ANALYSIS OF ECOLOGICAL SUSTAINABILITY AND COMPENSATION USING AN IMPROVED THREE-DIMENSIONAL FOOTPRINT MODEL: A CASE STUDY OF HUNAN PROVINCE, CHINA

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Abstract. Scientific assessment of regional ecological sustainability holds critical decision-making value for formulating conservation policies and advancing sustainable development. Taking Hunan Province as a case study, this research developed a Composite Index of Ecologically Sustainable Development and an ecological compensation model based on an improved three-dimensional ecological footprint model, systematically evaluating the evolutionary characteristics of ecological sustainability and compensation standards in Hunan Province from 2010 to 2022. The results indicate that: (1) From 2010 to 2022, both the ecological footprint and ecological deficit in Hunan Province showed fluctuating upward trends, while ecological carrying capacity exhibited a gradual annual increase. Notably, Changsha City demonstrated a significant inverse growth pattern in its ecological footprint. (2) The per capita footprint size and footprint depth in Hunan Province displayed oscillatory growth and decline, respectively, with footprint depth consistently exceeding 1, indicating enhanced efficiency in natural resource utilization alongside persistent natural capital stock depletion, albeit with reduced capital stock occupancy. (3) The overall level of ecological sustainable development in Hunan Province improved significantly, with Changsha City showing the most substantial optimization, while Xiangtan City remained in a state of extreme unsustainable development. (4) The ecological compensation area in Hunan Province expanded, with Yueyang City recording the highest average compensation payment, and Huaihua City, as the primary ecological compensation recipient, receiving the largest total compensation amount.

Keywords: *regional sustainability, entropy weight method, parameter correction, spatial difference, ecological protection*

Introduction

Nature is essential for human survival and development. Therefore, promoting ecologically sustainable development and harmonious coexistence between humans and the environment is a crucial prerequisite for the sustained advancement of humankind. In 1987, the WCED introduced the concept of sustainable development in its report *Our Common Future* (WCED, 1987), which gained global attention (Lemke and Bastini, 2020; Anaafo et al., 2023). In 2015, the United Nations General Assembly proposed 17 Sustainable Development Goals to protect natural resources and support sustained economic growth (Wang et al., 2024b). Currently, rapid economic development and urbanization have increased human production and consumption, leading to overloading ecological resources and highlighting the contradiction between economic advancement and environmental sustainability, so achieving sustainable development in the region now depends on striking a balance between ecological protection and development (Shabir et al., 2023; Niu et al., 2024). Accordingly, scientifically evaluating the use of regional ecological resources and their spatial-temporal characteristics, along with improving ecological protection policies tailored to local conditions, is essential for sustainable regional development.

Ecological footprint (EF) is an effectual method to harmonize the relation between region's economic progress and environmental protection, which can gauge human occupation of environmental capital and evaluate the sustainable developing of ecological environment (Kızılgöl and Öndes, 2022; Mamghaderi et al., 2023). Ecological economist Rees (1992) first put forward the notion of EF in 1992,Wackernagel et al. (1999) developed it into an EF model and introduced the notion of two-dimensional EF (EF_{2D}), at the same time, he applied the model to account for natural capital on worldwide and country-wide scales. To differentiate between human appropriation of natural capital flows and stocks, Niccolucci et al. (2009) developed the notion of three-dimensional EF (EF_{3D}) and inserted two indexes, footprint depth (EF_{depth}), and footprint size (EF_{size}), on the basis of the existing model. Fang and Li (2012) first presented the EF_{3D} model in China and improved it, and based on the improved model, they calculated and analyzed the natural capital of China and the worldwide based on the improved model (Fang et al., 2013). So far, by using the improved EF_{3D} model, scholars globally have examined the characteristics and drivers of changes in natural capital usage from national, city group, watershed, provincial and municipal scales (Chen et al., 2020; Li and Zhang, 2022; Li et al., 2024; Wang et al., 2024a). Most studies are based on the global or national hectare scale, but some scholars have pointed out that the calculation of small-scale regions based on large-scale parameters ignores regional differences and fails to show the reality of regional situation and changes (Wang et al., 2020; Zhang et al., 2024), so a local correction of the model parameters is necessary.

Currently, besides the EF method, other methods for assessing regional eco-sustainability mainly include energy-value analysis, information entropy, energy-value ecological network, and life cycle methods (Lo-Iacono-Ferreira et al., 2016; Sun and An, 2018; Pan et al., 2021; Zhao et al., 2022). However, the EF model is broadly applied in assessment due to its unique advantages of clear concepts, simple calculations, and intuitive results (Zhang et al., 2022; Wei et al., 2023). Additionally, to describe regional eco-sustainability more comprehensively and accurately, scholars have successively proposed and applied various indicators to evaluate the region's ecological sustainability, such as the Ecological pressure index (EPI), Ecological coordination coefficient (ECC), EF diversity index (EFDI), etc. (Wu et al., 2020; Guo, 2022). It is notable that most researchers evaluate and analyze the regional eco-sustainability situation one by one from the perspective of each indicator. However, a single indicator can hardly capture the complicated influence of anthropogenic activities on the environment (Li et al., 2020), so it is necessary to consider the construction of a composite evaluation indicator to evaluate the status of regional ecological sustainable development from a comprehensive perspective.

Ecological compensation represents an efficient economic instrument to facilitate the harmonized development of economic and ecological protection (Yang et al., 2022b; Wu et al., 2024). Consequently, academics have carried out a great deal of studies on compensation mechanisms, compensation standards, compensation subjects, and compensation schemes (Wei et al., 2022; Jiang et al., 2022; Liu et al., 2024). These studies are valuable in fostering harmonized regional progress and enhancing social equity (Du et al., 2023). Therefore, to foster eco-civilization construction and harmonious social development in Hunan, some scholars have studied the eco-compensation in Hunan Province. Yu et al. (2017) established an eco-compensation model, which is founded on the theory of carbon neutrality, and applied the model to quantitatively study the eco-compensation of cities and prefecture in Hunan. Xiao et al. (2017) calculated the provision and requirement of natural resources in Hunan Province using the EF model and quantified the eco-compensation standards for each city and prefecture in the province. Zhao et al. (2022) determined the eco-compensation priority and amounts for each city and prefecture in Hunan based on the principle of fair distribution from the perspectives of ecosystem service value and human well-being. Gong et al. (2020) However, most studies only analyzed Hunan’s eco-compensation for a single year and ignored the influence of local people's willingness to pay and ecological resource transformation efficiency when accounting for regional eco-compensation standards.

