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Spatial-temporal Evolution of Ecological Security in Beijing based on Emergetic Ecological Footprint

Keling Liu[1], Bin Chen[1,*]

1 State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, P.R. China (Corresponding Author, Email: chenb@bnu.edu.cn)

ABSTRACT

With high population density and intensive energy consumption, Beijing has long been facing the huge challenge of ecological security in context of coordinated development of environment and economy. Combining statistical and grid data, this paper analyzed the ecological security status in Beijing from three scales, i.e., city, sub-city and grid, based on an emergetic ecological footprint model. The emergetic ecological footprint (EEF), emergetic ecological carrying capacity (EEC), emergetic ecological deficit (EED) and emergetic ecological pressure index (EEPI) were used to evaluate the ecological security status of Beijing from different scales. Results show that Beijing has been in the state of ecological deficit from 2005 to 2017, and the multi-year average value of ecological pressure is 9.18 with great differences in the spatial distribution of ecological security. Concrete measures are then suggested to promote the ecological security of Beijing.

Keywords: emergetic ecological footprint, urban ecological security, grid scale

1.INTRODUCTION

Ecological security is the cornerstone to ensure the sustainable development of national and social economy [1]. Urban ecological security is particularly important because it detects whether the environment can support the urban development and residents' life, and whether the urban system can evolve with normal urban ecosystem functions considering atmosphere, water, food, energy, and ecosystem service.

Currently, ecological footprint has been widely used as a suitable metric of ecological security because of its convenient calculation, clear indicators, visual and strong operability [2]. It was proposed by Rees and Wackernagel and defined by transforming the biomass required by human activities into the land area that can provide biomass and absorb the waste produced by people [3-4]. Most often, it is calculated from the perspective of carrying capacity to measure the limit of regional ecosystem and the pressure of human consumption activities on the environment [5]. However, the conventional ecological footprint method ignores the impact of time and region on biological productivity and the ecological function of some unproductive land types [6].

Emergetic ecological footprint model combines the traditional ecological footprint with emergy theory. The calculation of regional ecological footprint from the perspective of emergy flow, and the adoption of more stable parameters such as solar energy conversion rate and regional emergy density, can simulate the regional ecological occupation and ecological carrying capacity, and then evaluate the current level of regional ecological security [7-8]. Regional emergy density and solar energy conversion rate are important parameters in emergetic ecological footprint model. The self-organization and order of natural ecosystem have reached a high level, so that the solar energy conversion rate, which convert different types of energy into unified solar energy value, and the regional energy density, which converts solar energy value into land area, are more stable, and their fluctuation with time is very small [9]. There are some studies using emergetic ecological footprint model to study different scales such as country [10], province [11], and city [12-14]. Smaller scales are rarely considered, such as the spatial distribution within cities.

Beijing has a growing population with a small share of per capita resources. Accurately identifying the current situation of ecological security in Beijing is an important basis for scientific decision-making. In view of this, taking Beijing as an example, this paper adopts a modified emergetic ecological footprint model to calculate and analyse the change trends of ecological footprint and ecological carrying capacity in Beijing from

2005 to 2017, and evaluates the current situation of ecological security in Beijing using evaluation indicators based on the scales of city, sub-city and grid.

2. MATERIAL AND METHODS

2.1 Data source and processing

The agricultural products, forest products, livestock products, aquatic products, energy consumption, precipitation, and average wind speed in Beijing from 2005 to 2017 used in this study are from the Beijing Municipal Bureau of Statistics. The emissions of SO_2, NO_x, dust, chemical oxygen demand (COD), and ammonia nitrogen in Beijing from 2005 to 2017 are derived from the Beijing Municipal Bureau of Ecology and Environment. Digital Elevation Model (DEM) data comes from the geospatial data cloud platform (http://www.gscloud.cn/), and the spatial resolution is 30m. The grid data including the kilometer grid GDP and population data in 2005, 2010, and 2015 come from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn). The grid data is processed by mask extraction to avoid errors in grid calculations, so that the numbers of rows and columns of each grid data are consistent.

2.2 Methods

2.2.1 Modified emergetic ecological footprint model (EEF)

EEF reflects the characteristics of regional ecological economy and represents the degree of human load. Previous studies calculated the production consumption and energy consumption, or incorporated the consumption of pollution, while ignored the consumption of water resources. Therefore, in this study, water resource consumption is included in the accounting for a modified EEF model. The resource consumption items of EEF are divided into four accounts, i.e., biological resources account (EEF_b), energy consumption account (EEF_e), water resources account (EEF_w) and pollution account (EEF_p). The calculation is as follows [9-11]:

$$EEF = EEF_b + EEF_e + EEF_w + EEF_p \tag{1}$$

For the biological resources and energy consumption [10]:

$$EEF_{b(e)} = \frac{p_i(c_i) \times T_i \times UEV_i}{RED} \tag{2}$$

where $p_i(c_i)$ is the production or consumption of item i; T_i is the energy conversion coefficient of item i; UEV_i is the unit emergy value of ith project; *RED* is the regional emergy density.

