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# Evaluation of Ecological Sustainable Development in the Yangtze River Delta Region Based on Ecological Footprint Theory

**DING Yumin**
(Tongling University, Tongling, Anhui 244000, China)

**Abstract** The ecological footprint was employed as a quantitative indicator of resource inputs, enabling a detailed account of the structure of biological resources and energy occupancy, as well as the variation of resource productivity in the Yangtze River Delta (YRD) Region. From 2004 to 2018, there were notable variations in the ecological productivity of different types of land on basis of China's equilibrium factor across the three provinces and one city in the YRD region. Jiangsu Province exhibited the highest ecological productivity of arable land, while Anhui Province exhibited the highest ecological productivity of forest land. Shanghai City exhibited the highest ecological productivity of pasture land, while Zhejiang Province exhibited the highest ecological productivity of water area. In 2018, the proportion of arable land within the total ecological carrying capacity of the YRD region reached 74.35%. Furthermore, the contribution of Jiangsu and Anhui provinces to the YRD's total ecological carrying capacity was 41.36% and 41.26%, respectively. In the construction of a new development pattern in the YRD region, which is dominated by the domestic cycle as the main body and mutually reinforced by domestic and international double-cycle, the YRD region should combine the utilization of natural forces with innovation in science, technology and cooperation mechanisms. Furthermore, the government should guide the concentration of social capital towards green industries. It is also recommended that the moderate reduction of ecological footprints should be encouraged, and that the security of biological resources and energy, the leadership in the field of cutting-edge science and technology should be ensured in YRD region. This will facilitate the formation of a new development pattern of higher-quality integration at the national level firstly.

**Keywords** Ecological footprint, Resource productivity, China's equilibrium factor, Yangtze River Delta region
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In both Marxian theory of natural forces and neoclassical economics, natural resources are regarded as established, inexhaustible, and therefore neglected exogenous variables. In the traditional economic system, natural resources are primarily considered to flow in a unidirectional manner, from resources, products to waste. This perspective fails to acknowledge that nature not only provides humans with material and energy resources but also acts as a vast "garbage dump" that absorbs human waste through the water system, soil, and air. The assumption that the degradation and self-purification functions of nature are sufficient to repair the environmental pollution and ecological damage caused by human beings has been proven erroneous. Consequently, there is a need for a new approach to economic theory that takes account of the internal biochemistry of environmental resources. As a consequence of the gradual scarcity of natural resources, the function of economics, which is to allocate resources in a sustainable manner, has shifted to the question of how to achieve equilibrium between human needs and natural supplies.

The increase in ecological footprints has resulted in an excess of ecological demand and deficits, which has led to an inevitable increase in environmental pollution and the deterioration of the ecological environment. This has become a serious threat to the sustainable development of human production and life. In the event that a region's ecological demand exceeds its supply, there are two potential avenues for meeting this demand. The first is through the depletion of future natural capital, which can be seen as a form of intergenerational inequity. The second is through the depletion of natural capital outside the region, which can be viewed as a form of contemporary inequity. The World Wide Fund for Nature (WWF) has been publishing the *Global Ecological Footprint Report* every two years since 1998. This report serves to continuously update the status of the global ecological footprint. The ecological footprint and ecological carrying capacity are both based on ecological producti-vity. Human beings use science and technology to integrate the natural production process with the human production process, continuously improve productivity levels, and realize the sustainable development of human, nature and society community.

This study made a marginal contribution to the field of ecological economics by developing a model of total ecological supply and total ecological demand in the YRD region. The equilibrium factor of China and the yield factor of different ecological lands in the YRD region were calculated to establish this model. The study then evaluated the sustainable development of the YRD region by examining the trend of ecological deficits in the region and the resource productivity indicator based on ecological footprints. Finally, the study proposed countermeasures and suggestions to address the identified challenges.

## 1 Literature review of ecological footprint theory

The theory of the ecological footprint was initially developed by Canadian ecological economist William E. Rees in 1992 and subsequently refined by his student Wackernagel Mathis in 1996. Wackernagel compared the ecological footprint to the footprints left by human beings' giant feet on the earth. The resources consumed by human beings are derived from the land, and the land is also necessary to absorb the wastes produced by human beings. All human activities, therefore, can be considered to originate from and return to the land.

The ecological footprint theory maps the total consumption of resources and energy

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in a given region to the land on which human beings depend, and compares it to the ecological production capacity that the region possesses. The ecological footprint analysis method employs a two-pronged approach to assess the sustainability of a region's development. First, the size of the ecological footprint is calculated based on the demand side, and then the size of the ecological carrying capacity is determined from the supply side. When the ecological footprint is smaller than the ecological carrying capacity, it is indicative of an ecological surplus, which signifies that the region's development is within the limits of its ecological carrying capacity and, thus, sustainable. Conversely, an ecological deficit indicates that the region's development has exceeded the scope of its ecological carrying capacity, which is unsustainable.

Scholars have made significant contributions to the field of ecological footprint analysis. These include improvements to the Wackernagel comprehensive ecological footprint model[1], the development of the time-series ecological footprint model with dynamic evolution characteristics[2], the input-output ecological footprint model based on input-output tables[3], the ecological footprint model based on energy analysis[4], the ecological footprint of international trade model[5], and the three-dimensional ecological footprint model[6], etc. The research on ecological footprint in China commenced with the efforts of Zhang Zhiqiang et al.[7] and Yang Kaizhong et al.[8], who were instrumental in introducing the concepts, models, and calculation methods associated with ecological footprint into the Chinese academic discourse. In a study conducted by Chen Min et al.[9], the change in China's ecological footprint from 1978 to 2003 was calculated. Over the 25-year period studied, the ecological footprint of fossil energy in China doubled, exacerbating the crisis of shortage of forest land in China.