Located in the middle reaches of the Yangtze River, Hunan Province holds significant ecological importance as a crucial economic and cultural hub in China, serving as the central-southern grain production base. However, characterized by fragile ecosystems and severe vulnerability to natural disasters, it represents a typical ecologically sensitive zone in China. Concurrently, in recent years, as Hunan Province's economic structure is still in transition, with rapid industrialization and urbanization leading to the expanding area of built-up and the encroaching on ecological land, the pressure on the ecological environment has been increasing (Zhang and Hao, 2016; Chen et al., 2021). Conducting systematic ecological assessment and analysis in Hunan Province through modeling approaches can clarify its current ecological status and spatiotemporal evolution patterns, thereby formulating effective strategies for regional ecological sustainability. Current ecological research in Hunan Province predominantly focuses on localized environmental quality evaluation (Chen et al., 2024), ecosystem service supply-demand relationships (Zhu et al., 2023), and agricultural sustainability (Tan et al., 2020), while relatively lacking long-term, region-wide comprehensive analyses of ecological sustainability and compensation criteria.

This study employed an improved EF_{3D} model to dynamically assess the ecological sustainability levels and ecological compensation standards in Hunan Province from 2010 to 2022. The findings reveal spatiotemporal characteristics of natural capital supply-demand dynamics and ecological sustainability patterns across the province, while delineating ecological compensation supply zones and quantifying specific compensation standards in recent years. These results provide scientific foundations for subsequent policymaking in regional ecological conservation, facilitating high-quality development supported by premium ecological environments and coordinated economic-environmental progress.

Materials and methods

Study area

Hunan Province lies in the midsection of the Yangtze River and is centrally positioned within China (24°08′N to 30°08′N,108°47′E to 114°05′E) (*Figure 1*). With a total size of 21.18 million $hm^{2,}$ the province makes up 2.2% of China's landmass. It includes 13 prefectural-level cities and 1 autonomous prefecture. The province's topography is diverse, and dominated by mountains and hills, with mountains covering 51.2% of the total area. Hunan Province experiences a subtropical monsoon climate, with average annual temperatures ranging from 16°C to 18°C and an average yearly rainfall of 1450 millimeters. The province is rich in minerals, boasting a complete range of them, earning it the titles "township of non-ferrous metals" and "non-metallic mines township".

The rich minerals provide resources for Hunan's economic development. The province had 66.04 million residents as of 2022, and its per capita GDP was 73,600 CNY/cap. Compared with 2010, the resident population increased by 0.5%, and the per capita GDP increased by 206.6%. Recently, with the rapid growth of the economy and the acceleration of urbanization, the province's resources have been continuously damaged and depleted, making the imbalance between natural resources supply and demand increasingly evident (Cai et al., 2020; Yu et al., 2023).

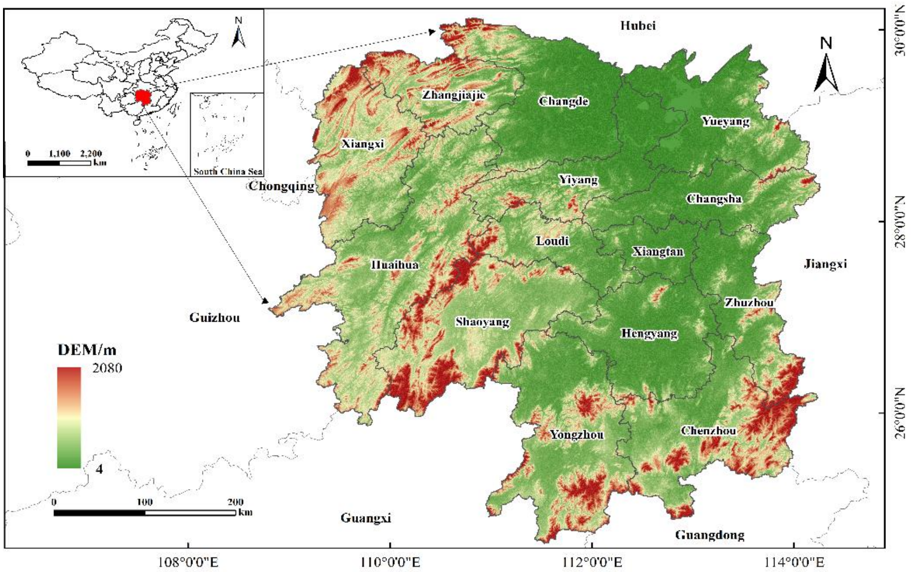

Figure 1. *Location of the study area*

Data sources

The data on biological resources, energy, and average production of agricultural and forestry products adopted in this research were derived from the Hunan Provincial Statistical Yearbook (2011-2023), in addition to the statistical yearbooks and bulletins of various cities and states. Specific accounts of biological resources and energy consumption are shown in *Table 1*, with unit calorific value data were taken from the Agricultural Technical and Economic Manual (Revised Edition, 1983). Energy conversion standard coal coefficients for various types of energy were sourced from the China Energy Statistics Yearbook (2023). Land use data were sourced from the China Land Cover Dataset, which has a spatial resolution of 30 meters (Yang and Huang, 2021).