For the pollution footprint [12]:

$$Q_i = d \times \frac{E_i}{con_i} \tag{3}$$

where Q_i is the mass of air or water required to absorb the ith discharge in the study area; d is the density of air or water (1.23kg/m^3 for air, 1000 kg/m^3 for water); E_i is the pollution emission of the ith type; con_i is the allowable emission concentration of the ith type.

$$E_p = Max\left(0.5 * Q_i * v^2 * UEV_{air}\right) + Max\left(Q_i * \rho * UEV_{water}\right) \tag{4}$$

where E_P is the solar energy value required for dilution of pollution emission; v is the annual average wind speed; UEV_{air} is the unit emergy value of air; ρ is the calorific value coefficient of water (2.5×10^4 J/kg); UEV_{water} is the unit emergy of water. Since both air and water can dilute different pollutants at the same time, only the maximum ecological services absorbed by air and water are calculated. Therefore, the calculation formula of pollution account is as follows [12]:

$$EEF_p = \frac{E_p}{RED} \tag{5}$$

For the water resources account [14]:

$$EEF_w = \sum_{i=1}^{n} \frac{E_{wi} \cdot T_{wi}}{P} \tag{6}$$

where E_{wi} is the water consumption of ith type (m^3); T_{wi} is the conversion rate of solar emergy value of the ith water type (*sej*/m^3); P is the regional emergy density (*sej*/hm^2).

2.2.2 Emergetic ecological carrying capacity (EEC)

EEC is a measure of the richness of regional resources, which reflects the ability of a regional ecosystem to provide resources and space for human survival. Previous studies have not described the supply capacity of water resources. This paper divides ecological carrying capacity into renewable resources account (EEC_r), socio-economic carrying capacity account (EEC_s) and water resources carrying capacity account (EEC_w). The calculation formulas are as follows [11]:

$$EEC = (1-0.12) \times (EEC_r + EEC_s + EEC_w) \tag{7}$$

The factor of 0.12 is set for biodiversity conservation area according to the recommendation of the World Commission on Environment and Development. For the renewable resource carrying capacity:

$$EEC_r = sunlight + earth\ cycle + net\ soil\ loss\ energy + Max\{wind\ kinetic, rain\ chemical\ potential, rain\ geopotential\} \quad (8)$$

For the socio-economic carrying capacity [11]:

$$EEC_s = \frac{EMR \cdot PPI \cdot (OVH + IFA + LS)}{GED} \quad (9)$$

where EMR is the ratio of regional emergy to currency (sej / yuan). PPI is the producer price index, which can eliminate the impact of price fluctuations on socio-economic accounts and ensure the comparability of annual values. This paper takes 2017-2018 as the base period. OVH is the output value of high and new technology (yuan); IFA is fixed asset investment (yuan); LS is labor service (yuan).

For the water resource carrying capacity [14]:

$$EEC_w = 0.4 \times \frac{E_G + E_U}{P_w} \quad (10)$$

where E_G is surface water chemical energy (*sej*); E_U is groundwater chemical energy (*sej*); P_w is the average energy density of regional water resources (*sej*/hm^2). The factor of 0.4 is to deduct 60% of the water resource ecological carrying capacity for maintaining the deterioration of the ecological environment.

2.2.3 Ecological security evaluation indicators

1) Emergetic ecological deficit / ecological surplus (EED/EES)

EED/EES can depict the relationship between ecological environment supply and human survival demand, and reflect the utilization intensity of resources by the ecosystem in the region [9].

$$EED(EES) = EEC - EEF \quad (11)$$

(2) Emergetic ecological pressure index (EEPI)

EEPI uses the pressure borne by the unit ecological capacity of the ecosystem in the region to evaluate the status of urban ecological security (Table 1) [10].

$$EEPI = EEF / EEC \quad (12)$$

Table 1 Classification of Regional Ecological Security (ES) Level Based on EEPI

ES level	ES	Range of EEPI
1	Security	0～1
2	Sub-security	1～10
3	Slightly insecurity	10～18
4	Moderately insecurity	18～24
5	Highly insecurity	24～30
6	Extremely insecurity	≥30

