



Urban ecological security dynamic analysis based on an innovative emergy ecological footprint method

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Received: 20 April 2020 / Accepted: 11 March 2021 / Published online: 23 March 2021
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Abstract

In China, with the rapid development of economy and the advancement of urbanization, the deterioration of urban ecological environment is obvious. In order to obtain the quantitative state of urban ecological security, this paper contributes an integrated and coupled emergy ecological footprint framework and Beijing city was selected to verify methodology effect in this paper. The results demonstrate that: (1) from 2010 to 2019, the change range of EEFB is from 6.37 to 9.29%; meanwhile, EEFI is from 7.95 to 17.72%; EEFE is from 36.36 to 63.71%; EEFP is from 18.45% to 41.65%. Comparing the proportions of four subparts, the energy resource products (EEFE) and emissions (EEFP) are the main factors, far more significant than biological resources (EEFB) and industrial products (EEFI). (2) Compared to all ECCS data, there is a definite growing trend in Beijing city, from 2.68E + 4 hm²/cap in 2010 to 4.72E+4 hm²/cap in 2019, approximately 42.22% growth range. (3) Four sustainable indicators analysis: The changes of EEFT, EBI, and EEF are from 3.1, 2.46, and 1.02 in 2010 to 0.688, 9.29 and 1.14 in 2019, respectively. For EDI, total proportions of fossil land and built-up land are 85.25% to 90.43% of the entire EEF in Beijing city. These results reflect that Beijing city is suffering from a substantial ecological challenge due to remarkable ecological deficit, awfully high emergy ecological footprint intensity, and low cooperation level between ecological system and economic system. To identify key improvement factors, Pearson correlation analysis was conducted in this paper and revealed the most positive and negative elements, which are the unbalanced industrial structure and a large proportion heavy and polluting industries in Beijing city. Finally, based on the pivotal influencing factors, corresponding strategies and measures are proposed to improve and optimize the ecological security in Beijing city.

Keywords Ecological security · Emergy analysis · Ecological footprint approach · Emergy carrying capacity · Ecological and economic coordination · Sustainability in Beijing

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1 Introduction

As a central goal, the sustainable and coordinated development of cities and human beings had been planned and executed by the United Nations General Assembly to make sure that cities are safe, resilient, and sustainable in 2017 (United Nations, 2016). In this sustainable agenda, eleven indexes were proposed to provide a reference for implementation for all over the world. However, the difficulty of data collection hinders the application of these indicators (Klopp & Petretta, 2017). Under such a background, an urban socioeconomic system that combines ecological characteristics and economic aspects is vital to achieve the UN's sustainable development goals.

The megacity, as a carrier of population aggregation, possesses the political, cultural, social, economic, and ecological characteristics (Fang et al., 2016). Since the reforms of the 1980s, China's urbanization process has been dramatically accelerated, from about 18% in 1980 to 60.6% in 2019 (National Bureau of Statistics of China, 2019). At this rate, it will be over 80% by 2050 (Chen and Chen, 2017). However, the rapid urbanization has led to severe environmental pressure and problems for cities, such as emissions pollution (air, water, and solid waste) (Hubacek et al., 2009; Wu et al., 2017; Geng, 2012), increased greenhouse effect (Feng et al., 2014), fossil energy and resource depletion (Guan et al., 2011), destruction of natural ecosystems (Su and Fath, 2012), and biological diversity loss (Xu et al., 2017). In order to boost the metabolism and economic development of the city, large quantities of natural resources and fossil energy are consumed, which are a negative impact on sustainable development in towns (Hubacek et al., 2009). Therefore, there is a complicated and interactive relationship between the economic system and the environmental system (Grimm et al., 2008; Zhang et al., 2009a). Only by analyzing the dynamic change of cities, these specific coupling relationships are identified and quantified. Based on this point, a systematic and quantifiable methodology should be set up to demonstrate the ecological and economic development trend of the city and reveal the main influencing factors so as to adopt corresponding improvement strategies and measures to promote urban sustainability further.

So far, urban ecological research has been studied by several methods, such as economic evaluation approach (EEA), material flow analysis (MFA), energy flow analysis (EFA). In particular, on the basis of the economic evaluation approach (EEA), the relationship between the economic system and ecosystem has been carried out a quantitative study (Jim & Chen, 2008; Li et al., 2010). Through direct and indirect material flow calculations, material flow analysis (MFA) has been adopted in the urban ecosystem (Chen & Chen, 2015; Rosado et al., 2014). Energy exchange has a critical impact on the ecological and economic systems of cities, leading to the widespread use of energy flow analysis (EFA) (Huang et al., 2012; Li et al., 2014; Zhang et al., 2016b). Nevertheless, the economic evaluation approach (EEA) mainly focuses on an artificial market rather than a natural system resulting in an inadequate consideration of the urban ecosystem (Zhang et al., 2009b). Material flow analysis (MFA) ignores the input of natural materials; meanwhile, energy flow analysis (EFA) lacks consideration for non-energy materials (Ukidwe & Bakshi, 2004).

Beyond these, the ecological footprint method (EF) is also a widely accepted sustainability research theory, which was founded by Rees (1992) and further expanded by Wackernagel (Wackernagel et al., 1997; Wackernagel et al., 1999). The core of this method is a land-based index so as to assess the sustainable degree, reflecting the ability of land transformation and utilization of the biosphere and including six types of land,

which are cropland, grassland, water area, forestry, built-up land, and fossil land (Wackernagel et al., 2006). Resources, production, and services in cities are consumed to invest in bio-productive lands. In order to obtain quantified ecological carrying capacity of the urban system, ecological footprint method (EF) can play to its unique advantages in many fields and revealing the spatial characteristics of urban land due to human interference and modification (Du et al., 2006; Geng et al., 2014; Moore et al., 2013; Rees and Wackernagel, 1996). Nakajima and Ortega (2016) Put forward the net production concept by using EEF (Nakajima and Ortega, 2006).

Despite this, there are also inevitable drawbacks to the ecological footprint method (EF), which have been listed in their studies (Peng et al., 2018; Hengyu et al., 2019). For instance, defects are lack of differential consideration of different ecological topography, insufficient computational accuracy for various types of land, not enough attention for greenhouse gas emissions, no non-productive land calculation in the inventory, omitted immaterial substances input and be short of dynamic change analysis of urban ecosystem, etc.

To make up the deficiency and further optimize of EF, a series of other approaches are integrated into EF, such as ecosystem dynamics analysis (Jin et al., 2009), embodied exergy calculation (Chen and Chen, 2007), input–output theory analysis (Turner et al., 2007; Hubacek et al., 2009), and emergy methodology analysis (He et al., 2016; Yang et al., 2018; Zhao et al., 2005). Therein, emergy methodology analysis can be complementary to EF and optimize EF to a great extent (Hengyu et al., 2019; Yang et al., 2018).

Emergy theory, as a sum, contains energy flow, resource flow, and service flow, which includes directly or indirectly demands in the ecosystem (Odum, 1996). In order to focus on the overall ecological environment and achieve the integration of social and economic systems and environmental systems, emergy method plays a vital effect (Liu et al., 2016; Pan et al., 2018). As the key parameter in emergy approach, unit emergy values (UEVs) implement the calculations from energy (mass or service) to emergy, and the unit of emergy method is solar-equivalent joules (seJ) (Geng et al., 2013a). Up to now, emergy method has been executed to measure sustainability in the urban system by several scholars. For example, based on the quantitative assessment of emergy in Shanghai, Beijing, and Guangzhou, results display that Shanghai has the highest index of economic development and ecological sustainability (Zhang et al., 2009a). By concentrating on the energy consumption patterns and emissions of Shanghai households, Tian et al. (2016) carried out emergy approach practice. Ecological security was measured and demonstrated through the assessment of urban ecosystems in 31 provincial capitals in China on the basis of emergy method by Liu et al. (2013). In addition, other emergy and urban system studies involved Beijing (Fang et al., 2017; Liu et al., 2014), Xiamen (Gao et al., 2016), Shenyang (Sun et al., 2016; Zhang et al., 2014), Shanwei (Lou et al., 2015), Macao (Lei et al., 2016), Rome (Viglia et al., 2016), Montreal (Vega-Azamar et al., 2013), etc. Moreover, emergy analysis with different orientations has also been applied in many papers, including urban ecosystem assessment (Huang et al., 2011), urban health analysis (Liu et al., 2009; Su et al., 2009; Wang et al., 2018), urban evolutionary dynamics (Ascione et al., 2009), urban symbiosis (Ohnishi et al., 2007), ecological security (Yang et al., 2018), etc.