Methodology

Three-dimensional ecological footprint

The traditional EF_{2D} model quantifies human occupation of ecological assets by biologically productive land area, but it fails to differentiate between ecological asset reserves and ecological asset flow, and it cannot represent the crucial effect of asset reserves in supporting the balance of the ecosystem. Building on this foundation, the EF_{3D} model imports two indexes: EF_{size} and EF_{depth}, which characterize the extent of human activities' appropriation of the flow and reserves of ecological asset, respectively. However, the basic EF_{3D} model neglects the discrepancy in the properties of ecological

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assets between ecological deficit (ED) and ecological surplus, leading to underestimation of EF_{depth} and overestimation of EF_{size} at the regional scale. Therefore, we use Fang Kai's improved method for calculation in this study with the following formula:

$$EF_{depth} = 1 + \frac{ED}{EC} = 1 + \frac{\sum_{i=1}^{6} max\{EF_i - EC_i, 0\}}{\sum_{i=1}^{6} EC_i} \quad \text{(Eq.1)}$$

$$EF_{size} = \sum_{i=1}^{6} min\{EF_i, EC_i\} \quad \text{(Eq.2)}$$

$$EF_i = N \times ef_i = N \times r_i \times \sum_{j=1}^{n} \frac{c_j}{p_j} \quad \text{(Eq.3)}$$

$$EC_i = N \times ec_i = N \times (a_i \times r_i \times y_i) \times (1 - 12\%) \quad \text{(Eq.4)}$$

where i denote the type of productive land in category i; j denote the different categories of consumption items; N denote the region's total population; EC denote the ecological carrying capacity; ef denote the per capita EF, ec denote the per capita EC ; r_i denote the equivalence factor of land category i; c_j denote the per capita consumption of item j; p_j denote the average production of consumption item j in the region; a_i denote the area of biologically productive land category i actually occupied per capita; y_i denote the yield factor of land category i; 12% denote the area deducted for biodiversity conservation.

Table 1. *EF accounts*

Account type	EF accounting project	Land use type
Biological resource accounts	Rice, wheat, corn, soybeans, potatoes, cotton, jute, ramie, tobacco, oilseeds, pork, eggs, beef (86%), mutton (57%)	Cropland
	Citrus, rapeseed, tea, dried bamboo shoots, wood, bamboo	Forest
	Beef (14%), mutton (43%)	Grassland
	aquatic products	Water
Energy consumption accounts	Liquefied petroleum gas, raw coal, coke, gasoline, diesel, fuel oil, kerosene, crude oil, natural gas	Fossil fuel land
	Construction area, roads	Building land

Note: The proportion of beef and mutton in parentheses indicates the proportion of cropland and grassland occupied

Improvement of EF3D model

Corrections for parameter factors

Owing to differences among the productive capacity of various ecologically productive lands and the differences in the productive capacity of similar lands across different regions, it is necessary to use parameter factors to transform various types of lands and similar lands in different regions into a unified and comparable ecologically productive land area for uniform calculation. Currently, most studies conduct EF accounting based on parameter factors at the global hectare or national hectare scale. However, some scholars (Wang et al., 2020; Zhang et al., 2024) have pointed out that the equivalence factor (r) and yield factor (y) at large scales cannot accurately reflect the land productivity conditions of smaller-scale regions. When calculating the EF at the provincial or municipal level, adopting parameter factors at the provincial hectare scale can improve the accuracy of regional EF calculations and more precisely reflect the land productivity and socio-economic development characteristics of each province or city. Therefore, this study calculates the r and y of the study area annually, using "provincial hectare" as the unit of measurement. The calculation formulas are presented in *Equations (5) and (6)* below, with results listed in *Appendix A*.

$$r_i = \frac{E_i}{E} \tag{Eq.5}$$

$$y_i^m = \frac{E_i^m}{E_i} \tag{Eq.6}$$

where E_i denote the average production capacity of land category i in Hunan Province; E denote the average production capacity of all land in Hunan Province; E_i^m denote the average production capacity of land category i in city m in Hunan Province.

Energy account adjustment

Since fossil fuel land does not actually exist, its EC is usually recorded as 0 in the calculation. This inconsistency with the actual situation leads to an overestimation of the regional ED. In this paper, we follow the methodology of Xiong et al. (2022) to calculate the EF and EC of fossil fuel land in combination with the carbon footprint accounting method. It is worth noting that by examining the calculation formula, it becomes apparent that the grassland and forest area needed to assimilate carbon emissions is determined by dividing carbon emissions or carbon absorption by the global average carbon sink capacity of grasslands and forests. However, when computing the EF of ecologically productive land, only the equivalence factor needs to be applied for conversion, without the need to multiply by the yield factor. Therefore, the calculation formulas for EF and EC of fossil fuel land use in this study are as follows:

$$CE = \sum_{i=1}^{n} Q_i \times S_i \times D_i \tag{Eq.7}$$

$$CS = \left(A_f \times NEP_f + A_g \times NEP_g\right) \tag{Eq.8}$$

$$CEF = CE \times \left(\frac{P_f}{NEP_f} \times r_f + \frac{P_g}{NEP_g} \times r_g\right) \tag{Eq.9}$$

$$CEC = \mathrm{C}S \times \left(\frac{P_f}{NEP_f} \times r_f + \frac{P_g}{NEP_g} \times r_g\right) \times (1 - 12\%) \tag{Eq.10}$$

where CE, CS, CEF, CEC are the total carbon emission, total carbon sequestration, EF of fossil fuel land, EC of fossil fuel land, respectively; Q_i, S_i, D_i denote consumption of the ith energy source, converted standard coal coefficient, and carbon emission coefficient, respectively; A_f, A_g denote the area of forest and grassland, respectively; NEP_f, NEP_g denote the global carbon sequestration capacity of forest and grassland, respectively; P_f, P_g denote the proportion of carbon sequestration of forest and grassland, respectively; r_f, r_g denote the equivalence factor of forest and grassland, respectively.

For building land, Zhou et al. (2015) pointed out that the EF and the EC are essentially equivalent to the biologically productive land actually occupied by construction facilities. Therefore, the EF of building land in this study adopts the calculation method of EC, and the two values are equal.

