Research on Sustainable Development of Beijing City Based on Ecological Footprint Model

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Abstract: With continuous socio-economic development and increasing urbanization, the sustainable development of Beijing, as the capital of China, has received widespread attention. Based on the ecological footprint model, this paper analyses the per capita ecological footprint, per capita ecological carrying capacity and ecological surplus/deficit in Beijing from 2017 to 2021, and at the same time applies the Ecological Footprint Index and Ecological Pressure Index to analyses the sustainable development situation in Beijing. The results show that Beijing is in a state of ecological deficit from 2017 to 2021, with a rising trend in per capita ecological footprint and ecological deficit, a slight decrease in per capita ecological carrying capacity, and extremely high ecological footprint index and ecological pressure index, indicating that Beijing is in a state of extreme insecurity, and that the regional ecological environment is under a very high degree of pressure. Based on this, this paper provides ideas, data and decision-making basis for the study of sustainable development in Beijing.

Keywords: Beijing City; ecological footprint model; ecological carrying capacity; ecological footprint index; ecological pressure index; sustainable development;

1. Introduction

With the continuous development of social and economic development, the number of populations is increasing, the degree of urbanization is gradually strengthened. The deepening conflict between human socio-economic growth and ecological and environmental protection. How to achieve sustainable development has gradually become a hot issue for scholars at home and abroad to study. Based on this contradiction, China has proposed a "dual-carbon" goal of achieving peak carbon dioxide emissions by 2030 and carbon neutrality by 2060, with the economic and social development mode gradually shifting from high-speed growth to high-quality development.

Beijing City is a hub city linking North China, Northeast China and Northwest China, and is also a world-famous ancient capital and a modern international city. As the capital of China and its political and cultural center, Beijing should play an exemplary leading role.

2. Literature Review

At present, the methods for measuring the level of sustainable development of cities mainly include the ecological footprint analysis method, the environmental sustainability index method, the Sustainability Evaluation using Indicators method and the energy analysis method.

Among them, the environmental sustainability index method is cumbersome and complex to calculate, requires a lot of data, and is more suitable for inter-country sustainability comparisons [1]; the comprehensive evaluation method of the indicator system is usually used for regions and small systems, and is highly targeted, but has a certain degree of subjectivity and one-sidedness; and the energy-value analysis method is commonly used between countries and regions, but the calculation requires a certain degree of knowledge of thermodynamics, and there is a certain degree of controversy [2].

The ecological footprint was proposed in 1992 by Professor Willian Rees [3] of Ecology Canada and he refined the model in 1996 in collaboration with Wackernagel [4]. This method has the advantages of easy to obtain the required data, intuitive results, simple calculation, etc., and has been recognized and widely used by many scholars at home and abroad. Studies such those by as Tian et al [5], Li et al [6], and Liu et al [7] improved the traditional ecological footprint model and combined it with relevant indices to evaluate the ecosystem security in Northwest China, Yunnan Province, and Northern Border, respectively.

As Chinese scholars continue to deepen their research on ecological footprint theory, a series of more targeted ecological evaluation systems on energy footprint, water footprint, tourism footprint, etc. have gradually emerged. Using the energy footprint calculation method and the STIRPAT model, Wang [8] analyzed the dynamic changes of China's energy footprint and the influencing factors from 1978 to 2013; Xiong [9] included non-fossil energy expenditure in the energy footprint calculation. And he measured the energy footprint of Anhui Province by using the NPP method and the carbon sink method, and analyzed its influencing factors; Qin [10] constructed a system dynamics model of water resource use in Jiangxi Province and designed four development scenarios to evaluate and predict the ecological footprint of water resources in Jiangxi Province; Zheng [11] calculated the ecological footprint of interprovincial tourism in China through this model, and concluded that the weight center of interprovincial tourism eco-efficiency in China moves from west to east, and the distribution shows a trend of expanding-shrinking-expanding.

At present, there are fewer articles on the sustainable development of Beijing. A quantitative method is adopted the ecological footprint model to measure and analyses the ecological footprint, ecological carrying capacity and ecological surplus/deficit of Beijing from 2017 to 2021. On the basis of the features of temporal and spatial variations of Beijing's ecological footprint, the assessment was carried out using relevant ecological security targets. with a view to serve as a foundation and reference for other cities to introduce policies related to environmental conservation.