However, urban metabolism and ecosystems are complicated, and the single emergy evaluation cannot cover the whole study scope and boundary of urban ecosystem sustainability. In this context, the hybrid application of emergy analysis (EmA) and ecological footprint (EF) was implemented to assess urban environmental issues by Zhao et al. (2005) firstly, which can be called as emergy ecological footprint (EEF). Given its

significant advantages, it can realize the quantitative calculation and analysis of urban regional ecology.

Until now, there are five studies to be conducted EEF studies. All details are shown in Table 1. For the sustainability of urban systems, these studies provide valuable ideas and directions. For instance, Chen & Chen (2006) proposed a modified and optimized EF method on the basis of EmA, through the study of resource consumption in China's society (Chen & Chen, 2006). He et al. (2016) utilized EEF to assess the eco-efficiency of Jiangsu province in China. An improved EEF approach has been adopted by Peng et al. (2018) to evaluate sustainability in Qingdao of China, which chose different focal points for analysis, such as labor service, high-tech industries impact, and fixed set investment (Peng et al., 2018). Taking Chinese provinces as the research objects, Yang et al. (2018) studied their ecological security in order to obtain the level of China's ecological security and predict its development trend. Pan et al. (2019) analyzed the urban ecological security of Shanghai in view of EEF. Most important of all, pollution emissions are taken into account, including air emission and wastewater discharge.

By comparing these five articles, several weak points can be found in these papers (be shown in Table 1), including (1) old emergy baseline. There are three papers based on old emergy calculation baseline rather than the latest version, which have a degree of precision impact. (2) Lack of renewable resource emergy consideration. In these five related articles, only one article considers renewable resources (Peng et al., 2018). (3) Waste discharges were neglected in four papers. As an essential section of urban metabolism and evolution, total emissions are not considered a lack of municipal solid waste EEF consideration in urban ecosystem evaluation and will lead to inaccurate results.

Under such a circumstance, in order to remedy the defects, this paper was been conducted to assess Beijing's emergy ecological footprint and emergy carrying capacity on the basis of new emergy baseline, renewable resource consideration and entire waste emergy calculation in this paper. Then, a series of indicators of ecological sustainability was used to analyze the ecological security of Beijing. Finally, the multiple indicator correlations were also calculated and demonstrated so as to provide targeted strategies and measures.

Table 1 Comparative study on regional ecological security in China based on EEF method until now

Author	Year	Emergy Baseline	Consideration comparison					Region
			RE	NR	NE	EI	WE	
Chen and Chen, 2006	2006	Old	✗	✓	✓	✓	✗	Chinese society
He et al.	2016	Old	✗	✓	✓	✓	✓	Jiangsu Province
Peng et al.	2018	Old	✓	✓	✓	✓	✗	Qingdao city
Yang et al.	2018	New	✗	✓	✓	✓	✗	Chinese provinces
Pan et al.	2019	New	✗	✓	✓	✓	✗	Shanghai city
This paper	2020	New	✓	✓	✓	✓	✓	Beijing city

RE: Renewable resource; NR: Non-renewable resource; NE: Non-renewable energy; EI: Economic input; WE: Waste emissions (Waste gas, waste water, solid waste)

All related calculation details can be found in the supplementary document.

2 Methodology for urban ecological security dynamic analysis

For megacities, an urban ecological security dynamic analysis is critical for sustainability. This paper proposes an integrated approach based on emergy method and ecological footprint. In order to build the framework, all details should be introduced, such as Beijing city situation, logical framework, emergy introduction, emergy ecological footprint method, emergy ecological footprint (EEF) and emergy carrying capacity (ECC).

2.1 The basic situation in Beijing city of China

Beijing city, the capital of the People's Republic of China, is located in between 115.7° to east longitude and 39.4° north latitude. The location of Beijing city is displayed in Fig. 1. The total area is 16,410.54 square kilometers in Beijing. It has a subtropical monsoon climate, with an annual temperature of 15.4°C and a yearly wind speed of 3.00 m/s based on meteorological data of 2019. As a political, economic, cultural, and scientific center, Beijing is a super metropolis in China, with a considerable population of 21.536 million (Statistical yearbook of Beijing from 2010 to 2019). In 2019, the GDP of Beijing city was 3537.13 billion RMB, with a 6.1% growth proportion than 2018 (Statistical yearbook of Beijing from 2010 to 2019). Taking the socioeconomic system in Beijing city as the target,



Figure 1 Location and topography of Beijing, the capital of China

six subsections have been selected, containing agricultural system, industrial manufacturing, energy product utilization, fixed assets investment, high-tech industry output, population, and emission amounts, etc. (Statistical yearbook of Beijing from 2010 to 2019). Besides, as the calculated basis, a series of meteorological data have been collected and organized according to Beijing Environmental Yearbook for 2010–2019. In the last, from some references, the unit emergy values of resource and energy were adopted, and all calculations have been executed on the basis of the latest baseline of $12.00E+24$ sej/yr (Brown & Ulgiati, 2016).

2.2 Study boundary and logical framework

In Fig. 2, the whole study boundary and logical framework were shown. Firstly, on the basis of an integrated and coupled effect of emergy method and ecological footprint method, the emergy ecological footprint methodology has been proposed to study the urban ecological security of Beijing city in China. Secondly, emergy ecological footprint (EEF) and emergy carrying capacity (ECC) indicators have been designed and measured to evaluate the status of urban ecological security, which have several indexes for EEF and ECC, respectively. The specific indicators can be found in Fig. 2, including biological resources (EEFB), industrial products (EEFI), energy resources (EEFE), pollution of waste (EEFP), ECC of renewable resources (ECCR), and ECC of socioeconomic (ECCS). Then, in view of these six indexes, the comprehensive indexes have been designed and presented, containing emergy ecological fluctuation (EEFT), ecological burden indicator (EBI), ecosystem diversity index (EDI) and ecological and economic cooperation indicator (EECI), etc. Finally, the correlation analysis of EECI and socioeconomic indexes has been executed so as to find the most influential factors. According to the negative analysis results, the countermeasures are proposed and suggested for city managers and government officials in order to achieve ecological sustainability and safety of cities.

In Table 2, the main proper noun and their abbreviations have been listed in order to help readers understand the article better.

2.3 Emergy method introduction

The emergy concept is defined as the effective energy, and the unit is solar emergy (sej). It was put forward by H.T. Odum (Odum, 1996) firstly. Emergy is an all-around view and contains the direct input, indirect part, energy part and labor and service section. The emergy approach can integrate some sections into the unified platform to evaluate the environmental level (Luís et al., 2016). Specifically speaking, the environmental sustainability of sludge reuse can be assessed by transforming all kinds of physical units, involving energy (J), mass (kg), and financial (\$) (Wei et al., 2016). Through multiplied by unit emergy values (UEVs), various types of emergy can be calculated (Zhou et al., 2009; Junxue et al., 2020), containing emergy/energy (sej/j), specific emergy (sej/g), and emergy/money (sej/\$), respectively (Junxue and lin, 2020).