Cao Shuyan et al.[10] employed the monetary input-output ecological footprint model to examine the ecological footprints of China's three industries in 1997. Their findings indicated that China's secondary industry exhibited the highest ecological footprint in that year. Sun Jiuwen et al.[11] studied the ecological footprint and sustainable development in the YRD region. Zhang Jiankun et al.[12] calculated the ecological footprint of the three major industries in Nanjing City and analyzed the appropriate population size of the three major industries. Tourism is a resource-consuming industry that encompasses a multitude of human activities, including food, clothing, housing, and transportation. Consequently, it has a profound impact on the ecological environment. Wackernagel et al.[13] employed the ecological footprint theory to assess the sustainability of tourism development, while Hunter[14] initially conceptualized the notion of a tourism ecological footprint. The tourism ecological footprint is a flow concept that is not typically associated with specific land resources or specific populations. However, the consumption of various resources in tourism can be incorporated into standard ecologically productive area for comparative analysis. Thomassen et al.[15] investigated the ecological footprint of the dairy sector. Cerutti et al.[16] examined the ecological footprint of four distinct fertilizer application methods throughout the life cycle of a commercial orchard in Piedmont, Italy. Their findings indicated that the ecological footprint of chemical fertilizer application was approximately 6 times higher than that of manure application, accounting for 6.6% of the total ecological footprint. In a pioneering study, Holland[17] applied the ecological footprint research method to the operation of the Anglian Water Services Company in the UK. Li Dingbang et al.[18-19] examined the structure of the household ecological footprint and the rationality of household consumption based on the Wackernagel household ecological footprint framework, and compared the differences and connections of ecological footprints among different households.

Ren Qunluo[20] posited that ecological footprint analysis offers a scientific foundation and convenience for the analysis of total demand and total supply of ecosystems. In a study on the ecological footprint of Hong Kong, Kimberley et al.[5] highlighted that the external dependence of Hong Kong's ecological footprint reached as high as 94.75%. Warren-Rhodes et al.[21] determined that the ratio of Hong Kong's ecological footprint to its ecological carrying capacity was 22 : 1, with 30% of the ecological footprint excess originating from mainland China and 60% from international trade with the rest of the world. In a time-series analysis of the ecological footprint contained in China's customs import and export commodities from 1991 to 2003, Chen Liping et al.[22] observed that China had undergone a significant shift in its ecological footprint profile, transitioning from a net importer to a net exporter since 1995. An analysis of international trade and its impact on the ecological footprint allows us to observe the transfer of this footprint between different countries or regions. From the perspective of the ecological footprint, international trade can be conceptualized as a process of international transfer of ecologically productive land which serves to alter the ecological surplus and deficit situation of a country or region.

It can be observed that the ecological footprint manifests in diverse contexts, encompassing different scales, industries, families, enterprises, and stages of the product life cycle. The field of ecological footprint research also exhibits a multifaceted structure, encompassing macro, meso, and micro levels. A range of factors, including economic growth, industrial structure, consumption patterns, per capita disposable income of urban residents, and population size, exert a considerable influence on the ecological footprint. The ecological footprint theory posits a universal nexus between human ecological demand, ecological supply, and ecologically productive land.

## 2 Analysis of total ecological demand and supply in the YRD region

### 2.1 Total ecological demand and supply model

The ecological footprint analysis method employs a calculation of the ecological footprint of a defined population within a specified region. This approach enables the assessment of the total ecological demand of the region, with the ecological carrying capacity representing the total ecological supply of the region. By comparing these two figures, the method allows for the analysis of the utilization of ecosystems by human beings in the region as well as the support of ecosystems to human beings. Based on this analysis, the method can then be used to further analyze the state of sustainable development in the region. In order to achieve this objective, a total ecological demand and total supply model is developed as follows:

$$\text{Total ecological demand}=\text{EAD}=\text{EAD}_{\text{biological resources}}+\text{EAD}_{\text{energy}}=\sum_{ij} r_i * C_j / P_{ij}+\sum_j G_j * C_j / S_j \quad (1)$$

$$\text{Total ecological supply}=\text{EAS}=(1-12\%)\sum_i r_i * y_i * S_{ir} \quad (2)$$

where $C_j$ denotes the consumption demand for various biological resources and energy; $P_{ij}$ represents the average productivity of the $i$-th land for the production of the $j$-th resource; $C_j/P_{ij}$ is the area of ecological land required for the consumption of the $j$-th resource, adjusted by the average yield of a given region; $r_i$ denotes the equilibrium factor of the $i$-th land, and the land demand adjusted by $r_i$ is the standard ecological land demand for biological resources $\text{EAD}_{\text{biological resources}}$; $S_j$ represents the ecological land demand per unit ($10^9$J)of energy; $G_j$ stands for the energy conversion coefficient, and the land demand adjusted by $G_j$ is the standard ecological land demand for energy $EAD_{energy}$. The sum of $EAD_{biological\ resources}$ and $EAD_{energy}$ is the total ecological demand EAD of a certain population in the studied area. $S_{ir}$ denotes the actual area occupied by the $i$-th land in a region; $y_i$ is the yield factor of the $i$-th land. Following the aforementioned adjustments and the deduction of 12% of the ecologically productive area utilized for the maintenance of ecosystem biodiversity, the resulting figure represents the total ecological supply (EAS) of a specific region.