Composite index of ecologically sustainable development

The ecological bias characteristic of EF model cannot comprehensively reflect the relationship between socio-economic development and resource-environment interactions, and a single indicator is insufficient to objectively and holistically assess the ecological sustainable development status of a region. Therefore, building on previous research (Zhang et al., 2022), this study introduces five indicators—EPI, ECC, utilization ratio of capital stocks to flows(R_{flow}^{stock}), ecological utilization efficiency(EUE), and ecological footprint diversity index(EFDI)—considering aspects such as regional ecological pressure, ecological-economic coordination, capital utilization structure, resource utilization efficiency, and ecological diversity. The EPI reflects the intensity of environmental stress within a region; a higher value indicates greater human interference with ecological balance. The ECC measures the degree of coordination between regional ecological conditions and socio-economic development. The R_{flow}^{stock} illustrates the relationship between stock and flow in the natural capital consumed by human activities. The EUE evaluates the efficiency of regional ecological resource utilization. The EFDI reflects the degree of equitable distribution of various biologically productive land areas within a region. A more balanced distribution of the EF indicates higher diversity in the ecological-economic system and greater stability of the ecosystem. The comprehensive application of the aforementioned indicators enables a more scientific and holistic evaluation of regional ecological sustainable development capacity and enhances the comparability of changes in regional ecological conditions. Therefore, this study employs the entropy weight method to determine the weights of each indicator and constructs the CIESD, and refer to *Appendix B* for the calculation method of each indicator. Simultaneously, we adopt the natural breakpoint method to categorize the regional sustainable development level, as shown in *Table 2*.

Table 2. *Classification of ecologically sustainable development levels*

CIESD	Ecological sustainable development level
1.18~1.72	Slight sustainability
1.72~2.42	Slight unsustainability
2.42~3.14	Quite unsustainability
3.14~4.18	Very unsustainability
＞4.18	Extreme unsustainability

Ecological compensation model

Based on the results of the EF_{3D} model, combined the practical conditions of the study area, and under the principle of fair distribution of environmental benefits, the two indicators of willingness to pay and ecological resource transformation efficiency are introduced to construct an eco-compensation model (Yang et al., 2022a). The formulae are detailed in *Appendix C*.

Results

EF and EC dynamics in Hunan

Analysis of the EF, EC, and ED in Hunan from 2010 to 2022

According to *Equations (3)-(4)*, we computed the EF and EC for Hunan Province and each city and prefecture. Subsequently, we computed the ED and ed (*Figure 2*). The results indicate that from 2010 to 2022, the overall EF of Hunan Province exhibited a fluctuating upward trend, with a 16.88% increase in 2022 compared to 2010. This suggests that the consumption of natural resources in Hunan continued to rise slowly during the 2010-2022 period, with a noticeable acceleration in recent years. The EC of Hunan showed a gradual increasing trend, with an average annual growth rate of 4.71%, and a 73.66% increase in 2022 compared to 2010. However, as seen in *Figure 2*, the overall EF of Hunan far exceeds its EC, and the growth of EC is slow. Therefore, the trend of the overall ED in Hunan is similar to that of the EF. In general, Hunan has experienced a long-term ED. Although the natural resource supply capacity of Hunan has been increasing year by year, the growth rate is slow, and the consumption of natural resources has accelerated in recent years.