Emergy baseline is another pivotal issue that will impact on accuracy in sludge reuse system sustainability, and it illustrates emergy of biosphere, including solar, tidal, and geothermal energy. Until now, there are currently five baselines, which are $9.44E+24$ sej/year (Odum, 1996), $9.26E+24$ sej/year (Campbell, 1998), $15.83E + 24$ sej/year (Odum, 2000), $15.2E+24$ sej/year (Brown & Ulgiati, 2010), $12E+24$ sej/year (Brown & Ulgiati, 2016),

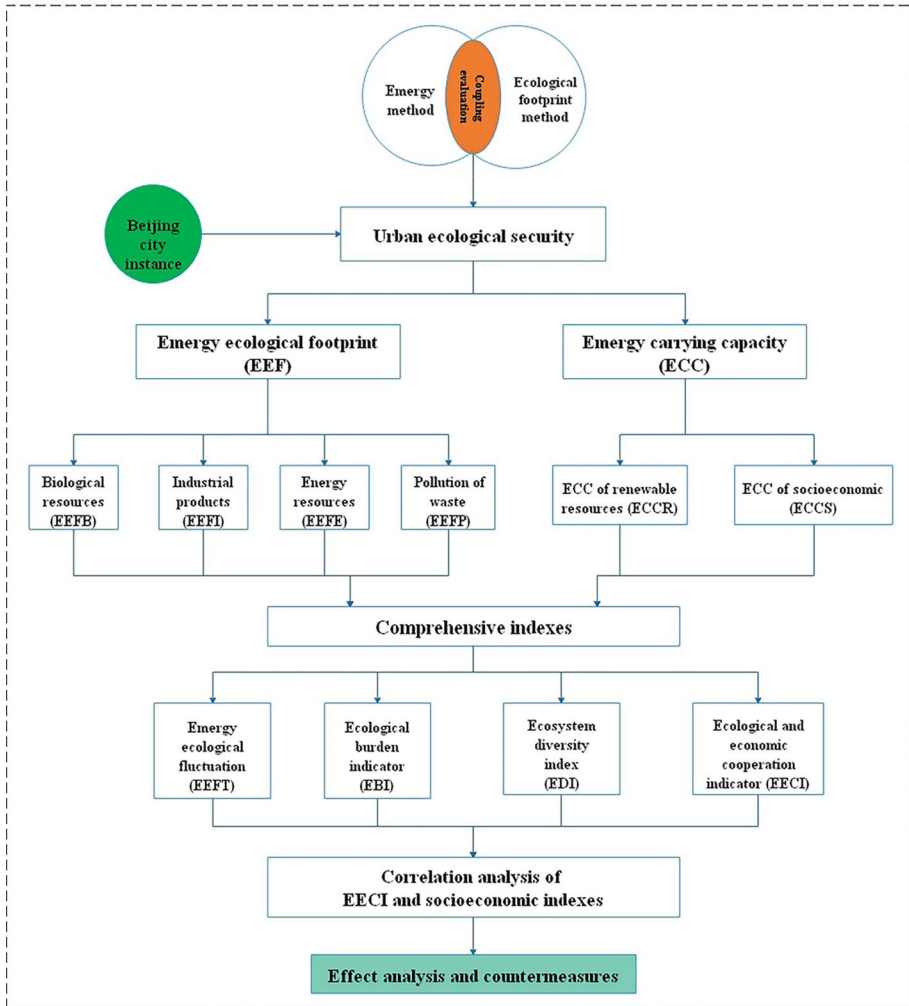


Figure 2 Study boundary and logical frameworks

respectively. In this article, the latest emergy baseline of 12E+24sej/year was used to calculate emergy in sludge reuse system.

Basic calculation formulas of emergy can be shown as three equations (Odum, 1996)

$$U(sej) = N(J) \times UEV(sej/j) \tag{1}$$

$$U(sej) = M(g) \times UEV(sej/g) \tag{2}$$

$$U(sej) = V(\$) \times UEV(sej/\$) \tag{3}$$

where U is the emergy; N, M, V represent the unit of Joule (J), grams (g), and money (\$), respectively.

Table 2 Proper noun list

Number	Proper noun	Abbreviation
1	Emergy analysis	EmA
2	Emergy carrying capacity	ECC
3	ECC of renewable resources	ECCR
4	ECC of socioeconomic calculation	ECCS
5	Ecological and economic cooperation indicator	EECI
6	Emergy ecological footprint	EEF
7	EEF of biological resources	EEFB
8	EEF of industrial products	EEFI
9	EEF of energy resources	EEFE
10	EEF of emissions parts	EEFP
11	Ecological footprint	EF
12	Ecological footprint intensity	EFIT
13	Emergy currency ratio	ECP
14	Gross domestic product	GDP
15	Annual global emergy density	AGED
16	fixed assets investment	FAI
17	Life cycle assessment	LCA
18	Labor services	LS
19	Material flow method	MFM
20	High-tech industry output	HIO
21	Population of the target city	PTC
22	Maker price index	MPI
23	Local emergy intensity	LEI
24	Solar-equivalent joules	seJ
25	Unit emergy values	UEVs

2.4 Optimized emergy ecological footprint method

Hengyu et al. (2019) implemented a city study based on the emergy ecological footprint and emergy carrying capacity method. However, in their studies, only part of the emissions are considered to lack of municipal solid waste calculation, which can hurt the sustainability of the city (Ulgiati & Brown, 2002). In this study, according to exhaust gas, wastewater, and solid waste emissions, environmental services have been assessed quantitatively utilizing EEF. In particular, the treating processes of solid waste focus on landfilling and incineration approach primarily in Beijing city and the related exhaust emissions have been considered and computed in our paper.

On the one hand, part of the solid waste is buried. Given landfill solid waste mass, land requirement per unit solid landfill, and local land emergy, the landfilling method can calculate the landfilling emergy. On the other hand, the rest of the solid waste was incinerated in the power plant of Beijing. Incineration solid waste emergy can be obtained based on electricity calculation. Hence, the total emissions have been considered and evaluated for the emergy ecological footprint in this study so as to provide accurate results.

2.5 Emeryg ecological footprint (EEF)

Emeryg ecological footprint calculation demonstrates the coupling impact on the city, including environmental, financial, and anthropic features (Hengyu et al., 2019). So far, a series of studies have uncovered the specific calculated details, containing three crucial elements, such as (1) biological resources (EEFB); (2) industrial products (EEFI); and (3) energy resources (EEFE) (Peng et al., 2018; He et al., 2016; Yang et al., 2018). Nevertheless, as the intrinsic part, emissions should be taken into account in urban systems. The emissions have three sections, consisting of exhaust gas, wastewater, and solid waste. Therefore, total emissions need to be computed in the urban system assessment (not only waste gas and water, but also solid waste(EEFP)).

The entire emeryg ecological footprint (EEF) formula is as follows (4).

$$EEF = EEFB + EEFI + EEFE + EEFP \quad (4)$$

Following Pan et al. (2019) (Hengyu et al., 2019), except for the emission part (EEFP), the other three parts of emeryg ecological footprint (EEF) can be calculated using equation 5.

$$EEFB + EEFI + EEFE = \frac{UEVs_i \times N_i}{PTC \times LEI} \quad (5)$$

Therein, UEV_i shows unit emeryg values of resources and industrial products (seJ/J or seJ/g); N_i represents values of resources or products (J or g); PTC is the population in the city; LEI is Local emeryg intensity, which reveals the proportion of renewable resources and city area (seJ/hm² · yr). The calculated details can be found in the supplementary document (Part B: Table C2-1 to table C2-10).

As a necessary part of the dynamic urban system, emeryg ecological footprint of emissions parts(EEFP) represents the urban output and can be calculated by using (4–6).

$$Q_j = \beta \times \frac{P_j}{\gamma_j} \quad (6)$$

where Q_j signifies the quantities of air or water in the studied city; β is the density of air or water (1.23 kg/m³ and 1.00E+03 kg/m³, respectively); P_j is the mass of the emissions in a year(Statistical yearbook of Beijing from 2010 to 2019). γ_j shows the acceptable concentration of all emissions. The specific emissions data and state-prescribed acceptable concentrations of standards in China have been displayed in the supplementary document (Part C: Table C3-1 to Table C3-10).

The consideration of solid waste emeryg is mainly concentrated on land occupation, which can be calculated based on the formula (7) (Zhang et al., 2016a, b, c).

$$SLM = \alpha_{landfill} + \delta_{incineration} = (Z_{landfill} * P_l * \beta_l) + (K_{Powerplant} * UEVs_{electricity}) \quad (7)$$

Therein, SLM is the total emeryg of municipal solid waste; $\alpha_{landfill}$ is the emeryg of dry solid waste, which has been buried in the landfill; $\delta_{incineration}$ represents the incinerated municipal solid waste emeryg; $Z_{landfill}$ is the mass of landfill solid waste; P_l shows the land requirement per unit solid landfill, and it is 0.285 t/m² (Wang et al. 2006a). β_l is the unit emeryg value of local land, which is 1.36×10¹⁵ seJ/t based on the latest baseline (12×10²⁴ seJ/a). $K_{powerplant}$ displays the electricity amount by using incinerated municipal solid waste; $UEVs_{electricity}$ is the electricity transformity.