In the context of ecological footprint theory, the consumption of biological resources, electricity, and fossil energy by human beings is transformed into standardized ecological lands that can be compared and calculated. These lands satisfy the ecological needs of human beings and record the ecological footprint of human beings. The ecological carrying capacity is used to provide human beings with the biological resources used for consumption or the capacity to absorb the waste discharged by human beings. The term "ecologically productive area" (EPA) is used to refer to all types of land in the natural ecological environment that have been standardized, including arable land, pasture land, forest land, construction land, water area, and fossil energy land. The EPA is thus the basic unit for measuring total ecological demand and total ecological supply (Table 1).

## 2.2 Data sources

The total ecological supply model encompasses the production and consumption of biological resources, electricity, and fossil energy. As indicated in the 2005−2019 *China Statistical Yearbook*, the production of biological resources was selected as follows. A total of 27 different agricultural products were selected, including rice, wheat, corn, sorghum, barley, mung bean, small red soybean, soybean, potato, cotton, peanut, rapeseed, sesame, sunflower seed, flaxseed, jute/kenaf, flax, hemp, ramie, sugarcane, sugarbeet, tobacco, flue-cured tobacco, vegetable, watermelon, melon, and strawberry. A total of 14 distinct forest products were selected for analysis: black tea, green tea, banana, apple, mandarin, pear, grape, pineapple, red jujube, persimmon, camellia seed, sliced bamboo shoot, timber, and bamboo wood. Four categories of animal husbandry products were included in the analysis: beef (pasture land), mutton (pasture land), milk, and sheep's wool. In addition, three categories of aquatic products were considered: fish, shrimp and crab, and shellfish. The total output of 48 kinds of agricultural, forestry, livestock, and fishery products from 2004 to 2018 was multiplied by the respective unit calorific value. In accordance with Equation 3, the national average biological productivity per unit area ($P_{ij}$) was determined for the four land types: arable land, forest land, pasture land, and water area. In accordance with Equation 4, the national total average biological productivity per unit area ($P_i$) was calculated for each type of land. In the formula, $i$ represents six types of EPA, with the value equaling 1, 2, 3, 4, 5, or 6, respectively; $j$ represents the type of biological resources; $Q_{ij}$ represents the total calorific value of biological resources, and $S_{ij}$ represents the cultivated area.

National average biological productivity of the $i$-th land $P_{ij}$=(Sum of the national production ($Q_{ij}$) of the $i$-th land for the $j$-th biological resource)/(Sum of the national cultivated area ($S_{ij}$)of the $i$-th land for the $j$-th biological resources)=$(\sum_j Q_{ij})/(\sum_j S_{ij})$ (3)

National total average biological productivity of all types of land $P_i$=(Sum of the national biological production of all types of land)/(Sum of the national biological cultivated land of all types of land)=$(\sum Q_i/\sum S_i)=(\sum_i \sum_j Q_{ij}/\sum_i \sum_j S_{ij})$ (4)

Biological resource accounts were established based on four types of land use: arable land, forest land, pasture land, and water area. The actual consumption item $C_j$ of the $j$-th resources was comprised of beef (pasture land), mutton (pasture land), and milk products for pasture land, fruits for forest land, aquatic products for water area, as well as 10 types of commodities for arable land, including grains, edible oils, vegetables and edible mushrooms, sugar, wine, pork, poultry, eggs and their products, beef (arable land), and mutton (arable land). The per capita consumption of major foodstuffs by urban and rural residents in the three provinces and one city in the YRD region was multiplied by the total population of each province (city) and then summed up, with data derived from the 2005−2019 *China Statistical Yearbook*. The total ecological demand calculated by this method was smaller than the actual demand because only the principal consumer goods were included in the statistical yearbook. $P_{ij}$ represents the national average productivity of the $i$-th land type for the production of the $j$-th resources; $C_j/P_{ij}$ denotes the area of ecological land required for the consumption of the $j$-th resources, adjusted by the national average production; $N$ signifies the total population in the region. The data utilized in this study were obtained from the 2005−2019 *China Statistical Yearbook* and the statistical yearbooks of Shanghai City, Jiangsu, Zhejiang, and Anhui provinces.

The consumption of coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, natural gas, and electricity was selected to establish an energy consumption account. The energy consumption was converted into the total calories consumed according to the calorie conversion factor. Finally, the energy consumption was converted into a certain amount of EPA based on the global average ecological footprint of each energy source. Among the various forms of energy consumed, coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, and natural gas were all converted to fossil energy land. Similarly, the consumption of electricity was converted to construction land. The energy ecological demand was calculated by converting the diverse energy sources utilized in the three provinces and one city through calorific value conversion, as illustrated in Table 2.

## 2.3 Comparison of equilibrium factor of China and regional yield factor of the YRD region

The equilibrium factor ($r_i$) is a coefficient value assigned to different types of land according to their productivity differences in the analysis of the ecological footprint model. This allows for the summation and comparative analysis of different types of land after they have been standardized by the equilibrium factor. The ecological footprint model analysis reveals significant discrepancies in resource endowment and productivity levels across different regions.