3. Empirical Research

3.1 Data Sources

In this paper, the overall population of Beijing, data on the utilization of various types of resources in Beijing, and the per capita consumption of different types of commodities are derived from the Beijing Statistical Yearbook (2018-2022). The land area of each type in 2017-2018 is derived from the Bulletin of Main Data of the Third National Land Survey issued by the National Bureau of Statistics. The data on the land area of each type in 2019-2021 is derived from the results of the land survey Shared Application Service Platform.

According to the actual production situation in Beijing, this study classifies biological products originating from arable land into grain crops, oilseed crops, sugar crops and vegetables; among livestock products, pigs and poultry are mainly reared on crops, corresponding to biologically productive land under arable land, and cattle and sheep are mainly kept in captivity, with pasture as the feed, so the biologically productive area is under grassland; forest land biological resources are mainly dried and fresh fruits and tea; waters biological resources are aquatic products; fossil energy land involve energy resources such as: coal, petrol, gasoline, diesel, fuel oil, liquefied petroleum gas, liquefied natural gas, and natural gas; and the energy resources considered for construction land are heat power and electrical power.

3.2 Model Construction

3.2.1 Ecological Footprint Model

The world's productive land can be classified into six main categories, namely: arable land, grassland, forest land, waters, construction land and fossil fuel land. The ecological footprint model measures the area of ecologically productive land required for the absorption of biological resources and waste consumed to sustain human survival and development in a region at a given economic level. The calculation formula is as follows [12]:

$$EF = N * ef = N * \sum_{i=1}^{n}(q_i * \frac{c_i}{p_i}) \quad (1)$$

In equation (1): EF denotes total ecological footprint; ef denotes ecological footprint per capita; N denotes total population; i is the type of consumed substance; $c_i$denotes the per capita consumption of the ith resource; $p_i$denotes the national average production capacity per unit area of the ith resource; andq_i is the equilibrium factor of the land type corresponding to the ith substance. The equilibrium factor values calculated by Wackernagel [13] are more widely used in the world. This paper adopts the average equilibrium factor in China measured by our scholars Liu et al [14] based on net primary productivity, and the specific values are shown in the Table 1 below.

Table 1. Equivalence factors of different land types in Beijing.

Land types	Equivalence factors
Arable land	1.03
Forest land	0.60
Grassland	0.62
Waters	0.48
Construction land	1.03
Fossil fuel land	0.60

In this study, the carbon sink method was used to calculate the per capita energy footprint [15]. The calculation formula is:

$$EEF = \sum_{i}^{n} \frac{c_i * J_i * 7000 * 4.1868}{m_i * 10^6 * N} \quad (2)$$

In equation (2): EEF is the energy footprint per capita; i denotes the ith energy consumption item; $c_i$is the ith energy consumption item in the year; j_i is the conversion factor; m_i is the global average energy footprint of the ith energy consumption item; and N is the population size.

3.2.2 Ecological Carrying Capacity Model

Ecological carrying capacity is the maximum number of biological resources and waste digestion that a regional ecosystem can provide, expressed as the area of biologically productive land. It is calculated as follows.

$$EC = N * ec = N * \sum(a_i \times q_i \times y_i) \quad (3)$$

In equation (3), EC is the total ecological carrying capacity; N is the total population; ec is the ecological carrying capacity per capita; a_i is the actual per capita occupancy of biologically productive land area of category; q_i is the equilibrium factor; and y_i is the productivity coefficients. In this paper, we use the values of yield coefficients across China measured by Liu et al [16] based on net primary productivity, as listed in Table 2.

Table 2. Productivity Coefficients of Different Land Types in Beijing.

Land types	Productivity coefficients
Arable land	0.83
Forest land	0.59
Grassland	1.94
Waters	1.94

3.2.3 Ecological Profit and Loss Calculation

Ecological surplus and ecological deficit are obtained by subtracting the ecological footprint from the ecological carrying capacity [17]. The calculation formula is:

$$ED = EC - EF = N * (ec - ef) \quad (4)$$

In equation (4), ED is the ecological deficit or surplus, EC is the ecological carrying capacity, EF is the ecological footprint, N is the total resident population of Beijing, ec is the per capita ecological carrying capacity, and ef is the per capita ecological footprint.