2.2.4 Emergetic ecological footprint in grid scale

Emergetic ecological footprint calculation is often restricted by the lack of statistical data. Most statistical data take administrative regions (provinces, cities, counties, districts) as statistical units, and the statistical data of smaller units are basically missing or difficult to obtain. Since GIS data can obtain spatial distribution data such as population and precipitation of different grid units, we use the mathematical analysis method in ArcGIS software to determine the grid scale of EEF, EEC and EEPI as 1km, and overlap it with administrative division vector data to analyze the correlation between scales.

$$EEF_{ij} = \frac{EEF_i}{p_i} \times p_j \quad (13)$$

where EEF_{ij} is the EEF of the *j*th grid in the *i*th administrative region; EEF_i is the EEF of the *i*th administrative region; P_i is the population of the *i*th administrative region; P_j is the population in the *j*th grid.

Since EEC is composed of three parts, it needs to be calculated separately. The natural resource account needs to calculate the corresponding grid data using the grid calculator in ArcGIS software according to the calculation. The socio-economic account is calculated according to the following formula:

$$EEC_{ij} = \frac{EEC_i}{p_i} \times p_j \quad (14)$$

where EEC_{ij} is the EEC of the *j*th grid in the *i*th administrative region; EEC_i is the EEC of the *i*th administrative region.

Here we assume that the per capita water supply level is consistent in the same administrative region. Combined with the spatial distribution data of 1 km grid precipitation, the water resource carrying capacity in each grid can be calculated as:

$$EEC_{wij} = (EEC_{wGi} + EEC_{wUi}) \times p_j \quad (15)$$

where EEC_{wij} is the EEC of water resources of the *j*th grid in the *i*th administrative region; EEC_{wgi} and EEC_{wui} are the per capita surface water ecological carrying capacity and per capita groundwater ecological carrying capacity of the *i*th administrative region, respectively.

The EEPI value of each grid unit can be obtained by dividing the EEF by EEC on grid scale.

3 RESULTS

3.1 Temporal variation characteristics of emergetic ecological footprint at city scale

From 2005 to 2017, EEF increased first and then stabilized. EEF increased from 1.52E+08 hm^2 in 2005 to

1.81E+08 hm^2 in 2017, with an average annual growth of 1.59%. The contribution of EEF_e is the highest, 77% -88%, followed by EEF_b, with a contribution rate of 8% -18%, while EEF_p and EEF_w have the lowest contribution rate, with a contribution rate of 1%-3%. Energy consumption is the main source of energy ecological footprint in Beijing. The decline of EEF per capita indicates that people's awareness of energy conservation and environmental protection is increasing, and the government's propagation has an explicit outcome.

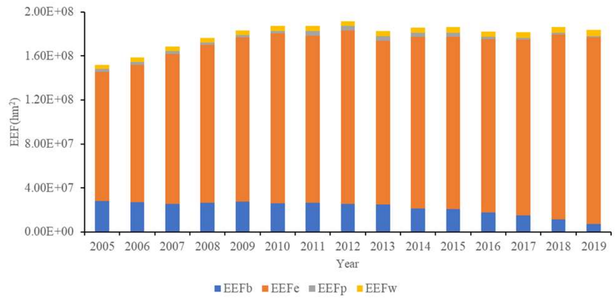

Fig 1 The changing trend of EEF and its components

The change of EEC showed an upward and downward fluctuation trend. The contribution rate of renewable resources is 40%-46%, the contribution rate of socio-economic carrying capacity is 38% - 43%, and the contribution rate of water resources is the least, 13% -22%. This shows that the main sources of ecological carrying capacity in Beijing are renewable resources and socio-economic carrying capacity.

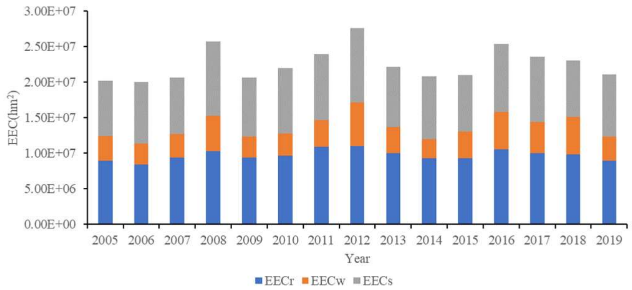

Fig 2 The changing trend of EEC and its components

Beijing is in the state of ecological deficit with an average of -8.24hm^2/cap. EED shows a decreasing trend with an average annual decrease of 1.28%. The average value of EEPI is 9.18, indicating that Beijing is in a sub-safe state. The overall trend of EEPI fluctuates with slight range. The change of EEPI is mainly affected by the size of EEC. If the supply of natural resources (rich precipitation or developed wind) or socio-economic supply increases in a certain year, the EEPI will be reduced that year.