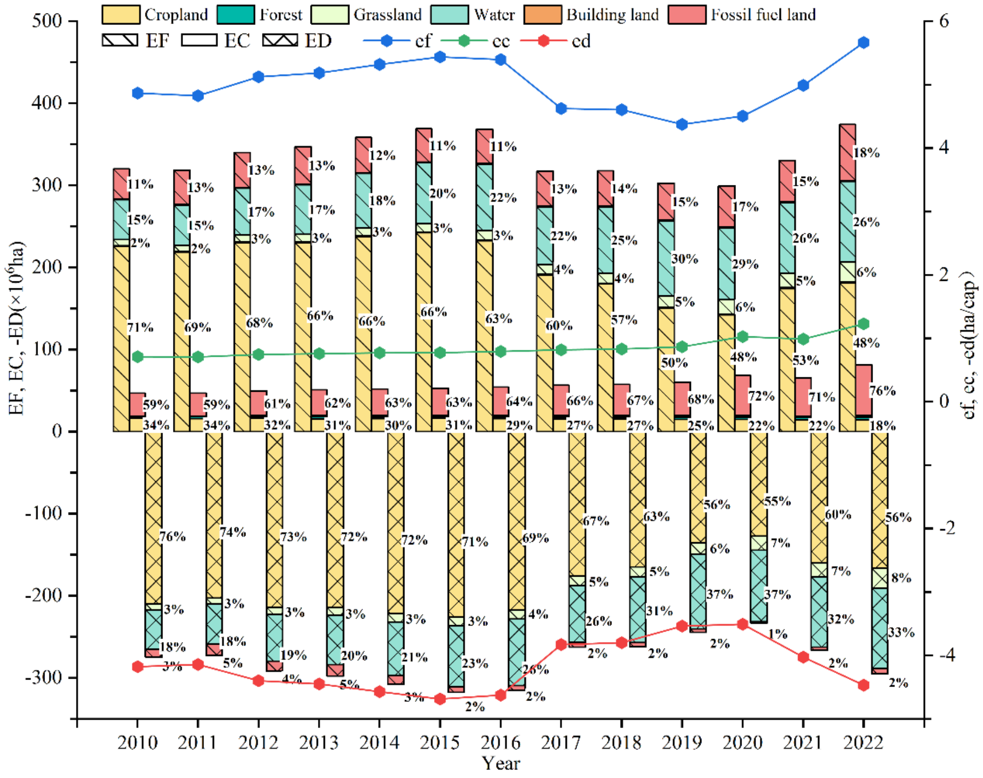

***Figure 2.** Changes of the EF, EC, and ED in Hunan Province from 2010 to 2022*

Analysis of the composition of EF, EC, and ED in Hunan

As shown in *Figure 2* and *Table 3*, from 2010 to 2022, the EF of Hunan Province primarily consists of cropland, and to a lesser extent, water and fossil fuel land. It is notable that the EF of cropland decreased over this period, while the EF of water and fossil fuel land increased. EC is primarily composed of fossil fuel land and cropland. The proportion of cropland gradually decreased by 9.7% in 2022 compared with 2010, while fossil fuel land increased annually, increasing by 124.2% over the same period, driven by reductions in cropland area and parameter factors, contrasted with increased grassland equivalence factor. ED is primarily composed of cropland and water, with the cropland decreasing from 76% in 2010 to 56% in 2022, while water and grassland increased from 18% and 3% in 2010 to 33% and 8% in 2022, respectively. In summary, agriculture, fishery, and industry play crucial roles in the socio-economic growth of Hunan. Over recent years, the consumption of cropland resources has declined with the advancement of industrialization, the development of fishery, and the reduction of cropland areas.

Table 3. *Composition of average EF and average EC for Hunan in 2010-2022*

	Cropland	**Grassland**	**Water**	**Forest**	**Building land**	**Fossil fuel land**
Ecological footprint composition (%)	60.4	3.7	21.8	0.2	0.3	13.6
Ecological carrying capacity composition (%)	27.1	0.04	0.61	4.21	1.66	66.37

From the composition of the ED of each city and prefecture (*Figure 3*), Zhangjiajie, Xiangxi, and Huaihua, located in the Wuling Mountain area, have consistently contributed relatively low rates to the ED of Hunan Province. In contrast, the ED levels of the secondary urban agglomeration around Changsha-Zhuzhou-Xiangtan (Chang-Zhu-Tan) are significantly higher. For example, Hengyang, Yueyang, and Changde each account for more than 10% of the province's total ED. The reason for this is that the Chang-Zhu-Tan secondary urban agglomeration is a crucial area influenced by the industrial activities of central cities, providing resource support and driving the rapid economic development of Hunan Province, which has led to higher ED in this region. From a temporal perspective, the proportions of ED in Yueyang, Changde, and Yiyang have shown noticeable increases, indicating that these three cities have failed to effectively balance socio-economic development with ecological protection. Conversely, the ED proportions of Changsha and Hengyang have significantly declined year by year, reflecting the progress these two cities have made in recent years in ecological environmental protection and natural resource utilization.

Analysis of ef, ec, and ed in cities and prefecture in Hunan Province

Selecting 2010, 2016, and 2022 for analysis as shown in *Figure 4,* the ef, ec, and ed in most regions exhibited an increasing trend. Overall, the ec in 2022 showed the most significant change compared to 2016, indicating that ecological construction in Hunan made progress during the 2016-2022 period. Among these, Yueyang experienced the fastest growth in both ef and ed, suggesting an intensifying contradiction between the supply and demand of natural resources in Yueyang. Huaihua, Xiangxi, and Zhangjiajie all showed notable increases in ec, reflecting improvements in the natural resource supply capacity of these regions. Notably, Changsha exhibited a clear inverse growth trend in its ef, and its EC increased by 943,000 hectares in 2022 compared to 2016. However, due to the continuous rapid population growth in Changsha (a 21.3% increase from 2016 to 2022), the ec decreased, indicating that the contradiction between ecological supply and demand in Changsha is gradually improving.