3.3 Measurement of Relevant Indicators

3.3.1 Ecological Footprint Index

The Ecological Footprint Index [18] is one of the metrics to measure sustainable development. The calculation formula is as follows:

$$EFI = \frac{EC-EF}{EC} * 100\% \quad (5)$$

In equation (5), EFI represents the ecological footprint index, EC represents the ecological carrying capacity, and EF represents the ecological footprint. The EFI can be divided into three classes, as listed in Table 3 below.

Table 3. Ecological Footprint Index Level.

serial number	Hierarchy	Mode
1	0 < EFI ≤ 100%	Sustainable development
2	-100% < EFI < 0	Unsustainable development
3	EFI < -100%	Seriously unsustainable development

3.3.2 Ecological Pressure Index

The ecological stress index reflects the degree of pressure on the ecological environment of a region [19]. The calculation formula is:

$$EPI = \frac{EF'}{EC} \quad (6)$$

In equation (6), EPI is the ecological pressure index; EF' is the ecological footprint of renewable resources (biological resources), and EC is the ecological carrying capacity. The criteria for ecological security level division are shown in Table 4.

Table 4. Criteria for Ecological Security Classification.

Hierarchy	Delineation criteria	Characterization state
1	EPI＜0.50	Very safe
2	0.50≤EPI≤0.80	Safer
3	0.80＜EPI≤1.00	Slightly insecure
4	1.00＜EPI≤1.50	Less secure
5	1.50＜EPI≤2.00	Very insecure
6	EPI＞2.00	Highly insecure

4. Calculations

4.1 Ecological Footprint Calculation

In this project, a biological resource ledger was established based on Equation (1) and the following Table 5 was obtained.

Table 5. Beijing Biological Resource Accounts 2021.

Biological resource accounts	World average production(kg/hm²)	Per capita consumption(kg)	Populations (10k person)	Equivalence factors	Per capita ecological footprint(hm²/person)	Land types
Grain crops	2744	109.90	2189	1.03	0.041252551	Arable land
Oilseed crops	1856	6.80	2189	1.03	0.003773707	Arable land
Sugar crops	18000	1.10	2189	1.03	0.000062944	Arable land
Vegetables	18000	119.00	2189	1.03	0.006809444	Arable land
Pork meats	74	18.50	2189	1.03	0.257500000	Arable land
Poultry meats	457	7.60	2189	1.03	0.017129103	Arable land
Bird eggs	400	16.20	2189	1.03	0.041715000	Arable land
Beef and Muttons	33	7.40	2189	0.62	0.139030303	Grassland
Dairy Products	502	29.80	2189	0.62	0.036804781	Grassland
Tea leaves	566	0.50	2189	0.60	0.000530035	Forest land
Fruits	3500	77.20	2189	0.60	0.013234286	Forest land
Aquatic Products	29	10.00	2189	0.48	0.165517241	Waters

Energy accounts are created based on energy consumption data from the 2018-2022 Beijing Statistical Yearbook, and units are first converted to kilojoules using Conversion Coefficient when calculating energy consumption. Heat is then converted at the rate of 1 million kilojoules = 0.03412 kg of standard coal, natural gas at the rate of 100 million cubic meters = 121,430 tons of standard coal, and electricity at the rate of 10,000 kilowatt-hours = 1.229 tons of standard coal. Bringing the converted data into Equation (2), the following Table 6 can be obtained.

Table 6. Beijing Energy Accounts 2021.

Energy accounts	Consumption (10k ton)	Global average energy footprint(GJ/hm²)	Conversion Coefficient(GJ/t)	Equivalence factors	Per capita energy footprint(hm²/person)	Land types
Coals	130.78	55	20.93	0.60	0.000666447	Fossil fuel land
Petrol	480.02	93	43.12	0.60	0.002980094	Fossil fuel land
Gasoline	496.28	93	43.12	0.60	0.003081040	Fossil fuel land
Diesel oil	130.68	93	11.84	0.60	0.000222747	Fossil fuel land
Fuel oil	0.61	71	50.20	0.60	0.000005774	Fossil fuel land
Liquefied petroleum gas	45.50	71	50.20	0.60	0.000430716	Fossil fuel land
Liquefied natural gas	20.42	93	38.98	0.60	0.000114591	Fossil fuel land
Natural gas	2306.68	93	38.93	0.60	0.012927785	Fossil fuel land
Heat power	695.82	1000	29.34	1.03	0.000273370	Construction land
Electrical power	1514.54	1000	11.84	1.03	0.000240087	Construction land

Summing up the consumption items in each land type yields the per capita ecological footprint of each land type in Beijing from 2017-2021, as shown in Table 7 below.