Table 3 Emery carrying capacity (ECC) calculated results of Beijing city from 2010 to 2019.

Item	2019	2018	2017	2016	2015	2014	2013	2012	2011	2010
ECCR	2.06E+1	2.28E+1	2.50E+1	2.39E+1	2.53E+1	2.74E+1	2.45E+1	2.87E+1	2.57E+1	2.30E+1
ECCS	4.72E+4	4.33E+4	4.33E+4	4.05E+4	3.80E+4	3.54E+4	3.32E+4	3.09E+4	2.90E+4	2.68E+4
ECC	4.72E+4	4.33E+4	4.33E+4	4.05E+4	3.80E+4	3.54E+4	3.32E+4	3.09E+4	2.90E+4	2.68E+4

$$G_w = Max(0.5 \times Q_i \times v^2 \times UEVs_{air}) + Max(M_{water} \times \rho \times UEVs_{water}) + Max_{SLM} \tag{8}$$

$$EEFP = \frac{G_w}{PTC \times LEI} \tag{9}$$

Herein, G_w shows integrated emission energy that should be diluted because of ecological service consideration; v represents the annual mean wind speed, using 2.48 m/s because of climatic data in Beijing city (Meteorological data for Beijing, 2019); $UEVs_{air}$ is the transformity of wind; ρ demonstrates water thermal coefficient (2.56E + 04 J/kg) (Pan et al., 2016); $UEVs_{water}$ is the unit emergy value of water. Given the dilute effect of air and water, ecological service demand has been calculated in this study.

2.6 Emery carrying capacity (ECC)

Emery carrying capacity (ECC) represents the global average capacity, which is a numerical value between available renewable resources and capita (Hengyu et al., 2019). Through ECC calculations, the support capacity of urban ecosystems can be displayed to human activities (Yang et al., 2018). Nevertheless, there is a weakness in ECC, lack of socioeconomic consideration. In order to optimize the ECC index, the socioeconomic subpart has been counted, which have three types, including fixed assets investment (FAI), high-tech industry output (HIO), and labor services (LS). Based on Pan et al. (2019) (Hengyu et al., 2019), the artificial initiative effect can be obtained via the considerations of FAI, HIO, and LS in socioeconomic ecosystems. Through computing them, integrated EEC of the socioeconomic section can be obtained.

In this article, emery carrying capacity (ECC) contains two subsections, which are ECC of renewable resources (ECCR) and ECC of socioeconomic calculation (ECCS), respectively. The unit of ECC is $sej/hm^2 \cdot yr$ and can be counted by formula (10). According to equations (11) and (12), ECCR and ECCS will be confirmed.

$$ECC = ECCR + ECCS \tag{10}$$

$$ECCR = (1 - 0.12) \times \frac{N}{AGED \times PTC} \tag{11}$$

where N shows renewable resource maximum flows of the city (seJ/yr). Based on emery method, N contains sunlight, geothermal energy, wind kinetic, rain chemical potential, and rain chemical potential(Chen & Chen, 2017). Given the biodiversity safety according to World Commission on Environment and Development, a 12% reduction is needed for the ECC per capita (Wackernagel, 1999; WCED, 1987). $AGED$ is the global emery density in a year ($sej/hm^2 \cdot yr$), and the latest baseline is $12.00E+24$ seJ/yr. Because of considered the global surface area as $5.10E+10$ hm^2 , $AGED$ is $2.35E+14$ $sej/hm^2 \cdot yr$. PTC is the population in Beijing city.

$$ECCS = (1 - 0.12) \times \frac{ECP \times MPI \times (FAI + HIO + LS)}{AGED \times PTC} \tag{12}$$

where ECP represents the emery currency ratio in the city and can be obtained by renewable natural resources emery and GDP(Chen & Chen, 2009). As the maker price index, MPI can reduce the price fluctuations reaction, making sure a comparable result

(Yang et al., 2018). In this study, the reference period is 2010–2019, and it can use 100.0. FAI displays the fixed assets investment (\$). HIO is the high-tech industry output (\$), and LS shows the labor services (\$). The calculated details can be found in Table C3 of the supplementary document. The 12% proportion signifies a similar principle as in formula (i).

2.7 EEF evaluated indexes

In order to assess sustainability in Beijing city, four indexes can be used in this study.

2.7.1 Energy ecological fluctuation (EEFT)

Emergy ecological fluctuation (EEFT) measures the gap between EEF and ECC, which reveals the ecological flux variation. When $EEFT > 0$, the emergy ecological surplus can be demonstrated, which means that local resources are sufficient for human use; if $EEFT = 0$, stock equals demand; when the gap is negative, ecological deficit signifies the resource stress on people.

The specific formula can be adopted as (13):

$$EEFT = ECC - EEF \quad (13)$$

The equilibrium provides the region state calculation method. In Eq. (k), EEF is emergy ecological fluctuation per capita (hm^2/cap); ECC shows emergy carrying capacity per capita (hm^2/cap), and EEF reveals emergy ecological footprint per capita (hm^2/cap).

2.7.2 Ecological burden indicator (EBI)

The ecological burden index (EBI) instructs the ecological pressure in a particular region based on EEF and ECC, which illustrates the regional ecological security. The EBI can be got in equation (14):

$$EBI = \frac{EEF}{ECC} \quad (14)$$

Compared to EEFT, EBI assesses the ecological load level through a unit of ecological capacity (Yang et al., 2018). If $EBI > 1$, excessive stress leads to an unsustainable state in the study city; when $EBI = 1$, the result reflects the ecological balance in the region; $EBI < 1$ is a favorable situation, and the city can realize ecological sustainability and safety.

2.7.3 Ecosystem diversity index (EDI)

Ecosystem diversity is closely related to the regional eco-economic system, which can be obtained based on the view of the systematic organization (Xie et al., 2008). On the basis of Ulanowicz's formula (Zhang et al., 2003; Ulanowicz, 1986), EDI can be counted as formula (m):

$$EDI = EEF \times \left(- \sum_i^n R_i * \ln R_i \right) \quad (15)$$

Therein, EDI represents development capacity level (hm^2/cap). EEF reflects ecological energy footprint for a unit of capita (hm^2/cap). R_i is the ratio of land type (Wang et al., 2011).

2.7.4 Ecological and economic cooperation indicator (EECI)

$$EECI = \frac{(EEF + ECC)}{\sqrt{EEF^2 + ECC^2}} \quad (16)$$

EECI points out the cooperation level based on the ecological and economic systems. To quantify the relationship between them, the formula can be utilized as (n). Three ranges can be adopted to demonstrate the coordination degree, including EECI close to 1, EECI close to 1.414, and EECI=1.414. When the EECI tends to 1, the cooperation level is weak. If EECI is more intimate to 1.414, the degree is higher. A particular case, if EECI =1.414, demand and supply balance will be formed in the city about ecology, representing the best level of cooperation (Yang et al., 2018).

2.8 Correlation analysis of EECI and socioeconomic indexes

The correlation analysis of EECI and socioeconomic indexes should be considered in order to obtain the ecological and economic coupling effect. In this study, IBM-SPSS statistical software (version 25) was chosen to execute the Pearson correlation analysis to point out the linear relationships. Six related indexes that may affect the EECI were selected to analyze, involving the GDP of study city (X1), the ratio of the output of service industries and GDP(X2), the ratio of heavy industry and GDP (X3), the urbanization proportion (X4), rural–urban salary ratio (X5) and the proportion of revenues and GDP (X6) (Yang et al., 2018). All calculations related indicators to X1-X6 of Beijing city have been listed in the supplementary document (Part E: Table C5).

The Kolmogorov–Smirnov analysis has been implemented, and all the data are in a normal distribution in the supplementary document (Part F: table C6).