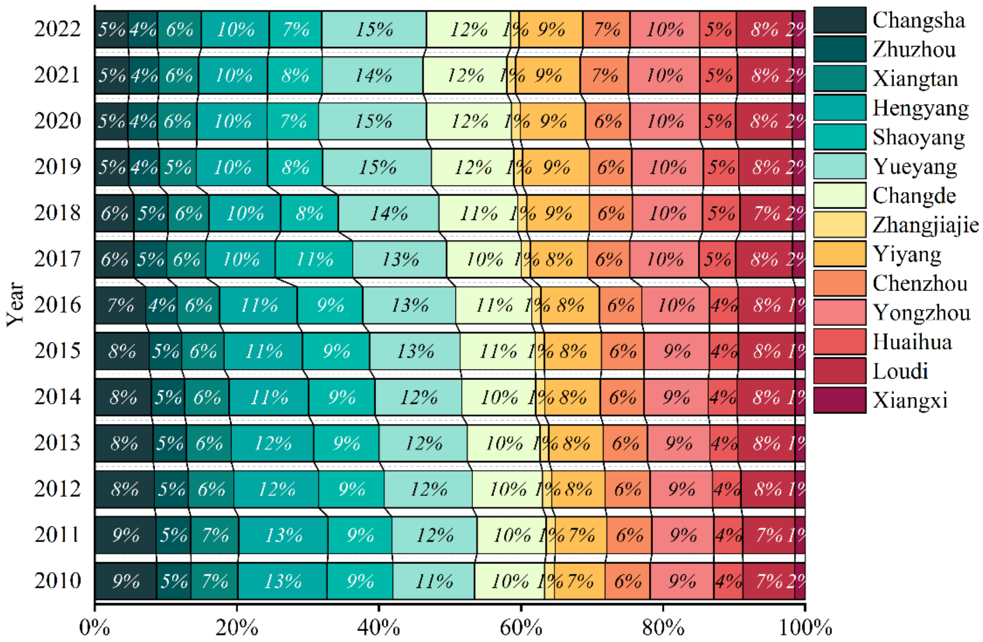

***Figure 3.** The composition of ED in Hunan Province by city and prefecture from 2010 to 2022*

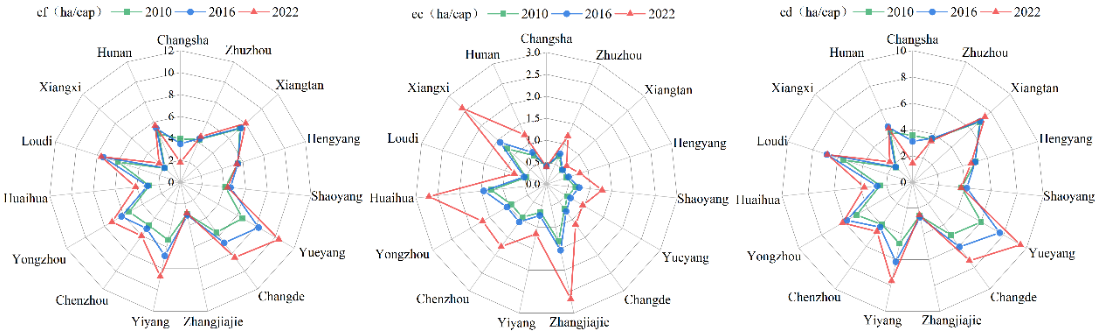

***Figure 4.** Spatiotemporal changes in ef, ec, and ed in cities and prefecture of Hunan Province*

Analysis of EF_{size} and EF_{depth} in Hunan

EF_{size} and EF_{depth} reflect the extent to which human activities have appropriated ecological asset flows and reserves, respectively. The EF_{size} and EF_{depth} of Hunan Province and each city and prefecture were calculated by *Equation (1)-(2)*. As shown in *Figure 5*, from the perspective of each city and prefecture, the per capita footprint size (ef_{size}) and EF_{depth} of Xiangxi, Huaihua, and Zhangjiajie are generally lower than those of other regions, indicating that the occupation of natural capital flows and stocks in these areas is relatively lighter compared to other regions. Notably, Xiangtan, Yueyang, and Loudi all exhibit significantly higher EF_{depth} than other regions, suggesting more severe ecological overshoot issues in these areas. Overall, the ef_{size} across Hunan and most of its regions shows a fluctuating upward trend, while the EF_{depth} exhibits a fluctuating downward trend, with EF_{depth} consistently greater than 1. This indicates an improvement in the overall natural resource utilization rate in Hunan, with consumption of natural capital stocks still occurring but a reduced degree of occupation of natural capital stocks, potentially reflecting an enhancement in ecological sustainability. However, a single indicator is insufficient to comprehensively reflect the sustainable development status of a region. Therefore, it is necessary to evaluate the ecological sustainable development levels of Hunan Province and its cities and prefectures by integrating other.

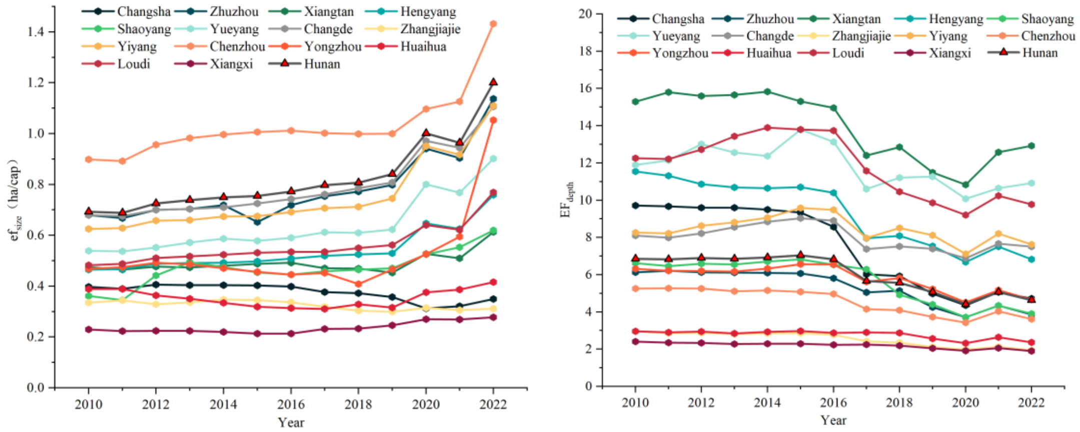

Figure 5. *Spatiotemporal changes of the ef_{size} and EF_{depth} in cities and prefecture of Hunan Province from 2010 to 2022*

Spatial-temporal evolution of ecological sustainability in Hunan

To gain a deeper understanding of the state of ecological sustainable development in Hunan Province and its cities and prefecture, the CIESD was used to express the comprehensive characteristics of five aspects: ecological pressure, EF diversity, R_{flow}^{stock}, ecological coordination capacity, and ecological utilization efficiency.

As shown in *Figure 6* and *Table* 4, during the study period, the ecological condition of Hunan Province has gradually improved, with a notable reduction in overall ecological pressure and capital stock occupation, as well as significant enhancements in ecological resource utilization efficiency and ecological diversity. Spatially, the ecological conditions of most cities and prefectures have improved to varying degrees. Xiangxi, Zhangjiajie, and Huaihua have consistently maintained sustainable levels, with slight improvements in their ecological conditions during the study period. Among these, Changsha has undergone the most significant transformation, shifting from a state of strong unsustainability in 2010 to weak unsustainability in 2022, marking remarkable progress and indicating the evident effectiveness of ecological construction efforts in Changsha during this period. In contrast, Xiangtan, Yueyang, and Loudi face severe ecological challenges. Xiangtan City has long been in a state of extreme unsustainability. Based on the calculated indicators, Xiangtan exhibited the highest ecological pressure and utilization ratio of capital stocks to flows in the province from 2010 to 2022, while its ECC remained the lowest, fluctuating between 1.06 and 1.09. This suggests that Xiangtan suffers from high ecological pressure, excessive consumption of stock capital, and a severe lack of coordination between its ecological environment and socio-economic development. Overall, the ecological condition of Hunan shows a trend of gradual improvement, although certain regions still face serious ecological challenges. This indicates that although Hunan has achieved initial achievements in ecological construction, environmental protection efforts require further enhancement.

