, energy and resources consumption increased yearly as the gross domestic product increased. Finally, the result of the data envelopment analysis model showed that the effective years only accounted for 20% during the 20 years. In the inefficient years, biological resources, energy resources, pollutant emission (wastewater, gas and solid) and labor were overmuch, and the efficiency of fund usage achieved the optimal in Jiangsu Province. Therefore, improving the level of agricultural modernization, increasing the proportion of non-fossil energy, developing renewable energy and reducing pollutant emission are recommended to promote the regional sustainability.

1. Introduction

Currently, China is undergoing rapidly increasing gross domestic product (GDP), accompanied by the world history's largest flow of rural-urban migration, fast urbanization, rapidly expanding urban infrastructure, and dramatic reduction in environmental carrying capacity (Li et al., 2012). In particular, high energy consumption and environmental pollution have become the most important problems in building a harmonious and sustainable society in China and have caused considerable concern (Zhang et al., 2008). To reverse this trend, studies should be conducted related to how economy, society, and environment affect the sustainable development in a region or a nation. Additionally, the conflict between short-term economic profits and long-term ecological sustainability needs to be addressed. Effective methods for combined economic, social, and environmental assessment can assist policymakers in making appropriate decisions related to sustainability policies.

Eco-efficiency has been proposed as an indicator for sustainability analysis, indicating an empirical relation in economic activities between environmental cost or value and environmental impact (Mickwitz et al., 2006; WBCSD, 2000). It plays an important role in expressing how efficient the economic activity is with regard to ecosystem goods and services. The concept of eco-efficiency was first described by Schaltegger and Sturm in 1989 and then widely publicized in 1992. Later, it was accepted as the key strategic theme for global business with respect to commitments and activities directed at sustainable development (Ehrenfeld, 2005). To date, the concept of eco-efficiency has been extensively used

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in various fields, such as firms or production levels (Bremberger et al., 2015; Zhu et al., 2014), industry sections and regional level (Yu et al., 2013; Yin et al., 2014; Zhang et al., 2008). Bremberger et al. (2015) proposed an approach to implement environmental standards into Data Envelopment Analysis (DEA) and to measure its regulatory impact on eco-efficiency of firms. Zhu et al. (2014) estimated the eco-efficiencies of ten comparable pesticides and their life-cycle environmental impacts. Zhang et al. (2008) conducted an eco-efficiency analysis for regional industrial systems in China by developing DEA based models. Yu et al. (2013) chose GDP as the added economic value, the pollutant emission indicators as the added environmental impacts from economic growth, and evaluated the eco-efficiency trends in China for 1978–2010. Yin et al. (2014) used eco-efficiency as an indicator to measure urban sustainable development.

Eco-efficiency is measured as the ratio between the (added) value of what has been produced (high quality goods and services, jobs, GDP, etc.) and the (added) environmental impacts of the product or service:

$$Eco-efficiency = \frac{Value\ of\ products\ or\ services}{Environmental\ impacts} \tag{1}$$

At the regional level, GDP is often used as the numerator, and material flow indicators (e.g., direct material input) and pressure indicators (e.g., emissions of CO_2) are usually placed in the denominator as indicators of environmental pressure (Zhang et al., 2008). In short, the eco-efficiency is concerned with creating more value with less impact (WBCSD, 2000). Therefore, reducing environmental impact of a product and increasing its economic value can promote eco-efficiency and sustainable development. In a broad sense, sustainable development means the capacity to meet the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987). Regional sustainable development does not mean the sustainable development of any single economic, social, or environmental subsystem, nor simply adding to the sustainability of these subsystems. Instead, it attempts to balance economic growth, ecological construction, environmental protection, and social progress (Li et al., 2009).