3 Case study

As a representative of China's megacities, Beijing city is facing the contradiction between economic development and sustainability. Taking it as an example, emergy ecological footprint method validity can be verified. Specifically, case study includes four parts, such as emergy ecological footprint (EEF), emergy carrying capacity (ECC), sustainability indicators evaluation and correlation analysis of socioeconomic indexes and EEF.

3.1 Emergy ecological footprint (EEF) evaluation and analysis

Figure 3 indicates the specific emergy ecological footprint values in Beijing city from 2010 to 2019, including four kinds of EEF. First of all, taking the total EEF of each year as the examples, there is a downward trend about the EEF, from $3.03\text{E} + 5$ in 2010 hm^2/cap to $1.65\text{E} + 5$ hm^2/cap in 2019. Some reasons should be responsible for the change, including the increasing population pressure in Beijing and environmental degradation. From 2010 to 2019, the change range of EEFB is from 6.37% to 9.29%; meanwhile, EEFI is

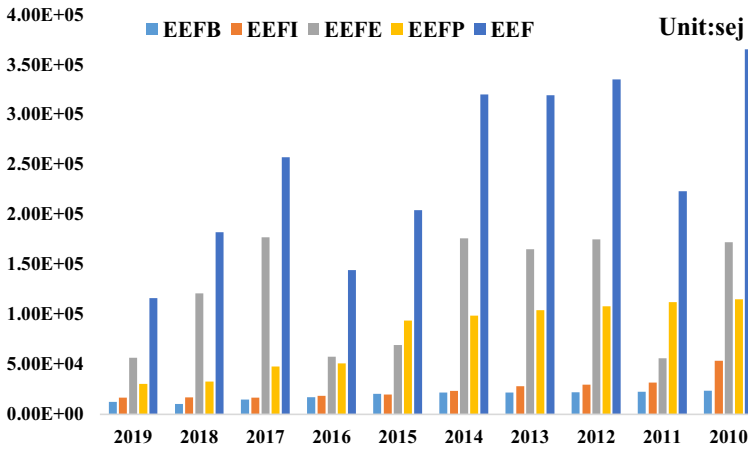


Figure 3 Energy ecological footprint (EEF) calculated results in Beijing city

from 7.95% to 17.72%; EEFE is from 36.36% to 63.71%; EEFP is from 18.45% to 41.65%. Based on the proportions of four subparts, the energy resource products (EEFE) and emissions (EEFP) are the main factors, far more significant than biological resources (EEFB) and industrial products (EEFI). For instance, taking the single item as the analysis object in 2019, EEFE is the major contributor and accounts for 63.71% of the total EEF in Beijing, followed by EEFP of 18.45%, EEFI of 10.13%, and EEFB of 7.71% (shown in Fig. 4). Similar law can be obtained from 2014 to 2019, whereas from 2010 to 2013, EEFP contributes the primary rather than EEFE. In general, EEFE and EEFP dominate the energy ecological footprint (EEF) degree.

In this study, the emission (EEFP) has a vital impact on the calculated result and should not be ignored. Within EEFP, it consists of three types, which are exhaust gases,

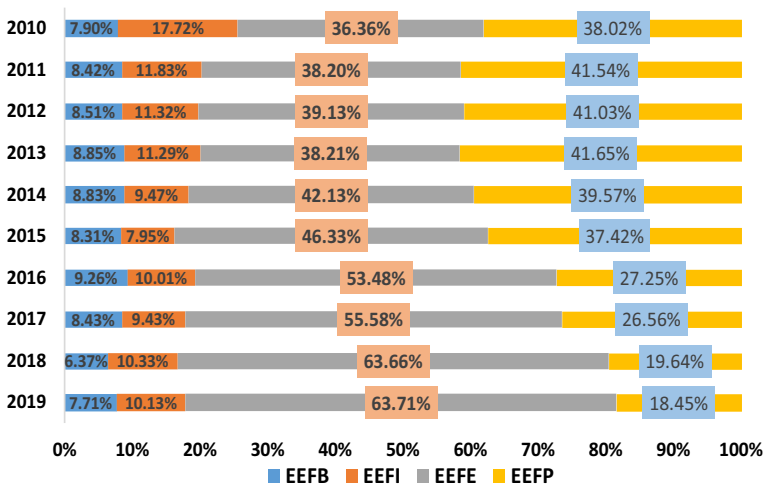


Figure 4 All types of energy ecological footprint analysis in Beijing city

wastewater, and municipal solid waste, respectively. Municipal solid waste is basically in the dominant position from 2010 to 2019 (shown in Fig. 4). In previous studies, EEF of municipal solid waste is all ignored, resulting in an inaccurate analysis.

(1) energy ecological footprint of biological resources(EEFB) analysis

EEFB has a 46.9% lower from $2.39E+4$ in 2010 hm^2/cap to $1.27E+4$ hm^2/cap in 2019. Two reasons can explain the results. On the one hand, population growth will reduce the values of EEFB; on the other hand, the biological resources emery of each year in Beijing points out a downward trend year by year, from $3.42E+22$ sej in 2010 to $1.811E+22$ sej in 2019. A total of 13 elements inputs contribute the emery to EEFB. However, only three inputs are pivotal parts, containing meat, egg, and milk. For example, in 2019, meat accounts for the major proportion of 63.5% in the entire emery of EEFB, corresponding to 73.6% of meat in 2010, respectively. Relevant results can be referred to Table C2-1 to Table C2-10 in the supplementary document (Part B).

(2) emery ecological footprint of industrial products(EEFI) analysis

EEFI decreases 68.8% from $5.36E+4$ in 2010 hm^2/cap to $1.67E+4$ hm^2/cap in 2019. Within EEFI, cement accounts for 46.2% of the total emery, followed by the steel of 37.9% and chemical fiber of 14.7%, and others are negligible. Taking the steel as an instance, steel emery proportion changes from 55.8% in 2010 to 37.9% in 2019, which is one of the reasons that lower EEFI from 2010 to 2019. This trend demonstrates the structural adjustment effect in heavy industry in Beijing city, and the aim is to reduce the economic weight of heavy industry and raise the proportion of tertiary industry. All the positive changes have been attributed to a series of industrial policies by the Beijing municipal government, including developing high-tech industries, limiting the development of heavy industry rationally, even relocating the necessary heavy industries. For example, as China's top ten steel mills, the Capital Steel Company moved from Beijing to Tangshan city of Hebei province during this period, reducing emery ecological pressure in Beijing.

(3) emery ecological footprint of energy resource products(EEFE) analysis

As the largest emery ecological footprint contributor, EEFE plays a vital impact on the entire emery ecological footprint. Although EEFE decreased 67.9% from $1.72E+5$ hm^2/cap in 2010 to $5.66E+4$ hm^2/cap in 2019, EEFE remains the biggest influence from 2010 to 2019. In 2019, EEFE accounted for 48.63% of the total EEF. Within EEFE, electricity is the key input, followed by crude oil. The electricity proportion in EEFE changes from 40.4% in 2010 to 41.7% in 2019. Compared to electricity, crude oil varied by a large percentage from 2.95% in 2010 to 14.1% in 2019. These results reflect the adjustment of energy structure in Beijing based on crude oil imports on a large scale year by year. The electricity of Beijing city is supplied by the North China power grid, which mainly comes from the thermal power plant because of coal energy (Gan & Griffin, 2018)

Hence, clean energy is getting more and more attention in Beijing city. For example, natural gas has been used as a new source of energy in Beijing's 13th five-year plan. Due to the increased demand for petrol year by year, petrol and diesel oil have the second and third roles according to the proportions of EEF. In 2019, petrol accounted for 12.35% of total EEF, compared to 11.82% of diesel oil. The reason for this phenomenon is the explosion of private cars from 2010 to 2019. According to the statistics of the Beijing municipal bureau (BMB) in 2019, there are 6.365 million private cars in 2019; meanwhile, only 4 million private cars are in Beijing, roughly 37.2% growth. The fossil fuels widespread use results in excessive emissions of polluting gases and greenhouse gases, which lead to two negative effects for Beijing's environmental issues. On the one hand, a large number of harmful gases emission have caused serious air pollution in Beijing, such as dust and SO_2 ; on the other hand, massive emissions of carbon dioxide are harmful to China's efforts to achieve

the Paris climate agreement. To relieve environmental pressure, several positive measures have been executed in Beijing, such as financial subsidies for new energy vehicles, build public transportation (subway), and specific license number vehicles passed during the rush hours. The EEF details of Table C2-1 to Table C2-10 have been calculated in the supplementary document (Part B).