Table 7. Per Capita Ecological Footprint of Beijing City from 2017 to 2021.

Land types	**2017**	**2018**	**2019**	**2020**	**2021**
Arable land	0.25801	0.32213	0.30192	0.32572	0.36824
Forest land	0.01162	0.01334	0.01520	0.01457	0.01376
Grassland	0.13658	0.14296	0.15269	0.16681	0.17584
Waters	0.14201	0.14731	0.16647	0.15724	0.16552
Fossil fuel land	0.02146	0.02146	0.02213	0.01960	0.02043
Construction land	0.00044	0.00044	0.00048	0.00050	0.00051
Per capita ecological footprint	0.57012	0.64763	0.65889	0.68445	0.74430

4.2 Ecological Carrying Capacity Calculation

According to the data of the Third National Land Survey Main Data Bulletin of Beijing, the total area of each type of land in Beijing is obtained and calculated by using formula (3). It should be noted that according to WCED's suggestions, 12% of the ecological capacity should be deducted from the calculation to protect biodiversity, the results of which are shown in Table 8 below. Note that since there is no actual land area for fossil fuel land, the yield factor for fossil fuel land is 0 and the ecological carrying capacity is also 0.

Table 8. Ecological Carrying Capacity of Beijing City from 2017 to 2021.

Land type	**2017**	**2018**	**2019**	**2020**	**2021**
Arable land	0.00741	0.00743	0.00327	0.00322	0.00412
Forest land	0.01259	0.01271	0.01582	0.01564	0.01536
Grassland	0.00412	0.00414	0.00071	0.00070	0.00058
Waters	0.00288	0.00290	0.00235	0.00231	0.00239
Fossil fuel land	0	0	0	0	0
Construction land	0.02576	0.02575	0.02658	0.02583	0.02537
Per capita ecological capacity	0.05276	0.05295	0.04873	0.04770	0.04783

4.3 Ecological Profit and Loss Calculation

By subtracting the data from Tables 7 and 8, the ecological deficit of Beijing is obtained, and the results are shown in Table 9.

Table 9. Ecological Remainder of Beijing City from 2017 to 2021.

Land type	**2017**	**2018**	**2019**	**2020**	**2021**
Arable land	-0.25060	-0.31469	-0.29865	-0.32250	-0.36412
Forest land	0.00097	-0.00062	0.00062	0.00107	0.00160
Grassland	-0.13246	-0.13882	-0.15197	-0.16611	-0.17525
Waters	-0.13913	-0.14441	-0.16413	-0.15493	-0.16313
Fossil fuel land	-0.02146	-0.02146	-0.02213	-0.01960	-0.02043
Construction land	0.02532	0.02532	0.02610	0.02532	0.02486
Ecological remainder	-0.51737	-0.59468	-0.61016	-0.63675	-0.69648

5. Results and Analyses

5.1 Analysis of Changes in the Ecological Footprint

From Figure 1 we can see the changes of per capita ecological footprint in Beijing from 2017 to 2021. The overall trend is upward, and the growth rate is first fast, then slow and then accelerated. The per capita ecological footprint of Beijing increases from 0.57hm²/ capita in 2017 to 0.74hm²/ capita, an increase of 30.55%, with the fastest year-on-year growth rate of 13.60% in 2017-2018. Beijing is in ecological deficit from 2017-2021, expanding from -0.52 hm²/capita to -0.70 hm²/capita at a faster and then slower rate.