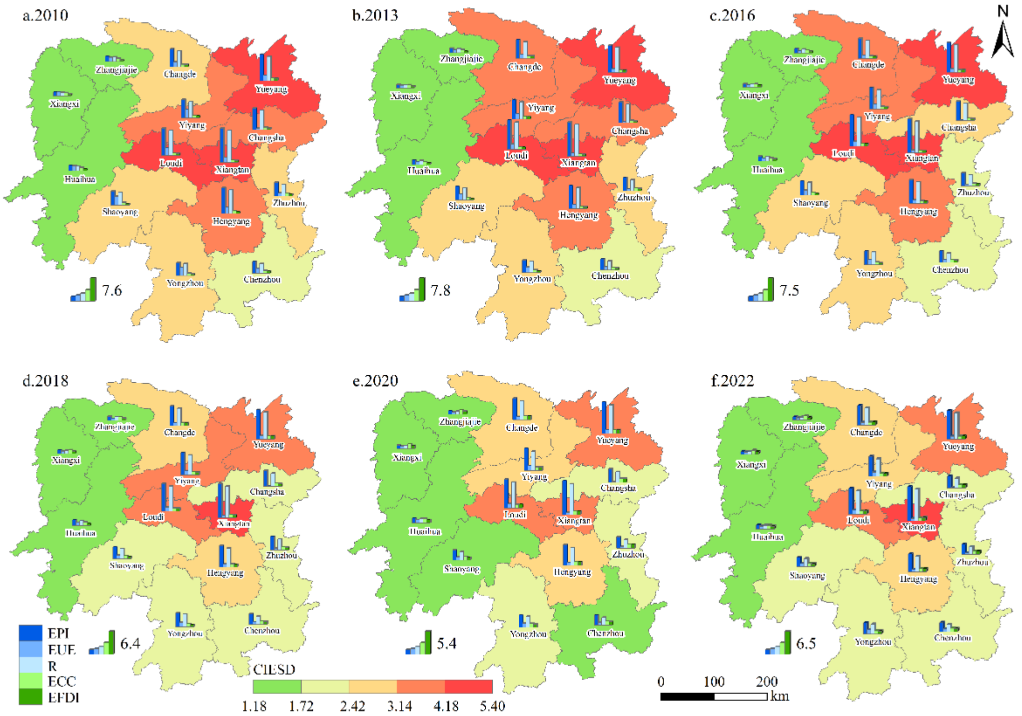

***Figure 6.** Temporal and spatial distribution characteristics of the CIESD*

***Table 4.** 2010-2022 Evaluation indicators of ecological sustainability in Hunan*

	EPI	EUE	R_{flow}^{stock}	ECC	EFDI	CIESD
2010	6.83	1.97	5.86	1.13	0.89	2.75
2013	6.82	1.36	5.85	1.13	0.97	2.71
2016	6.79	1.10	5.82	1.13	1.00	2.69
2018	5.53	0.83	4.56	1.16	1.10	2.31
2020	4.38	0.71	3.41	1.20	1.22	1.99
2022	4.60	0.77	3.63	1.19	1.22	2.06

Ecological compensation for cities and prefecture in Hunan

As shown in *Figure 7* (Specific data are detailed in *Appendix D*), the results indicate that Huaihua receives the highest average eco-compensation (136 million RMB), while Yueyang has the highest average amount that needs to be paid (133 million RMB). From a per capita level, Zhangjiajie receives the highest average per capita eco-compensation (30.87 CNY/cap). Xiangxi and Huaihua, which are close to Zhangjiajie in terms of per capita compensation, receive 30.59 CNY/cap and 28.15 CNY/cap per year, respectively. The city with the highest average per capita amount of eco-compensation to be paid is Yueyang (24.20 CNY/cap). Although Huaihua receives a high total amount of eco-compensation, its per capita level is much lower than that of Zhangjiajie City and Xiangxi Prefecture due to its larger population base. In terms of the time scale, except for Changsha, which changed from an ecological payment area to a compensation area, there were no changes in other regions. Notably, Xiangtan and the sub-city cluster around Chang-Zhu-Tan were consistently used as eco-compensation payment zones during the study period, suggesting that these regions suffer from a chronic shortage of natural resources. Additionally, the total amount of ecological services gradually decreased after 2015, leading to a reduction in the amount of eco-compensation across all areas and a narrowing of differences in eco-compensation.