**Table 1 Six types of ecologically productive area**

| No. | Land type | Characteristics |
|---|---|---|
| 1 | Arable land | It exhibits high biological productivity and aggregated bioenergy |
| 2 | Forest land | It is known as the "lung of the earth", providing humans with timber, fruits, and a variety of forest products |
| 3 | Pasture Land | The site serves as a food source for herbivores, and converts plant energy into animal energy |
| 4 | Water area | It encompasses both inland and offshore water areas that are capable of providing aquatic products |
| 5 | Construction land | The majority is obtained through the occupation of arable land, in addition to a modest quantity of forest lands and pasture land |
| 6 | Fossil energy land | Given that fossil energy is a non-renewable resource, it can be argued that fossil energy land represents a form of virtual natural capital |

Consequently, when calculating the ecological footprint and ecological carrying capacity of a specific region, similar lands in different regions are also assigned a coefficient value, which is known as the yield factor ($y_i$).

The Chinese equilibrium factor and the yield factor for the three provinces and one city in the YRD region were calculated based on China-wide average productivity data, which were more readily available and therefore more accurate than global average productivity data. The ecological footprint thus calculated is more consistent with the characteristics of a country's resource endowment and can more accurately reflect the ecological footprint and ecological carrying capacity of each location. Furthermore, it facilitates comparative analysis between different regions in China[23]. The calculation formulae for China's equilibrium factor and yield factor are as follows:

China's equilibrium factor $r_i$=(National average biological productivity of the $i$-th land $P_{ij}$)/(Total average biological productivity of all types of land $P_i$)$=[(\sum_j Q_{ij}/\sum_j S_{ij})/(\sum_i \sum_j Q_{ij}/\sum_i \sum_j S_{ij})]=[(\sum_j q_{ij}*\gamma_{ij}/\sum_j S_{ij})/(\sum_i \sum_j q_{ij}*\gamma_{ij}/\sum_i \sum_j S_{ij})]$ (5)

Yield factor $y_i$=(Average biological productivity of the $i$-th land in the $r$ region $P_i^r$)/(National average biological productivity of the $i$-th land $P_i$)$=[(\sum_j Q^r_{ij}/\sum_j S^r_{ij})/(\sum_j Q_{ij}/\sum_j S_{ij})]=[(\sum_j q^r_{ij}*\gamma_{ij}/\sum_j S^r_{ij})/(\sum_j q_{ij}*\gamma_{ij}/\sum_j S_{ij})]$ (6)

In accordance with Equation 5, the equilibrium factor $r_i$ was determined for each type of land in China, including arable land, forest land, pasture land, and water area. The variable $q_{ij}$ represents the actual yield of each biological resource, while $\gamma$ represents the unit calorific value corresponding to each biological resource. The results of the calculations in Equations 3 and 4 were substituted into Equation 6, and the yield factors for the four types of land in three provinces and one city of the YRD region were calculated with respect to the national average yields (Table 3).

From 2004 to 2018, China's arable land exhibited the highest ecological productivity, approximately 3.5 times higher than the national average land productivity. The balance factor of arable land reached a maximum in 2008, at a value of 3.65, after which there was a slight decline and then a rebound in recent years. The ecological productivity of pasture land was the lowest, which was mainly due to the low productivity of pasture land in China. Concurrently, the productivity of pasture land was primarily quantified in the ecological footprint calculation model through the energy value of livestock products, such as beef and mutton. However, when plant energy is converted to animal energy, it is subject to the "10% law of diminishing energy", which is a phenomenon whereby the conversion of energy from one form to another results in a loss of energy. The equilibrium factor of water area generally demonstrated a gradual upward trend. The ecological productivity of water area was comparable to the national average land productivity. This is related to the adjustment of the industrial structure within China's agriculture and the tendency of people to consume more aquatic products in their food consumption structure. The low ecological productivity of China's forest land is not only related to the low productivity of China's forestry industry, but also to China's overall low forest coverage. With the exception of a small fluctuation in 2009, the equilibrium factor of forest land was steadily improving. The primary reason for the improvement is the efficacy of China's initiatives to expand forest coverage and the economic advantages of forestry, guided by the principles of the new development philosophy. The data indicated that the productivity of all types of land in China remained relatively stable during the study period. This can be attributed to the fact that China had fully entered the period of new urbanization and new industrialization, which had created an environment conducive to the development of agricultural productivity. Furthermore, these findings demonstrate the effectiveness of China's stable agricultural policy and the advancement of agricultural modernization.

The yield factor of arable land in the three provinces and one city of the YRD region exhibited fluctuations from 2004 to 2018. Among the provinces and the city, Shanghai City exhibited the most pronounced fluctuations. Shanghai City and Zhejiang Province exhibited a general downward trend, while the remaining two provinces exhibited a general downward and then upward trend. Among the three provinces and one city, Jiangsu Province exhibited the highest yield factor of arable land, indicating that the agriculture of Jiangsu Province is the most developed among the three provinces and one city. This was followed by Anhui Province, with the lowest yield factor observed in Zhejiang Province. The yield factor of forest land in the three provinces and one city exhibited fluctuations and a relatively large decline, with Shanghai City experiencing the most significant decline. Anhui Province had the highest yield factor of forest land, followed by Jiangsu Province. In the past two years, the yield factor of forest land in Zhejiang Province has shown slight improvement, exceeding that of Shanghai City and ranking third. Among the three provinces and one city, the yield factor of forest land in Anhui and Jiangsu provinces was slightly higher than the national average,

