Science of the Total Environment 649 (2019) 582–591

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Evaluation of ecological sustainability based on a revised three-dimensional ecological footprint model in Shandong Province, China

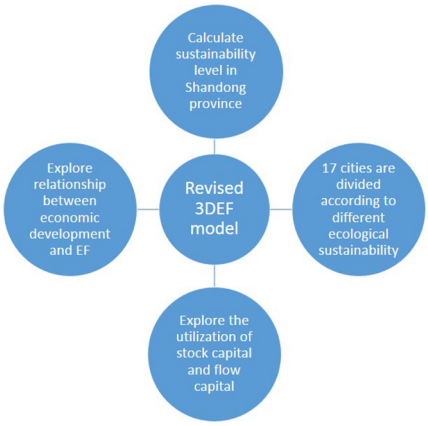
Fangfang Xun [a], Yecui Hu [a,b,*]

[a] School of Land Science and Technology, China University of Geosciences, 29 Xueyuan Rd, Beijing 100083, China
[b] Key Lab of Land Consolidation and Rehabilitation, Ministry of Land and Resources, 37 Guanying Rd, Beijing 100035, China

HIGHLIGHTS

- Shandong Province consumes numerous stock capital and in an unsustainable development state.
- 17 cities widespread showed ecological deficits, and energy has a positive correlation with footprint depth.
- The relationship between economic development and ecological footprint is roughly "n" Kuznets curve.
- 17 cities are classified to four types according to the difference in natural capital utilization.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 24 March 2018
Received in revised form 20 July 2018
Accepted 8 August 2018
Available online 9 August 2018

Editor: P. Kassomenos

Keywords:
Three-dimensional ecological footprint
Sustainable development
Shandong Province
Capital flow
Capital stock

ABSTRACT

This study used the revised three-dimensional ecological footprint model (3DEF), to calculate the status of sustainable ecological development in Shandong Province in 2010–2015, analyze dynamic changes in sustainability characteristics, and explore factors affecting sustainable development. The results showed the following (Wackernagel & Rees, 1996). Seventeen prefecture-level cities featured varying degrees of ecological deficits, and ecological development was unsustainable in all cities (Wackernagel et al., 2004). Footprint sizes differed between the cities, but changed little over time. Cropland was the main contributor to footprint size, as it was the main capital flow utilization component (Daly, 1994). For all cities, footprint depth exceeded the original length of 1; lack of capital flow caused capital stock depletion. There was a significant positive linear correlation between changes in energy footprint and footprint depth (Zhou et al., 2015). The 17 prefecture-level cities were divided into four natural capital utilization categories using clustering: zone I (2 cities), in which capital stock consumption greatly exceeded capital flow occupancy, contain the most severe ecological stress; zone II (9 cities), wherein the level of stock capital consumption was significantly higher than capital flow consumption, the regional development pressure was greater, and the ecological sustainability was lower; zone III (4 cities), which featured mild natural capital utilization and a relatively high capacity for sustainable development; zone IV(2 cities), which featured lagging stock capital utilization, relatively, and the highest capacity for sustainable development. These results would help coordinate resource utilization and economic development in Shandong Province.

* Corresponding author at: Key Lab of Land Consolidation and Rehabilitation, Ministry of Land and Resources, 37 Guanying Rd, Beijing 100035, China.
E-mail addresses: 2112160027@cugb.edu.cn (F. Xun), huyc@cugb.edu.cn (Y. Hu).

https://doi.org/10.1016/j.scitotenv.2018.08.116
0048-9697/

1. Introduction

The rational use of natural resources and protection of the environment are crucial for sustainable regional sustainable development. The ecological footprint (EF) model established by Wackernagel and Rees (1996) provides a new perspective in regional sustainable development assessment and has been widely recognized and applied by scholars. EF represents the ecological environmental occupancy in terms of resource consumption in a certain population. Biological capacity (BC) represents the ability of the natural capital to supply. Then, the sustainability of local development is assessed by comparing the natural capital supply and demand (Wackernagel et al., 2004). Natural capital can be divided into capital flows and capital stocks (Daly, 1994). Unfortunately, the traditional EF model does not distinguish the relationship between natural capital flows and capital stocks, nor does it reflect the temporal accumulation of ecological overdraft (Zhou et al., 2015). Numerous scholars have sought to overcome these deficiencies (Dai et al., 2010; Niccolucci et al., 2009; Niccolucci et al., 2011; Peng et al., 2006; Zhang and Zhang, 2006; Zhou et al., 2015). Niccolucci et al. (2009) introduced ecological footprint depth (EF_{depth}) and ecological footprint size (EF_{size}) into a new spatio-temporally resolved three-dimensional ecological footprint(3DEF) model, in which EF_{depth} and EF_{size} reflects the depletion of capital stocks and use of capital flows, respectively. The original EF_{depth} value is 1; in this case, natural capital supply and demand are in dynamic equilibrium, i.e., a state of sustainable development. EF_{depth} values exceeding the original value of 1, indicate ecological overloading and unsustainable natural capital use (Niccolucci et al., 2011; Wang and Wang, 2011). To explore global EF_{depth} and EF_{size} values from 1961 to 2006, Niccolucci et al. (2011) used national footprint date to test and verify the 3DEF model at the national scale. The 3DEF model as a new approach provides a multidimensional perspective from which to explore regional sustainability. Fang first applied the 3DEF model concept and method in China, analyzing provincial capital utilization patterns in China and conducting cluster analysis for the provinces; the provincial natural capital utilization patterns feature obvious geographical agglomeration (Fang and Li, 2012). Using Beijing as an example, Peng discussed the multidimensional framework of "ecological equality and efficiency" by combining natural capital and Human Development Index (HDI). Based on an analysis of EF_{size} and EF_{depth}, Peng et al. (2015) observed that the consumption of capital stock and capital flow complement each other. Subsequently Fang explored the development of the classical EF model and the 3DEF model, observing that previous studies did not provide clear calculations of EF_{size}, and that offsets in ecological deficits and surpluses for different land types affected the accuracy of the results; therefore, Fang and Reinout (2012) optimized the indicator calculation method and suggested that the improved model required further empirical research. Then, Fang conducted empirical research in China, the world, and the G20 countries, finding that the revised 3DEF model more accurately reflects natural capital utilization in these regions (Fang, 2013, 2014, 2015; Fang et al., 2013). Liu et al. performed research at the city scale using the revised 3DEF model, calculating the level of sustainable development in Zhangjiakou City and observing that BC decreases - when 3DEF and deficit increase; the results were used to predict trends of sustainable development in 2014–2020, providing data to support future development in Zhangjiakou (Liu et al., 2016).