(4) energy ecological footprint of emissions(EEFP) analysis

As a core component of the city ecosystem, emissions cannot be ignored, including gas emission, wastewater, and municipal solid waste. According to Figs. 3, 5, the impact of emissions has been displayed, and there is a reduction tendency year by year. In Beijing city, although the EEFP proportion tends to get smaller, from 38.02% of the entire EEF in 2010 to 18.45% in 2019 (Fig. 5), EEFP still plays an important impact on EEF of Beijing city. The reduction should be attributed to strict environmental emission standards set by the Beijing environmental protection bureau. For instance, polluting industries will be forced to install decontamination facilities, or even move out of the Beijing city. Clean energy alternatives are also required by law, and there will be serious penalties if the plants break the rules (Liu et al., 2016). Besides, the Beijing environmental protection bureau has established a sound system of regular supervision to monitor factory emissions. In the composition of the emissions of Beijing city (Fig. 5), wastewater EEF and municipal solid waste EEF are the primary contributors. For example, municipal solid waste EEF accounts for 51.17% of total EEF, followed by wastewater (48.82%) in 2019. In order to ease environmental stress, ecological services need to dilute, mainly about wastewater and municipal solid waste inputs in Beijing city (refer to Table C3-1 to Table C3-10 in the supplementary document-Part C). In general, so as to settle the environmental emission issue, some strategies for mitigating the environment have been proposed and implemented by Beijing environmental protection bureau, containing the establishment of the eco-industrial park, subsidies for new energy use, environmental penalty, etc. On the basis of analysis in Fig. 5, as the pivotal influence, municipal solid waste energy ecological footprint must be considered and counted in the calculation. In previous studies of EEF, no one thought municipal solid waste in energy ecological footprint resulting in inaccurate results in the city. This

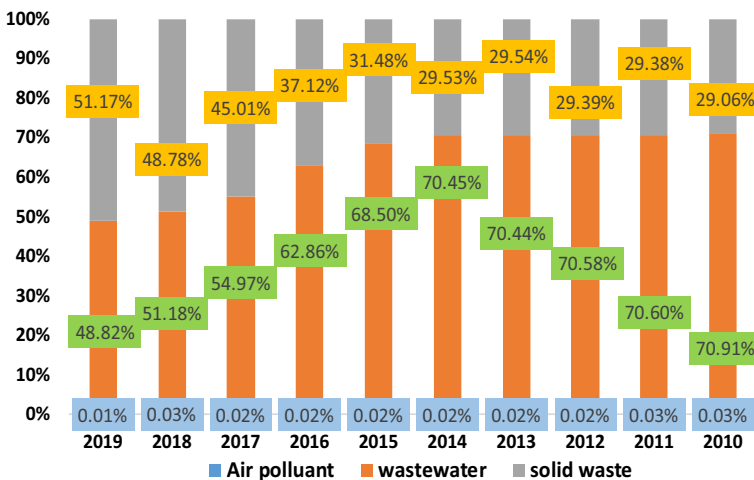


Figure 5 The proportions of different emissions types in Beijing from 2010 to 2019

study bridged the gap and provided a complete urban assessment based on emergy ecological footprint (EEF).

3.2 Emergy carrying capacity calculations (ECC) and analysis

The final calculated results are revealed in Table 3 and Fig. 6. There is a distinct feature of emergy carrying capacity (ECC), which is the dominant position of ECCS. ECCS dominates the emergy carrying capacity (ECC) result. This phenomenon illustrates the socioeconomic ability is a crucial input in Beijing city rather than a renewable resource, including investment in fixed assets, high-tech industry output, and labor service. Compared to all ECCS data from 2010 to 2019, there is a definite growing trend in Beijing city, from $2.68\text{E}+4$ hm²/cap in 2010 to $4.72\text{E}+4$ hm²/cap in 2019, approximately 42.22% growth range. Beyond that, ECCR tends to shrink due to significant growth in population, about 8.9% growth from 2010 to 2019. Under data in Table 3, socioeconomic capacity and people are the vital influencing factor. To enhance the emergy carrying capacity of Beijing, two measures can be focused on and considered, including improving the proportion of investment in fixed assets, high-tech industry output and labor service, and reducing the population of Beijing. The primary data and calculation of ECC can refer to Table C4-1 to Table C4-10 in the supplementary document-Part D.

3.3 Four sustainability indicators evaluation

3.3.1 Emergy ecological fluctuation (EEFT) analysis

Table 4 depicts the necessary data of four sustainability indexes from 2010 to 2019 in Beijing city. Figure 7 shows the changing trend of the indicator group. Emergy ecological fluctuation (EEFT) is a relative value between EEF and ECC, which illustrates emergy ecological deficits from 2010 to 2019 in Beijing city. In Table 4 and Fig. 7, EEFT values are all negative from 2010 to 2019, showing an unfortunate ecological security issue in Beijing city. There has been a marked decline (absolute value) in ecological security, from a peak

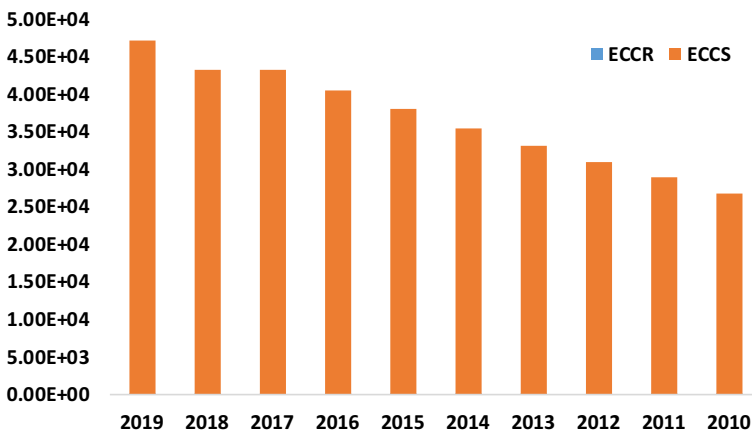


Figure 6 emergy carrying capacity (ECC) change and structure in Beijing from 2010 to 2019

Table 4 The calculation results of four kinds of sustainable indexes from 2010 to 2019

Item	2019	2018	2017	2016	2015	2014	2013	2012	2011	2010
EEFT	-6.88E4	-1.39E5	-2.14E5	-1.04E5	-1.66E5	-2.85E5	-2.86E5	-3.04E5	-3.10E5	-2.22E5
EBI	2.46	4.20	5.94	3.56	5.37	9.04	9.61	10.84	11.69	9.29
EDI	0.217	0.201	0.248	0.263	0.268	0.281	0.286	0.279	0.280	0.263
EECI	1.14	1.12	1.08	1.07	1.04	1.03	1.03	1.03	1.03	1.02

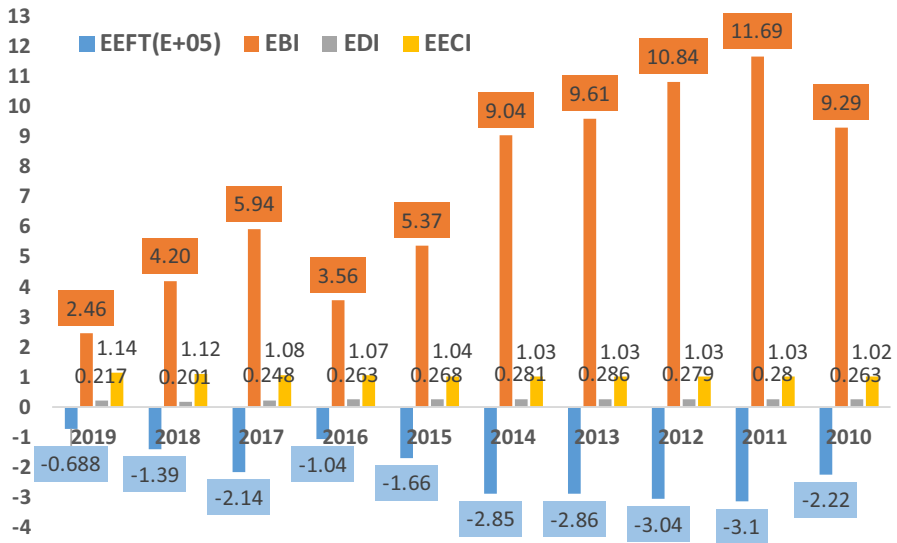


Figure 7. Variation trend of four sustainable indicators in Beijing city

of 3.1 in 2011 to 0.688 in 2019. This can attribute to a series of improvement strategies and measures, involving improving the energy structure, reducing the proportion of polluting enterprises, adopting new energy and active tax policies, etc. These positive measures resulted in a reduction in the energy ecological footprint (EEF), leading to a trend of EEFT reduction.