**Table 2 Energy account coefficient**

| Energy type | Energy conversion factor $G_i$//$10^9$ J/t | Unit ecological land demand $S_i$//$10^9$ J/hm | EPA type |
|---|---|---|---|
| Coal | 20.908 | 55 | Fossil energy land |
| Coke | 28.435 | 55 | Fossil energy land |
| Crude oil | 41.816 | 93 | Fossil energy land |
| Gasoline | 43.070 | 93 | Fossil energy land |
| Kerosene | 43.070 | 93 | Fossil energy land |
| Diesel | 42.652 | 93 | Fossil energy land |
| Fuel oil | 41.816 | 93 | Fossil energy land |
| Natural gas | 38.931 | 71 | Fossil energy land |
| Electricity | 11.826 | 1 000 | Construction land |

**Table 3 Balance factors of all types of land in China and yield factors of the three provinces and one city in the YRD region from 2004 to 2018**

| Factor type | Arable land | Forest land | Pasture land | Water area | Construction land | Fossil energy land |
|---|---|---|---|---|---|---|
| Balance factor | 3.54 | 0.28 | 0.03 | 0.93 | 3.54 | 0.28 |
| Yield factor of Shanghai City | 1.24 | 1.18 | 4.88 | 2.95 | 1.24 | 0 |
| Yield factor of Jiangsu Province | 1.36 | 1.62 | 3.60 | 1.45 | 1.36 | 0 |
| Yield factor of Zhejiang Province | 0.77 | 0.61 | 0.15 | 4.10 | 0.77 | 0 |
| Yield factor of Anhui Province | 1.13 | 1.76 | 1.08 | 0.93 | 1.13 | 0 |

while the yield factor of forest land in Shanghai City and Zhejiang Province was much lower. In 2018, the yield factor of forest land in Shanghai City was only 1/4 of the national average, and that of Zhejiang Province was less than 1/2 of the national average, which was approximately 40% of the national average. The yield factor of pasture land in the three provinces and one city in the YRD region had exhibited a relatively stable trend since 2006 in Jiangsu, Zhejiang, and Anhui provinces, with the exception of Shanghai City, which had demonstrated a notable fluctuation range. The yield factors of pasture land in Shanghai City and Jiangsu Province were found to be considerably higher than the national average, while those of Anhui Province exhibited a slight increase above the national average. Conversely, the yield factors of pasture land in Zhejiang Province were observed to be the lowest, with a value of only 13% of the national average in 2018. With the exception of Anhui Province, which exhibited a yield factor slightly below the national average, the yield factors of the water area of Zhejiang, Shanghai, and Jiangsu were all higher than the national average. The yield factor of the water area of Zhejiang Province ranked first in the YRD region. The lowest yield factor was observed in Anhui Province, which can be attributed to the fact that Anhui is a landlocked province, whereas Zhejiang, Shanghai, and Jiangsu are situated in close proximity to the East China Sea. Additionally, Zhejiang Province is endowed with a superior quality and extensive offshore fishing grounds.

## 2.4 Analysis of total ecological demand in the YRD region

In accordance with the aforementioned model of total ecological demand and total ecological supply, it can be observed that the biological resources, electricity, and fossil energy consumed by human beings are transformed into standardized lands that can be compared and calculated. These lands satisfy the needs of human beings and document their ecological footprints. In contrast, the total ecological supply represents the EPA utilized by humans to provide themselves with biological resources for consumption or to absorb waste discharged by humans. In order to calculate specific indicators such as per capita ecological demand, ecological supply, and ecological deficit, as well as production demand, the following formulae were employed:

Per capita ecological demand $ead=EAD/N=(\sum_{ij} r_i * C_j/P_{ij})/N$ (7)

Ecological carrying capacity factor $c_i=r_i * y_i$ (8)

Per capita ecological supply $eas=EAS/N=[(1-12\%)\sum_i c_i * S_{ir}/N]$ (9)

Ecological deficit $ED=EAD-EAS$ (10)

Per capita ecological deficit $ed=ead-eas$ (11)

Per capita energy demand $ead_{energy}=EAD_{energy}/N$ (12)

Biological resource production demand $PAD=\sum_{ij} r_i * P_j/P_{ij}$ (13)

Per capita biological resource production demand $pad=PF/N=(\sum_{ij} r_i * P_j/P_{ij})/N$ (14)

Per capita energy production demand $pad_{energy}=PAD_{energy}/N=(\sum_j G_j * P_j/S_j)/N$ (15)