3.2 Temporal variation of emergetic ecological footprint at administrative scale

The EED of Daxing and Shunyi were the highest, and the average values were -19.44 hm^2/cap and -21.05 hm^2/cap, respectively. Obviously, only Mentougou is always in the state of ecological surplus. Yanqing has changed to ecological surplus since 2012, showing a trend of surplus growth year by year, and other administrative regions are in ecological deficit. There is a trend of ecological deterioration in Dongcheng and Xicheng, and their EED increases year by year.

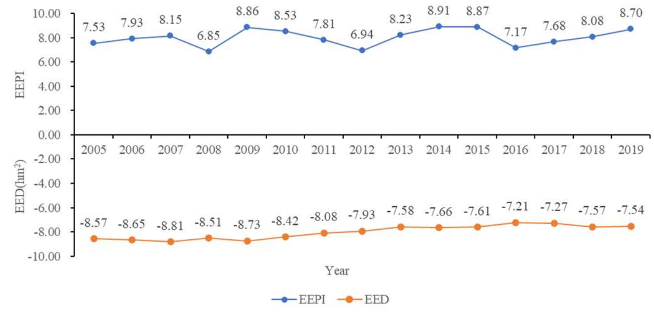

Fig 3 The changing trends of EED and EEPI

3.3 Temporal variation characteristics of emergetic ecological footprint at grid scale

EEF, EEC and EEPI show the spatial distribution of high center and low surrounding. The highest value of EEF increased continuously, from 50149.9hm^2 in 2005 to 647348hm^2 in 2015, an increase of about 12 times. The area with the highest EEF value has also expanded with the passage of time. By 2015, the EEF value in the central urban area is basically greater than 50000 hm^2. In the early stage (2005-2010), the EEF gradually shifted from the west to the east of the city, the EEF of Mentougou and Fangshan decreased, and the EEF of Daxing and TongZhou increased, which may lay a foundation for the construction of urban sub centers. In the later stage (2010-2015), the EEF of Yanqing, Huairou, Miyun, Mentougou, Tongzhou, Fangshan continued to decline, which may be closely related to the efforts of the environment construction. The highest value of EEC increased from 3315 hm^2 in 2005 to 30780 hm^2 in 2015, which may be related to the rapid growth of GDP during the study period, which increased nearly 10 times during the study period. The carrying capacity of the surrounding urban areas mainly depends on the carrying capacity provided by renewable resources, while the economic carrying capacity of the central urban area plays a decisive role.

Therefore, the EEC of the surrounding urban areas is often less than that of the central urban area. The EEPI of central district has a significant growth trend. Although Beijing was in a state of sub-security from 2005 to 2017, there were great differences in its spatial distribution. Specifically, most of the surrounding urban areas are in a sub-safe state, while the central urban area has gradually changed from a mild unsafe state to a moderate unsafe state. By 2015, some areas have shown extreme insecurity.

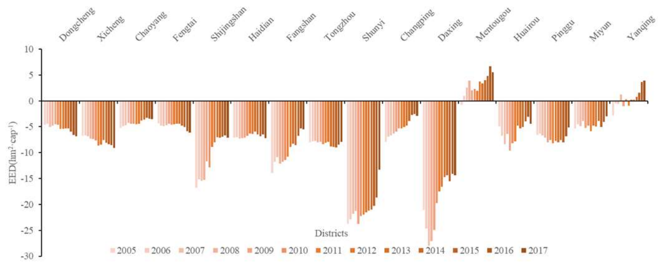

Fig 5 The changing trends of EED in Beijing districts

4 DISCUSSION

A modified emergetic ecological footprint model is proposed to evaluate the ecological security status in Beijing. The results show that Beijing is in the state of ecological deficit and sub-security all the year round, which is consistent with the previous results of Yang and Zhang [10,14]. In comparison, we increase the consideration of ecological occupation of water consumption, ecological carrying capacity of water resources and pollution absorption function. The water resources security situation in Beijing also shows that the consumption is greater than the carrying capacity all year round. Therefore, the ecological pressure calculated in this paper is slightly high (Table 2), which reflects the tension between supply and demand of water resources in Beijing. Water scarcity has become a key issue affecting the social and economic development of Beijing. From 2005 to 2017, the energy consumption footprint accounted for more than 50% of the total footprint. The development of new energy is one alternative for the future energy in Beijing. The promotion of new energy vehicles and transformation technologies such as using electricity and gas to replace coal in heat supply will reduce the energy consumption appropriately.