Eco-efficiency assessment is a complicated and multidisciplinary task. There are numerous approaches to deal with this problem. However, because the numerator and denominator of Eq. (1) have different units, these environmental impact indicators in Eq. (1) need to be aggregated into top-indicators. In the economic dimension, there is a common unit-money; in the environmental dimension, data and indicators are extensive, complex, and measured on different scales. To build up an encompassing environmental impact score, a weighted sum of the various environmental impacts is usually used (Zhang et al., 2008). Indeed, this is a kind of subjective appraisal method which may lead to inaccurate results (Rashidi and Saen, 2015). DEA is considered to be a solution for aggregating economic, social, and environmental indicators with different units to construct an encompassing of eco-efficiency indicators (Huang et al., 2014; Picazo-Tadeo et al., 2011). As one of the most popular techniques in estimating relative efficiency, DEA has some advantages as compared to other approaches that measure efficiency. (1) It does not require the identification of the relationships between the inputs and the outputs; (2) the information required in DEA is less than that in traditional methods; (3) it can change an inefficient decision-making unit (DMU) into an efficient one by slack and radial adjustment, analyzing the reasons for the inefficiency, and then correspondingly proposing plans to improve it (Shi et al., 2010). However, this method has some limitations. For instance, WBCSD (2000) and UNCTAD (2003) proposed several environmental-performance indicators, such as energy consumption, water consumption, waste, and ozone-depleting substance were one-sided and incomplete. In previous studies, the ecological inputs of regional eco-efficiency have been only considered the pollutant emission (undesirable outputs) or energy consumption (Alves et al., 2015; Bian and Yang, 2010; Jin et al., 2014; Yin et al., 2014; Zhang et al., 2008). Although these environmental impact indicators of DEA seem direct and manageable from a decision-maker's perspective, the evaluation results of eco-efficiency are rather unilateral and subjective. In contrast, ecological footprint (EF) is an aggregate index of environmental impacts with a scientifically sound calculation procedure (Li et al., 2010). However, the focus of the EF method is only on the quantity of biomass produced from different types of biologically productive areas, and it fails to consider the resource's quality, which is the intrinsic value of the ecological products (Wu et al., 2015).

To address this issue, there were some potential improvements proposed in the current EF method. Wackernagel and Monfreda (2004) indicated, embodied energy should be considered, especially the free energy source dominated by the energy embodied in most renewable resources infrastructure. Recently, a modified approach based on EF and emergy analysis, namely the emergy ecological footprint (EEF) was originally proposed by Zhao et al. (2005). After that, several researchers, mostly from China, introduced the new method to evaluate the sustainable development (Chen and Chen, 2006; Liu et al., 2008; Wu et al., 2015; Zhao et al., 2013). This EEF method introduced the emergy density instead of the equivalence factor and yield factor of conventional EF to assess sustainable development more comparable, comprehensively and accurately.

Unfortunately, the evaluation of sustainable development with eco-efficiency analysis based on the EEF method is still lacking. In addition, in evaluating regional eco-efficiency with DEA method, many studies used GDP as the "desirable output" (Bian and Yang, 2010; Jin et al., 2014). But, GDP has been severely criticized for its failure to adequately capture human welfare and progress (Van den Bergh, 2009). In other words, only part of nature's value is captured in the GDP, because the GDP ignores a large number of economically valuable inputs and outputs that are not bought and sold in the marketplace, such as the wide range of ecosystem services (Talberth and Bohara, 2006). Different from the GDP, the green gross domestic product (GGDP) is meant to account for nature's value on an equal footing with the market economy, requires measurement of the benefits arising from public goods provided by nature for which there are no market indicators of value (Boyd, 2007). Although some studies stated that the GGDP should be used in future regional-scale eco-efficiency measurements, these kinds of studies are few, especially in China (Yin et al., 2014).

Thus, this paper introduces a developed eco-efficiency framework based on ecological footprint, emergy theory, GGDP and DEA to provide a more comprehensive and accurate evaluation for sustainable development.

2. Methods

2.1. Emergy analysis

Emergy, first proposed by Odum in 1980s, is defined as a measure of the total available energy directly and indirectly involved in the processes of making a product or service (Brown and Ulgiati, 2010). Emergy analysis is based on the principle of energetic, system theory, and system ecology, which can convert different types (and incomparable forms) of energy in the ecosystem into a standard energy unit by using different transformities to evaluate the characteristics and eco-economic benefits of the functions and structures of different systems (Wei et al., 2012; Yang et al., 2014; Zhao et al., 2005). The transformity is defined as the amount of