Using the revised 3DEF model, scholars have examined the factors affecting the ecological footprint. Fang et al. (2013) observed that fossil fuels are the most important means of capital stocks utilization and a dominant driving force behind ecological overload. Resource-rich countries have higher capital flows, less need for capital stocks, and they always have higher EF_{size} and lower EF_{depth}; the opposite is true for resource-poor countries. According to an analysis of G20 countries, natural capital flow occupancy and capital stock consumption are complementary; and sustainable development is constrained by resource endowments and economic development (Fang, 2014). There is a negative correlation between capital flow occupancy and capital stock consumption in 11 countries worldwide, and the natural resource flow occupancy level is mainly constrained by renewable resource endowments, while the consumption of natural capital stock is driven by the level of socio-economic development (Fang, 2015). Using the 3DEF model, Du et al. observed that all 13 cities in the Beijing-Tianjin-Hebei urban agglomeration showed ecological deficits. EF_{depth} is affected by the quantity and structure of energy consumption and shows an "inverted N-type" Kuznets curve when plotted against the regional economic development level (Du et al., 2016). Research results from the 3DEF model were reviewed, and the revised 3DEF model was found to be more accurate for calculating regional sustainable development levels; in addition, economic development and energy consumption were found to have substantial impacts on the footprint. However, many previous studies analyze only single samples or compare different regions within a single year; few studies have compared different regions over different periods.

China has undergone continuous urbanization, and the urbanization rate in Shandong Province increased from 49.71% in 2010 to 59.02% in 2016 (Shandong Provincial Bureau of Statistics, 2011, 2016), at an average annual growth rate of 1.55%. As the second largest province of China, in terms of population, Shandong Province ranks third in the country in gross domestic product (GDP). Because they pose a great challenge to sustainable ecological development, energy consumption and waste disposal cannot be ignored. Although Qingdao and Weihai have been listed among the top 10 most livable cities in China for many consecutive years, the extensive, energy resource-based development model in Shandong Province has become a bottleneck, restricting economic development; and creating great pressure on the ecological environment.

Shandong Province, an important economic region in northern China, and faces serious ecological fragility, environmental pollution, and resource consumption issues; faces the challenge of replacing old growth drivers with new ones. In order to improve the level of ecological environment and promote regional coordinated development, this paper explored the level of sustainable development, the relationship between economy, population and natural resources utilization, sustainable level of natural capital utilization and causes of differences in natural capital consumption. This study uses the revised 3DEF model to provide scientific and objective ideas for green development, analyzed the composition of and differences in per capita EF_{depth} and EF_{size}, and distinguishes and tracks capital flow consumption and capital stock depletion. The results will provide a reference for the coordinated development of social economy and ecological environment.

2. Overview of research area

Shandong Province (114°47.5′E to 122°42.3′E, 34°22.9′N to 38°24.01′N) is located along the eastern coast of China and lower reaches of the Yellow River (Fig. 1). It contains 17 cities, including 2 sub-provincial cities (Jinan, Qingdao) and 15 prefecture-level cities. The province includes the peninsula and inland areas. Rich in marine resources, the offshore area accounts for 37% of the total area of the Bohai and Yellow Sea; beaches account for 15% of the area. The total land area of Shandong Province is 15.79 million hm^2, making it the 20th largest province in China. The warm, temperate monsoon climate features an annual average temperature of 11–14 °C. Shandong has abundant mineral reserves, and occupies an important position in China. According to the 6th Chinese census, the province had a resident population of 95.79 million in 2010 With a concurrent, GDP of 3.9 trillion yuan. The population increased to 98.47 million and the GDP increased to 6.3 trillion yuan in 2015.

3. Data sources and three-dimensional ecological footprint accounting

3.1. Data sources

This study uses primarily socioeconomic data and land use data. The socioeconomic data used herein include biological resource consumption