Daxing and Shunyi have the highest per capita emergetic ecological deficit. Daxing is a typical industrial development area with great energy consumption, and the EEF is in the forefront of all administrative regions. Shunyi is a typical agricultural development area with good environment. Chaobai River flowing through this area is also of the best water quality in Beijing. However, Shunyi has a high per capita ecological deficit, which reflects the high degree of people's consumption of resources. There may exist obvious waste and overuse of resources. Therefore, it is necessary to strengthen the popular science education on environment protection and resource conservation in Shunyi, and increase the awareness of environmental protection and resource conservation of Shunyi citizens, so as to reduce the burden of environmental bearing pressure in Shunyi.

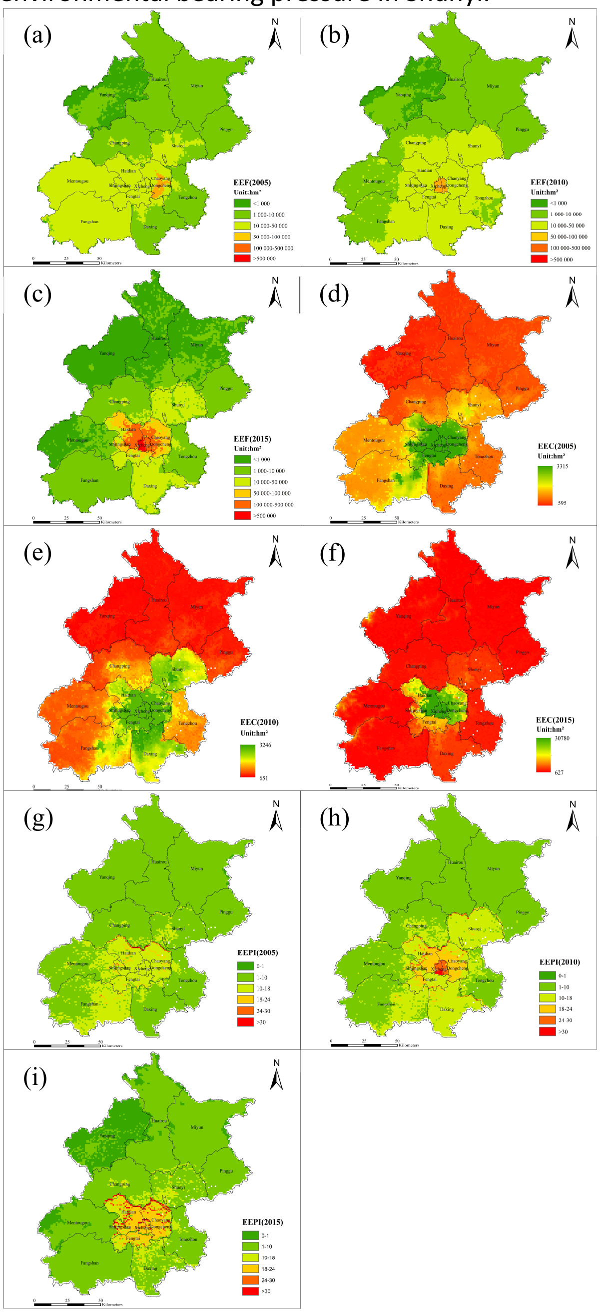

Fig 7 The spatial distribution and change trends of EEF, EEC, EEPI at grid scale. (a)-(c),2005-2015 EEF; (d)-(f), 2005-2015 EEC; (g)-(i),2005-2015 EEPI.

The spatial distribution of ecological security in Beijing has significant uneven spatial distribution. The maximum difference between the ecological pressure of the central urban area and the surrounding administrative areas is more than 100 times. Therefore, from the perspective of internal configuration, a reasonable population layout is a very important measure to alleviate the urban ecological security situation in Beijing. It is suggested to transfer high-tech industries to the surrounding administrative regions, attract talents, improve educational resource and realize population transfer adjustment, so as to alleviate the ecological pressure of the central urban area and ensure the sufficient and continuous supply of energy, water resources, agricultural products and other resources.

Table 2 The comparison with other studies of EEPI

	2006	2007	2008	2009	2010	2011
This Study	9.18	9.41	7.90	10.22	9.83	9.00
Yang [9]	9.12	9.13	8.79	8.47	8.05	7.03
Zhang [13]	-	-	-	-	9.29	11.69
	2012	2013	2014	2015	2016	2017
This Study	7.98	9.49	10.28	10.23	8.25	8.84
Yang [9]	6.77	5.86	5.97	5.47	-	-
Zhang [13]	10.84	9.61	9.04	5.37	3.56	5.94

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