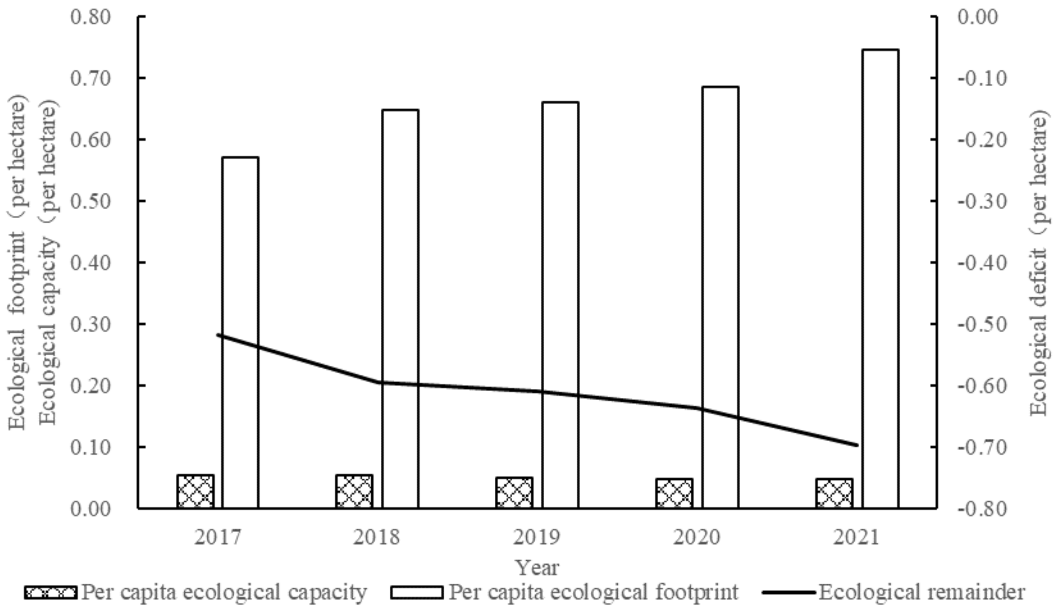

Figure 1. Per capita ecological footprint and ecological carrying capacity of Beijing City from 2017 to 2021.

5.2 Ecological Footprint Distribution Characteristics

This study measured data related to six land use categories in Beijing: arable land, forest land, grassland, water, fossil energy land and construction land. As can be seen from Figure 2, the per capita ecological footprint in 2017-2021 is dominated by the contribution of arable land, grassland and waters, with the combined share of the three being 95.34%. Among them, arable land has the largest share, 49.48 per cent. In terms of time-varying characteristics, Fossil fuel land is on a volatile downward trend, and waters are volatile and rising. Forest land rises first and begins to drop in 2019. Construction land is growing faster. From 2017 to 2021, Beijing as a whole has grown by 30.55 per cent. The arable land increasing by 42.73%, the largest increase. The remaining grasslands (28.74 %) > forest land (18.42 %) > construction land (17.54 %) > waters (16.55 %) > fossil fuel land (-4.80 %).

The per capita ecological carrying capacity is dominated by the contribution of construction land (53.05%) and forest land (32.11%), with grasslands and waters contributing to a lesser extent. In terms of the characteristics of temporal changes, arable land, grasslands and waters are on a downward trend, forest land and fossil fuel land are on a downward and then an upward trend, and construction land has basically remained stable. Beijing as a whole decline by 9.35 per cent in 2017-2021, and forest land improves by 22 per cent. The rest grasslands (-85.91%) > arable land (-44.31%) > waters (-17.15%) > construction land (1.50%) > fossil energy land (0%).

Overall, all land use types in Beijing City are in ecological deficit, with the ecological deficit of arable land, waters and grasslands expanding steadily, and the ecological deficits of forest land, fossil fuel land and construction land fluctuating and decreasing.

5.3 Evaluation of Sustainable Development

As can be seen from Figure 3, the sustainable development of Beijing faces serious challenges in 2017-2021. In 2021, Beijing's Ecological Footprint Index will be -14.56, at the third level, indicating that Beijing's regional development is in a serious unsustainable condition. The ecological pressure index rises from 10.39 to 15.12, meaning that Beijing is in a state of extreme insecurity and the regional ecological environment is under great pressure.