3.3.2 Ecological burden indicator (EBI) change

The ecological burden indicator (EBI) indicates the ratio between EEF and ECC and also points out the urban ecological security. According to Table 4 and Fig. 7, all EBI values are more significant than 1 in this decade, reflecting excessive ecological pressure and an unsustainable state in Beijing city. Between 2010 and 2019, EBI amounts decrease from 9.29 in 2010 to 2.46 in 2019, approximately 3.78 times reduction, which signifies that the ecological security degree of Beijing was improving from 2010 to 2019. Similar to EEFT, the same reason supports this reduced variation.

3.3.3 Ecosystem diversity index (EDI) analysis

The index changed little from 0.263 in 2010 to 0.217 in 2019, as shown in Table 4. It presents low ecosystem diversity in Beijing city due to the uneven distribution of EEF. In particular, Fig. 8 displays that the land-type EEF change trends from 2010 to 2019. An obvious fact can be found: Fossil land and built-up land are the most important contributors, no matter which year the data is. From Fig. 8, the total proportions of fossil land and built-up land are 85.25% to 90.43% of the entire EEF in Beijing city. This phenomenon demonstrates that there is a deep dependence on industrial manufacturing for economic development in Beijing. The energy types of supporting industrial products are electricity, oil, and coal, respectively. In general, there is a reduction trend of the fossil land EEF proportions from 2010 to 2019, about 7.54% reduction. This is the result of industrial product structure

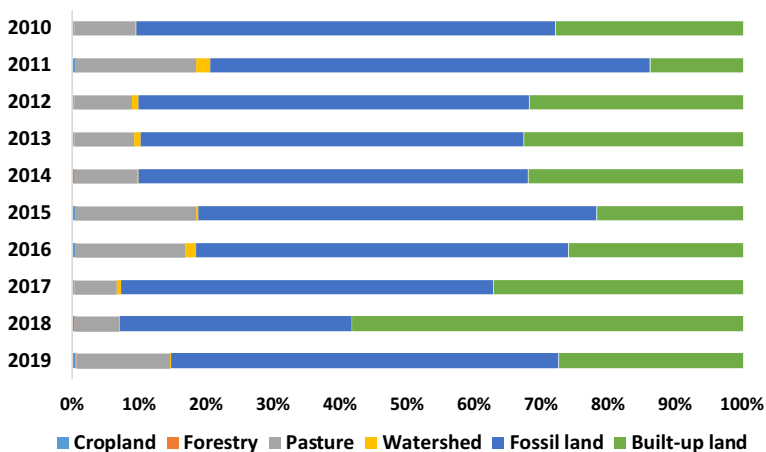


Figure 8 Land-type EEf change trends from 2010 to 2019

adjustment in Beijing; meanwhile, the energy structure is also an adjustment aspect. Taking electricity and coal as the examples, coal is gradually being replaced by electricity resulting in 34.22% electric power EEf growth and 67.88% of coal EEf reduction from 2010 to 2019 in Beijing city (refer to Table C2-1 to Table C2-10 in the supplementary document-Part B). Beijing's primary source of electricity mainly comes from thermal power generation. For the thermal power plants, coal is the most abundant energy supply type. To sum up, coal consumption can be further reduced through clean energy alternatives, such as solar energy, wind power, and geothermal power.

3.3.4 Ecological and economic cooperation indicator (EECI) analysis

Based on Table 4 and Fig. 8, there is a relatively stable change in EECI, from 1.02 in 2010 to 1.14 in 2019, which represents a weak cooperation level between ecological and economic aspects in Beijing city. However, compared to values in 2010 and 2019, the level of cooperation in Beijing has been improved in view of formula (n), because the value is closer to 1.414 in 2019 (shown in Fig. 9). Three contributors should be responsible for cooperation level promotion in 2019, such as economic structure adjustment, strict pollution control measure, and socioeconomic proportion increment in Beijing city.

3.4 Correlation analysis of socioeconomic indexes and EEf

All socioeconomic indexes have been listed in the supplementary document-Part E (shown in Table C5) from 2010 to 2019 in Beijing. Table 5 displays the correlation analysis between EECI and socioeconomic indexes. According to Table 5, there are six correlation levels, and the maximum level is X2, followed by X1, X3, X6, X5, X4. As the significant decisive correlation parameters, X2 and X1 mean tertiary industries ratio and the GDP of Beijing city. Tertiary industries and gross domestic product are conducive to decreasing EEf and enhancing ecological security in Beijing city. The more significant the proportion of tertiary sectors, the smaller the energy ecological footprint (less stress). A similar principle applies to gross domestic product effect. Except for X2 and X1, government revenue (X6) is also favorable

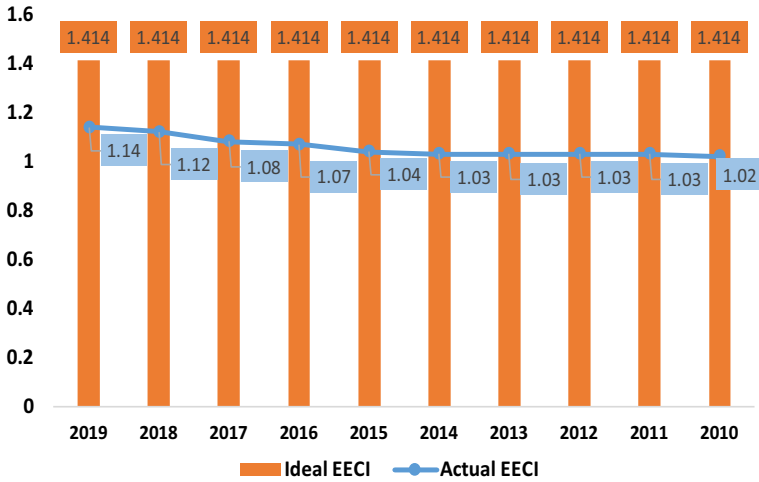


Figure 9 Cooperation degree between ecological and economical in Beijing city.

Table 5 EECI and socioeconomic indexes correlation analysis

Item	EECI	X1	X2	X3	X4	X5	X6
EECI	1	.951**	.965**	-.939**	-.448	-.866**	.907**
X1	.951**	1	.985**	-.986**	-.427	-.868**	.902**
X2	.965**	.985**	1	-.994**	-.461	-.871**	.923**
X3	-.939**	-.986**	-.994**	1	.449	.672	-.926**
X4	-.448	-.427	-.461	.449	1	.563	-.528
X5	-.866**	-.868**	-.871**	.672	.563	1	-.317
X6	.907**	.902**	.923**	-.926**	-.528	-.317	1

Note: X1 is the GDP of Beijing city. X2 represents the ratio between tertiary industries and GDP. X3 is the heavy industry proportion to GDP. X4 demonstrates the urbanization rate. X5 reveals the income ratio of urban and rural.