The overall fluctuation trend of changes in ecological demand for biological resources in the three provinces and one city in the YRD region from 2004 to 2018 was relatively consistent. According to the Engel guideline, as income levels rose, the proportion of food consumption in total consumption showed a decreasing trend. The trajectory of changes in the ecological demand for biological resources in the three provinces and one city in the YRD region revealed a decline that was followed by a slight increase. The latter occurred primarily in 2013 and was associated with the implementation of the national strategy of new urbanization construction at this stage of China's development. The rise in urbanization and the migration of a proportion of agricultural population to urban areas has resulted in an uptick in the consumption of biological resources. As illustrated in the change trend chart of the ecological demand for construction land, the three provinces and one city exhibited a notable increase. In terms of the rising speed, Jiangsu and Zhejiang provinces exhibited a more rapid increase and surpassed Shanghai City in 2011. Anhui Province demonstrated a notable surge in growth, while Shanghai's rising rate exhibited a downward trend, suggesting that the municipal government's construction measures, including the reduction of construction land and the implementation of smart city initiatives, have been met with some success. The accelerated expansion of construction land not only impinges upon regional ecological space but also impairs the material transformation between humanity and nature. The trend chart of the change in ecological demand for fossil energy revealed a notable differentiation between the three provinces and one city. Shanghai City, however, exhibited a slight decline within a relatively minor fluctuation. Zhejiang Province demonstrated an upward trajectory from 2004 to 2011, followed by a period of relative stability from 2012 to 2018. Anhui Province exhibited an upward trend from 2004 to 2013, after which it experienced a period of relative stability. Jiangsu Province displayed an overall upward trend, with a more pronounced increase from 2004 to 2010, and surpassed Shanghai City for the first time in 2014. The continued increase in fossil energy consumption in Jiangsu Province can be attributed to two main factors: the significant contribution of fossil energy to the province's industrial added value, and the sustained growth of private transportation.

The trend of total ecological demand per capita in the three provinces and one city in the YRD region from 2004 to 2018 essentially mirrored the trend of fossil energy ecological demand, suggesting that fossil energy ecological demand remained the predominant component of total ecological demand. The overall decline in ecological demand per 10,000 yuan of GDP was a consequence of the sustained transformation and upgrading of industrial structure and energy in the YRD region. Anhui Province exhibited the most precipitous decline in ecological land area per 10,000 yuan of GDP among the three provinces and one city, yet still maintained the highest consumption rate. In contrast, Zhejiang Province demonstrated a relatively stable trend, exhibiting the lowest ecological demand per 10,000 yuan of GDP among the three provinces and one city. The per capita production footprint of the three provinces and one city in the YRD region exhibited an upward and then a downward trend from 2004 to 2018. However, Shanghai City experienced the most significant decline, followed by Jiangsu Province. In contrast, Zhejiang and Anhui provinces demonstrated a slight upward trend in 2018 compared to 2017. Among the three provinces and one city, Anhui Province exhibited the most significant production and demand, which can be attributed to the fact that the production and demand, like the ecological demand, predominantly encompass two categories: biological resources and energy. This is largely due to the province's substantial agricultural output and its status as a major energy producer.

## 2.5 Analysis of total ecological supply in the YRD region

The total ecological supply objectively restricts the economic development of a region. The regional economy can only develop healthily to the extent permitted by the ecological carrying capacity. The application of scientific and technological principles by humans can consistently enhance productivity. When the production process of humans is integrated into the virtuous cycle of the ecosystem, a harmonious coexistence of humans and nature will be ultimately realized.

The trend of changes in per capita ecological supply in the three provinces and one city in the YRD region from 2004 to 2018 was characterized by relatively stable conditions in Anhui and Jiangsu provinces, with a slight increase observed in Anhui Province. Shanghai City and Zhejiang Province exhibited a decline, with a 28.4% decline observed in Zhejiang Province. Among the three provinces and one city, Anhui Province contributed a slightly lower proportion of the total ecological supply of the YRD region than Jiangsu Province, accounting for 41.26% (Figs.1–2). This is due to the fact that Anhui Province has more abundant arable land and forest land resources, and the implementation of the ecologically robust province strategy in recent years has been more effective.

## 3 Evaluation of ecological sustainable development in the YRD region

### 3.1 Trends based on ecological deficits

The regional economy can only develop in a healthy and sustainable manner if it is constrained by the ecological carrying capacity (Table 4). Given that fossil energy is a non-renewable resource, it is imperative from a sustainable development perspective that 12% of EPA should be deducted from the calculation of the ecological carrying capacity to maintain ecosystem biodiversity. Concurrently, it is essential that humans reserve a portion of land to offset the total amount of natural capital consumed by non-renewable fossil energy.

Fig.3 presents a comparison of the per capita ecological footprint, per capita production footprint, per capita ecological carrying capacity, and ecological footprint per 10,000 yuan of GDP for the YRD region as a whole from 2004 to 2018. The figure illustrated that the per capita ecological carrying capacity for the YRD region as a whole had remained relatively stable over the period. Nevertheless, the per capita ecological demand had been on the rise due to the increasing ecological demand for fossil energy, which had resulted in a growing per capita ecological deficit. Shanghai City exhibited an overall downward trend, while Jiangsu, Zhejiang, and Anhui provinces demonstrated a 158%, 77%, and 142% increase, respectively. Jiangsu Province exhibited the most rapid increase in total ecological demand, surpassing Zhejiang Province in 2010 and then Shanghai City in 2018. This resulted in the largest ecological deficit among the three provinces and one city, indicating that the unsustainability of the economic development of Jiangsu Province had intensified.

### 3.2 Comparison based on resource productivity

The enhancement of resource productivity is not only conducive to the economical utilization of resources, but also serves to safeguard resources and the environment. The term "labor productivity" is typically defined as the ratio of output produced to the amount of labor input in a given time period. Similarly, "resource productivity" can be defined as the ratio of output produced to the amount of resource input in the same time period. Pearce posits that the productivity of a given resource can be quantified by measuring the amount of output produced per unit of factor input.

$$R=Y/m \tag{16}$$

where $Y$ denotes the quantity of output, and $m$ denotes the quantity of resource or material inputs. It is now common practice internationally to express the output quantity, $Y$, in terms of GDP. However, this makes it exceptionally difficult to account for resource productivity due to the variety of types and lack of uniformity of units involved in the input quantity of resources or materials.