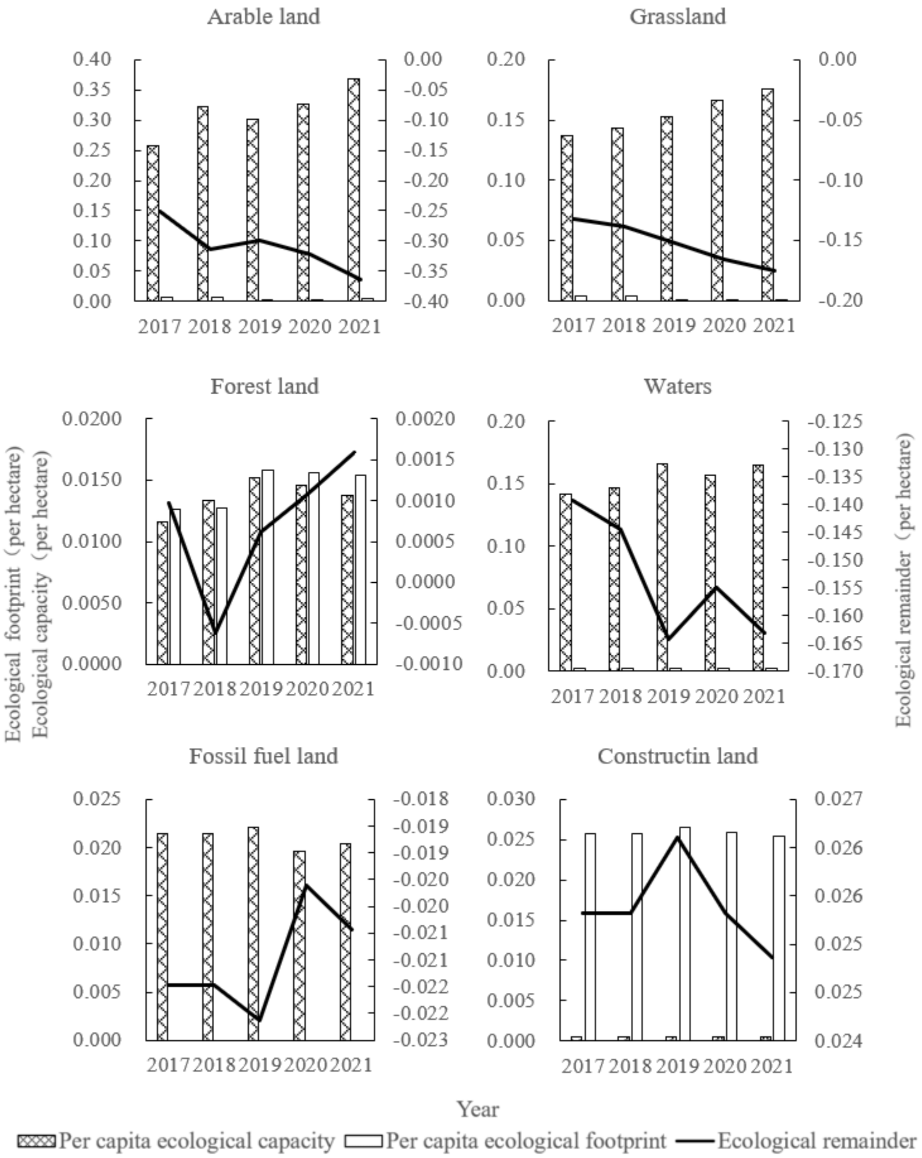

Figure 2. Changes in ecological footprint and carrying capacity of different land use types in Beijing City.