X6 depicts the ratio based on government revenues to GDP. The flag (**) presents the strong correlation level (Less than 0.01)

and beneficial to correlation with EECI, due to lots of investment in pollution control. The most negative correlation is the heavy industry in Beijing city because of natural inputs and outputs, such as a mass of energy expenditure, excessive material input, and severe environmental pollution. That is to say, so as to improve the ecological security of Beijing city, the two main measures that need to be done, as follows: increasing tertiary industry proportion, and the decreasing ratio between heavy industry and total GDP in Beijing city.

4 Discussion and implications

According to the correlation analysis of socioeconomic indexes and EEF, corresponding measures and strategies of three aspects are put forward to enhance the sustainability and ecological security in Beijing city, which are economic improvement strategies, energy-positive measures, and recycling of municipal waste, respectively.

On the one hand, economic improvement strategies can be summarized as follows:

Economic structure readjustment should be maintained, such as upgrading the service industry proportion, increasing the portion of the logistics industry, and vigorously developing high-tech and tourism industries. A series of interesting explorations were discussed in some papers. For instance, He et al. (2016) proposed the similar suggestions and measures to enhance the sustainability and ecological security in the Jiangsu province by developing the tertiary industry. Taking a city in the north China, Peng et al. (2018) discussed the sustainability evaluation by some suggestions, such as developing high-level tertiary industries and increasing the proportion of service industries. Yang et al. (2018) assessed the dynamic changes of ecological security for all the provinces in China and also mentioned industrial and energy restructuring policies. In addition to economic and industrial policies, Pan et al. (2019) believes that favorable tax strategy is an effective means to ensure urban ecological security.

On the other hand, positive energy improvement measures can be considered and optimized from the following parts.

(1) Enhancing the efficiency of fossil energy use or multistage utilization. The fossil energy use efficiency promotion can contribute to the sustainable development in Beijing city. The large-scale application of fossil energy plays a great negative role, which is necessary to take some measures for mitigating the passive effect. The residual energy reutilization of advanced systems should be deemed as the optimal sustainable approach and be adopted to realize the sustainability of city. Other multistage utilization systems can be given priority to application and promotion, which consist of enhancing heat transfer performance of photovoltaic thermal systems (Afroza et al., 2019), increasing the energy and exergy efficiencies of a collector (Akbar et al., 2019), energy-water management in urban residential buildings (Evan and Xia, 2017), etc.

(2) Improving the proportion of renewable energy use in Beijing city, such as solar power, hydropower and wind power. The more renewable resources, the bigger the ECC of city, which can lead to a more ecologically safe in Beijing city (see specific calculation details of part D in the supplementary document). Because Beijing city is located in the north of China, there are abundant light and wind resources, providing a convenient geographical condition of solar power and wind power. To some extent, unreasonable energy structure should be responsible for the negative effect on the ecological security in the Beijing city. To adjust the energy structure, several new renewable energy types should be adopted in this paper, containing solar power, hydropower, and wind power, which are the familiar sources of renewable energy in China. However, a few weak points obstruct their usages as renewable energy sources, such as enormous investment, professional and technical barriers, and geographical conditions. For example, financial subsidies and favorable tax policies should be considered carefully to improve the applied proportion of clean energy. Based on the development status, many researchers have performed related studies involving solar power (Peronato et al., 2018; Liu et al., 2019), hydropower (Ludovic et al., 2014; Tang et al., 2019), wind power (Wang et al., 2019; Sayed et al., 2019).

(3) Reducing municipal waste emissions and improving waste recycling in Beijing city. In this paper, three types of wastes have been considered and calculated, such as air pollution, wastewater, and municipal solid waste (see specific calculation details of part C in the supplementary document). Pollution emission reduction and waste reuse measures can reduce the emergy ecological footprint (EEF), thus improving the ecological security of the Beijing city. For example, Liu et al (2017) conducted the full life cycle emergy study of municipal solid waste in order to provide quantitative policy support for scientific management of municipal solid waste. Wei et al. (2018) put forward the ecological compensation standard in the industrial solid waste field on the basis of emergy calculation to realize the sustainable development in the city. The research of both scholars can achieve the reduction of waste emissions. In addition, waste recycling is also an important means for urban ecological security. Currently, several scholars have done some research on material substitution so as to improve sustainability. For instance, T. Gonçalves et al. (2020) used the recycled concrete aggregate and reactive magnesium oxide to replace the cement material, which can promote the mechanical and environmental performance. In view of the new treatment technology, the wet-milling concrete slurry waste can be adopted to substitute cement based on the study of Xingyang et al. (2020). In this way, the sustainable urban environment can be realized and the ecological security of Beijing can be improved.

5 Conclusion

In this study, the coupling relationship between the urban ecosystem and the economic system has been presented. Quantifying this coupling relationship can contribute to the sustainable development of cities, especially for megacities. An integrated framework of emergy ecological footprint was set up and implemented to assess the sustainability of Beijing city. As the capital and megalopolis of China, Beijing's sustainable development and ecological security are the benchmark for other cities in China, so there is a strong need to figure out Beijing's ecological and economic levels.

Quantitatively speaking, EEF, ECC, and four sustainable indexes can be displayed, as follows.

(1) EEF analysis: EEFB has a 46.9% lower from $2.39\text{E}+4$ in 2010 hm^2/cap to $1.27\text{E}+4$ hm^2/cap in 2019. EEFI decreases 68.8% from $5.36\text{E}+4$ in 2010 hm^2/cap to $1.67\text{E}+4$ hm^2/cap in 2019. As the largest emergy ecological footprint contributor, EEFE plays a vital impact on the entire emergy ecological footprint. Although EEFE decreased 67.9% from $1.72\text{E}+5$ hm^2/cap in 2010 to $5.66\text{E}+4$ hm^2/cap in 2019, EEFE remains the biggest influence from 2010 to 2019. In 2019, EEFE accounted for 48.63% of the total EEF. In Beijing city, although the EEFP proportion tends to get smaller, from 38.02% of the entire EEF in 2010 to 18.45% in 2019, EEFP still plays an important impact on EEF of Beijing city. In particular, from 2010 to 2019, the change range of EEFB is from 6.37% to 9.29%; meanwhile, EEFI is from 7.95% to 17.72%; EEFE is from 36.36% to 63.71%; EEFP is from 18.45% to 41.65%. Based on the proportions of four subparts, the energy resource products (EEFE) and emissions (EEFP) are the main factors, far more significant than biological resources (EEFB) and industrial products (EEFI).

(2) ECC analysis: Compared to all ECCS data from 2010 to 2019, there is a definite growing trend in Beijing city, from $2.68\text{E}+4$ hm^2/cap in 2010 to $4.72\text{E}+4$ hm^2/cap in 2019, approximately 42.22% growth range.

(3) Four sustainable indicators analysis: There has been a marked decline (absolute value) in EEFT, from a peak of 3.1 in 2011 to 0.688 in 2019. Between 2010 and 2019, EBI amounts decrease from 9.29 in 2010 to 2.46 in 2019, approximately 3.78 times reduction. EDI trends from 2010 to 2019: Fossil land and built-up land are the most important contributors, no matter which year the data is. The total proportions of fossil land and built-up land are 85.25% to 90.43% of the entire EEF in Beijing city. For EECI, there is a relatively stable change from 1.02 in 2010 to 1.14 in 2019, which represents a weak cooperation level between ecological and economic aspects in Beijing city.

The results demonstrate that Beijing is under enormous negative ecological pressure, including three reasons, which are excessive heavy industry, a mass of fossil energy consumption, and vast amounts of pollution emissions, respectively. Meanwhile, reduced cooperation level of ecological and economic systems has also been discovered in Beijing city. Fortunately, after the implementation of partial measures, there is a tendency to get better from 2010 to 2019 through the display of a series of parameters. In addition, the correlation parameter analysis proves that the most significant positive factors and negative factors are tertiary industries ratio and heavy industries ratio to GDP, respectively. These crucial findings provide strategic support for the further sustainable development of Beijing city. At the same time, this study provides a positive reference for city managers and policy makers in Beijing city.

Appendix

All the data and detailed calculation process in the supplemental document.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10668-021-01341-z>.

Acknowledgement The work described in this paper was supported by the postgraduate research & Practice innovation program of Jiangsu province (KYCX18_0104).

Declarations

Conflict of interest The authors declare no conflict of interest.

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