In his 1865 treatise, *The Coal Problem*, British economist and logician William Stanley Jevons advanced the concept of resource productivity as a means of addressing the significant rise in the price of coal and the concomitant surge in demand for coal during the Industrial Revolution. The European Environment Agency (EEA) defines resource productivity as the increase in total social welfare per unit of natural resources, given that natural resources not only provide factor inputs for humans, but also absorb human-generated waste and provide ecological services such as suitable landscapes and living environments. Since the 1990s, theoretical research on resource productivity has also undergone a change in focus, shifting from the traditional emphasis on the efficiency of output per unit of resource input to a more comprehensive approach that considers the material input per service unit (MIPS). This shift reflects a growing recognition that resource productivity entails not only the optimization of output per unit of resource but also the reduction of resource consumption for a given output. Given that the earth's capacity to absorb and self-purify a range of pollutants and wastes is an inherent natural resource, it is also necessary to consider the ability of the earth's ecosystems to absorb wastes when calculating resource productivity. In his study of the urban green competitiveness of the YRD urban agglomerations, Zhu Yuan[24] employed a two-index system approach to resource productivity, comprising input and output indicators. The input indicators encompass energy, water, and land productivity, while the output indicators include waste water, waste gas, and solid waste productivity. This approach remains an aggregation of single-factor resource productivity, and thus is unable to provide a comprehensive indicator for resource productivity.

As Meng Weihua[25] asserts, the ecological footprint, which serves as a unified indicator for a multitude of natural resources, can be utilized to represent the inputs of natural resources in the production function. Consequently, it is possible to calculate resource productivity and total factor productivity based on natural resource inputs. The term "resource productivity" is defined as the GDP (10,000 yuan) output per unit of ecological footprint. It is calculated using the following formula:

$$R=GDP/EF=1/(EF/GDP) \tag{17}$$

The ecological footprint is a metric that converts the amount of biological resources

**Table 4 Comparison of total ecological demand, total ecological supply, and total production demand in the three provinces and one city of the YRD region in 2018**

| Region | Ecological demand of biological resources//$hm^2$/person | Ecological demand of construction land $hm^2$/person | Ecological demand of fossil energy $hm^2$/person | Per capita total ecological needs ead/$hm^2$/person | Per capita total ecological supply eas//$hm^2$/person | Per capita ecological deficit ed//$hm^2$/person | Ecological demand per 10,000 yuan of GDP//$hm^2$/10,000 yuan | Per capita production footprint pad $hm^2$/person |
|---|---|---|---|---|---|---|---|---|
| Shanghai City | 0.189 057 276 | 0.214 011 961 | 2.188 146 039 | 2.591 215 275 | 0.109 277 614 | 2.481 937 661 | 0.192 201 065 | 0.400 667 340 |
| Jiangsu Province | 0.188 305 260 | 0.252 048 415 | 2.380 390 661 | 2.820 744 335 | 0.324 644 155 | 2.496 100 180 | 0.245 258 540 | 0.912 333 900 |
| Zhejiang Province | 0.207 568 809 | 0.261 625 174 | 1.671 911 072 | 2.141 105 054 | 0.187 730 605 | 1.953 374 449 | 0.187 730 605 | 0.477 098 103 |
| Anhui Province | 0.201 989 103 | 0.111 793 400 | 1.385 086 554 | 1.698 869 056 | 0.390 291 044 | 1.308 578 013 | 0.358 040 203 | 1.364 751 138 |

and energy consumed by human beings into a standard EPA. If GDP is employed to quantify the output of economic growth over a specified period, the resource productivity calculated on the basis of the ecological footprint can be expressed as the output per unit of EPA.

Fig.4 illustrates the trend of the ecological footprint per 10,000 yuan of GDP in the three provinces and one city in the YRD region from 2004 to 2018. The data indicated a general decline over this period. The ecological footprint of 10,000 yuan GDP is indicative of the relationship between economic growth and ecological footprint depletion. A larger ecological footprint of 10,000 yuan GDP is indicative of lower resource productivity, while conversely, a smaller ecological footprint is indicative of higher resource productivity. From 2004 to 2018, the ecological footprint of 10,000 yuan GDP in the YRD region exhibited a persistent decline, suggesting a sustained downward trajectory in the demand for ecological land for economic expansion, a consistent rise in land utilization, and an escalation in the intensity of economic development. Among the three provinces and one city in the YRD region, Anhui Province exhibited the most pronounced decline in ecological footprint, yet still exhibited the highest ecological footprint per 10,000 yuan of GDP consumed. Zhejiang Province exhibited a relatively stable trend and had the lowest ecological footprint per 10,000 yuan of GDP consumption among the three provinces and one city. After reaching its lowest value in 2016, the province demonstrated a slight rebound. Shanghai City continued to exhibit a decline, approaching the lowest level observed in Zhejiang Province. In general, three provinces and one city demonstrated a convergence trend.

## 4 Conclusions and suggestions

The ecological footprint per 10,000 yuan of GDP in the three provinces and one city in the YRD region is generally demonstrating a downward trajectory. Developed regions exhibit elevated ecological deficits and a greater reliance on external ecological resources, while fossil fuel land use is identified as the primary contributor to the per capita ecological deficit in the YRD region.