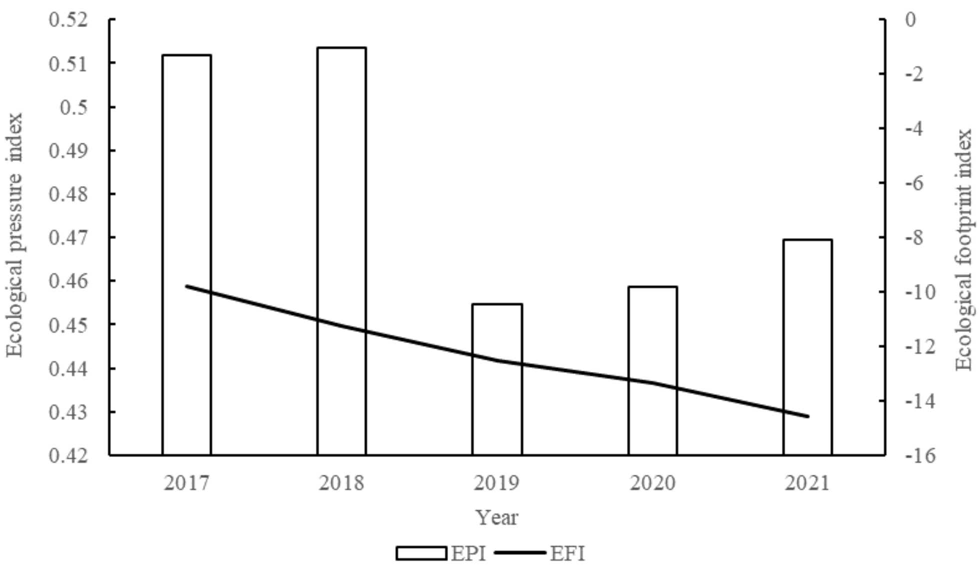

Figure 3. Analysis of sustainable development indicators of Beijing City.

5.4 Conclusions

(1) From the data of Beijing's ecological footprint in the past five years, it can be seen that Beijing's per capita ecological footprint is generally on an upward trend, and the growth rate first decreases and then increases. This suggests that Beijing is at a critical stage of transition to peak carbon. Moreover, Beijing is a relatively small city with an increasing foreign population, a large and mobile population, insufficient carbon removal and reduction measures in production, and consumption habits that are still not environmentally friendly. Beijing City should accelerate its transformation and upgrading and change its production and consumption patterns.

(2) The per capita ecological footprint and ecological deficit in 2021 will be 15.56 and 14.56 times the per capita ecological carrying capacity respectively. This demonstrates that Beijing is in a situation of grave ecological deficit, and the ecological burden is seriously exceeding the limit. Beijing's natural resources cannot fulfil the demands of its own development and its need to rely on the support of other cities is, to some extent, due to Beijing's urban positioning and natural geographical conditions, but this should not lead to the neglect of Beijing's serious ecological burden.

(3) The Ecological Footprint Index of Beijing is -14.56 per cent, indicating that the sustainable development of Beijing is in a seriously unsustainable state. The ecological pressure index is 15.12, indicating that the ecological environment of Beijing is in a state of extreme insecurity. The pressure on Beijing's ecological resources is high, and the efficiency of resource use is low. This has led to more serious environmental pollution and certain contradictions between environmental protection and economic development. Beijing should enhance resource utilization efficiency and facilitate green economic development.

6. Suggestion

(1) We should continue to enhance the ecological footprint statistical indicators to increase the comprehensiveness and accuracy of the measurement results. In counting biological resource accounts, 12 representative commodities were selected for this paper. Incomplete data may result in small data and some error. Also, when calculating the ecological footprint of the grassland, due to the difficulty of capturing the complete area of the pasture, the overall area of the grassland was used as a proxy calculation. The calculated ecological carrying capacity per capita may therefore be smaller than the actual data. In future studies, data quality should be improved, statistical methods should be refined, and data types should be refined. Factors such as GDP and industry can also be introduced to make horizontal and vertical comparisons to get a more comprehensive conclusion.

(2) Strengthening spatial coordination and planning conduction to improve the rational use of resources. It has coordinated the spatial layout of energy and water conservancy corridors in the municipal area, and has taken measures such as ecological access to areas with different types of use, so as to build up ecological space in an orderly manner. Increase the production of ecological products and promote green and low-carbon development in Beijing. Strengthening resource control, adjusting the spatial structure of vegetation, optimizing the land-use structure, carrying out the construction of ornamental vegetation and optimizing the ecological spatial pattern of Beijing.

(3) Optimizing the population layout and evacuating the functions of the capital. Strictly guarding the incremental population size and promoting the reasonable and orderly movement of population. Unswervingly relieving non-capital functions and continuously optimizing the spatial layout of the city. In the next five years, we will gradually relocate key universities under the Ministry of Education, Grade 3A hospitals and the headquarters of central enterprises. We will create a pattern of multiple urban centers, including the Beijing Urban Vice-Centre, the "Three Cities and One Region" and the Beijing Free Trade Zone.

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