The transfer of polluting industries or industries with high resource consumption from developed to economically backward regions is a common consequence of industrial structure adjustment in developed regions. This phenomenon illustrates a shift from a low-grade industrial structure to a high-grade environmental structure. Consequently, the pollution generated by the relocation of polluting industries in a high-gradient environment will flow downstream along the high-gradient environment. As a result, a deeper contradiction between economic development and the ecological environment emerges. In specific technical circumstances, the exploitation of natural forces by human beings can not exceed a threshold value that natural forces are capable of bearing. Otherwise, the functionality of natural forces will decline, leading to a reduction in production capacity. If human activity disrupts the system of natural forces to an excessive degree, the internal operational mechanism of these forces will be disrupted, and the service function of natural forces for human beings will be diminished or even completely lost. It is imperative that humans curtail the emission of pollutants, halt the process of deforestation, and cease the depletion of all types of land. Otherwise, the natural material function and quality of the land will inevitably decline. It is thus incumbent upon humanity to respect the laws of natural forces. The exploitation of natural productive forces by human beings, whether through excessive use, abuse, or even man-made destruction, can lead to a strained relationship between humans and the earth. This, in turn, can give rise to a global ecological crisis, which poses a significant threat to the sustainable development of human beings.

In order to reduce the excessive use of fossil fuels and address the critical shortage of pasture land, it is essential to prioritize a new

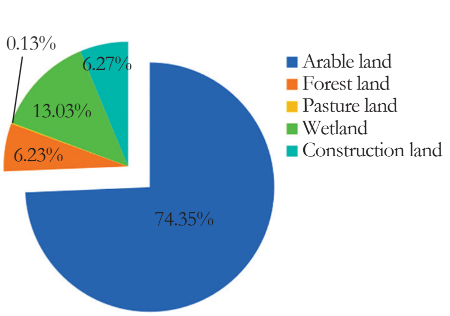


**Fig.1 Proportion of different land types in total ecological supply of the YRD region in 2018**

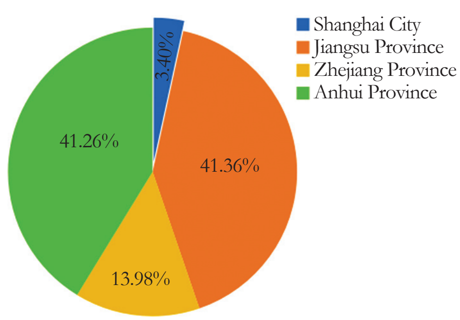


**Fig.2 Proportion of total ecological supply of the three provinces and one city in total ecological supply of the YRD region**

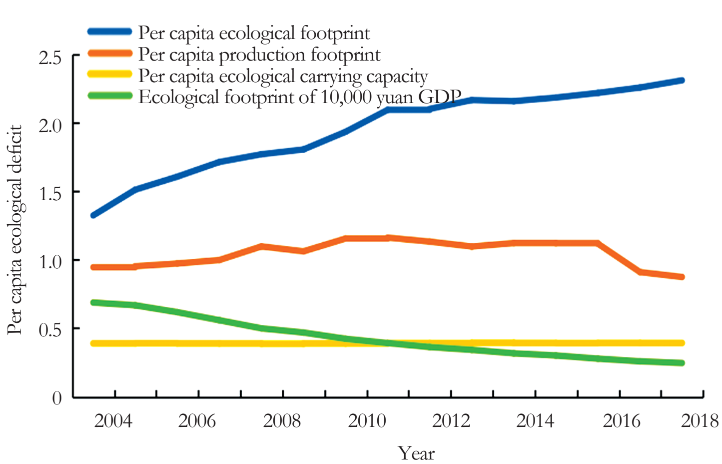


**Fig.3 Trends in per capita ecological deficit in the three provinces and one city in the YRD region from 2004 to 2018**

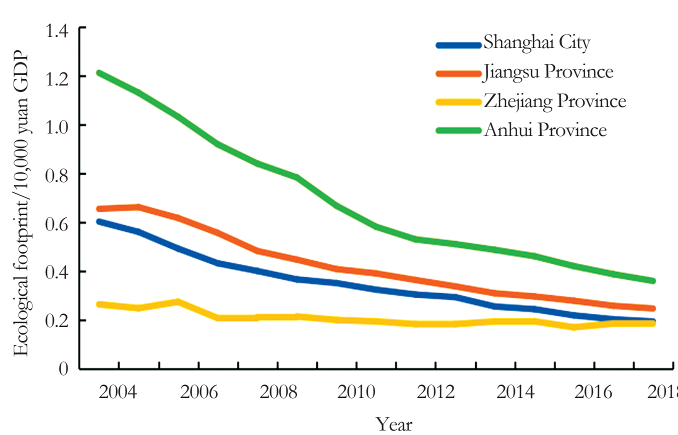


**Fig.4 Changes in ecological footprint per 10,000 yuan of GDP in the three provinces and one city of the YRD region from 2004 to 2018**

concept of green development. This entails minimizing the ecological demand for fossil fuels through technological innovation, enhancing the ecological carrying capacity of the land, and promoting comprehensive coordination and sustainable development of human and natural systems. Secondly, it is imperative to practice economic restraint and to minimize the ecological footprint. Finally, the land use structure should be adjusted in order to enhance the ecological carrying capacity of pasture lands, wetlands, and forest lands.

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