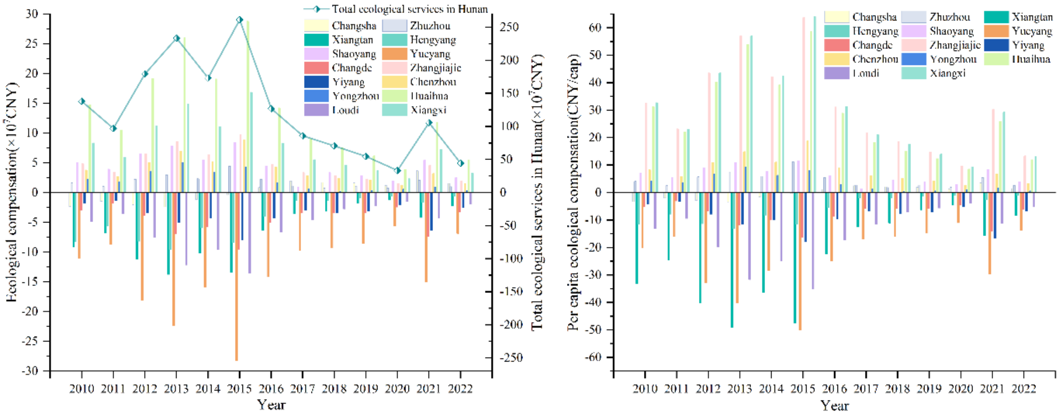

Figure 7. *Changes in eco-compensation by city and prefecture from 2010 to 2022*

Discussion

Necessity of parameter correction

Currently, there is a large number of research on evaluating the ecological status of regions based on EF. For example, Chen et al. (2022) analyzed the eco-sustainability of Chengdu-Chongqing city cluster using an improved EF_{3D} model, while Dai et al. (2023) calculated the EF of Xiamen based on the national hectare parameter factors, and explored the city's sustainable development status. These studies effectively analyzed the provision and consumption of natural resources and changes in sustainable development within their respective study areas. However, they overlooked the effects of interannual variations in parameter factors and scale differences, thereby limiting the accuracy of their regional ecological assessments. In contrast to previous studies, this research calculates provincial hectare-scale equivalence factors and yield factors on an annual basis. Assessing the ecological status of small-scale regions using small-scale parameters offers a more precise description of the region's ecological status. Besides, the results from this study indicate that parameter factors varied to different extents each year, with some exhibiting significant changes during the study period. Consequently, employing parameter factors that are appropriately scaled and annually updated for natural capital accounting will yield a more realistic and accurate depiction of the region's ecological situation and the dynamics of natural resource provision and consumption. Additionally, the findings of such studies offer a more precise and effective reference for the development of ecological construction and protection strategies.

Analysis of changes in ecological condition

According to the results, although the EC of Hunan Province was consistently much smaller than its EF during the period from 2010 to 2022, the ecological status of the province has significantly improved over this 13-year period. According to the calculations, the EF of Hunan Province began to decline after reaching a turning point in 2015, with a significant reduction observed in 2017. This indicates that after 2015,

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following the inclusion of ecological civilization construction in the national Five-Year Plan at the Fifth Plenary Session of the 18th Central Committee and the establishment of "harmonious coexistence between humans and nature" as one of the fundamental strategies for upholding and developing socialism with Chinese characteristics in the new era at the 19th National Congress of the Communist Party of China, the consumption of natural resources in Hunan Province has noticeably decreased. At the same time, with the implementation of national policies such as "returning farmland to forests, lakes, and grasslands," the EC of cropland has shown a declining trend year by year. However, in recent years, the EF of cropland has continued to grow, leading to an increasingly prominent supply-demand contradiction. Based on this, it is essential to establish a comprehensive ecological compensation system, improve resource utilization efficiency and cropland productivity, alleviate the contradiction between natural resource supply and demand, and promote the coordinated development of ecology and the economy.

Suggestions

According to the results of the study, the construction of ecological civilization in Hunan Province has begun to bear fruit, and the ecological situation has improved, but Hunan Province as a whole and most of its cities are still in an unsustainable development state. Therefore, to improve the level of ecological sustainable development in Hunan Province, a few suggestions are put forward.

Firstly, Hunan Province should strengthen the implementation of ecological protection measures, promote technological innovation, and enhance resource utilization efficiency and cropland productivity to reshape the regional development framework with green industries. Additionally, regional ecological policies should be tailored to local conditions based on the ecological differences across various areas. For Xiangtan, Yueyang, and Loudi, which face poor ecological conditions, the EF of these cities during the study period was primarily composed of cropland and fossil fuel land. Therefore, these cities should focus on transforming high-energy-consuming industries, restructuring regional industrial policies, encouraging low-carbon restructuring of fossil energy industries, and transitioning economies reliant on cropland to improve land utilization efficiency.

Secondly, ecological compensation is an effective economic tool for promoting environmental protection and improvement. However, in recent years, the investment in ecological services in Hunan Province has gradually decreased, leading to a narrowing gap in ecological compensation among cities and prefectures and a reduction in compensation standards. To ensure the sustainability of ecological compensation policies, it is essential to transition from "fiscal reliance" to "market-driven" mechanisms, truly embodying the principle that "lucid waters and lush mountains are invaluable assets." Hunan Province can establish an ecological compensation policy system and foster a positive interaction between ecological protection and economic development through three major measures: innovating funding sources for ecological compensation, optimizing the allocation mechanism of ecological compensation funds, and promoting the market-based value transformation of ecological products.

Limitations and prospects

This study selects statistical data over the past 13 years and builds a suite of assessment indexes to evaluate the level of ecologically sustainable development in Hunan Province from 2010 to 2022. It also studies the eco-compensation of each city and prefecture in Hunan. The conclusions of the study are scientifically based and can provide a reference for regional ecological construction and sustainable assessment. However, due to the significant challenges in obtaining long-term time-series data, this study only provides a comprehensive evaluation of the ecological sustainable development level in Hunan Province from 2010 to 2022. Future research could consider extending the time interval to analyze ecological conditions over a longer time series. Additionally, since cropland serves as both a carbon sink and a carbon source, this study excluded cropland from the calculations of fossil fuel land EF and EC to avoid greater inaccuracies. Future studies could incorporate cropland into the calculations to enhance the precision of the results.

Conclusion

This study built a comprehensive evaluation index of ecological sustainability based on the EF_{3D} improved by the carbon footprint principle, using the provincial hectare as the unit of measurement. The index was then applied to integrate multiple perspectives for a more thorough evaluation of eco-sustainability in Hunan Province. Additionally, an eco-compensation model was constructed by considering the ecological and economic conditions of Hunan Province's cities and prefecture. The major conclusions are summarized below.

(1) From 2010 to 2022, the EF and ED of Hunan Province exhibited a fluctuating upward trend, while the EC showed a slow annual increase. The results indicate that the natural resource supply capacity of Hunan has been gradually improving year by year, but the demand for natural resources in the province has also been growing. Among the cities and prefectures, Changsha demonstrated a notable inverse growth in its EF, while Yueyang experienced the fastest growth in both EF and ED.

(2) From 2010 to 2022, the per capita EF_{size} of Hunan Province as a whole and most of its regions showed a fluctuating upward trend, while the EF_{depth} exhibited a fluctuating downward trend, with EF_{depth} consistently greater than 1. This indicates an overall improvement in natural resource utilization efficiency in Hunan, with consumption of natural capital stocks still occurring but a reduced degree of occupation of natural capital stocks. Among the cities and prefectures, the EF_{depth} of Xiangtan, Yueyang and Loudi was significantly higher than the provincial average and other regions, suggesting more severe issues of resource overconsumption in these areas.

(3) The ecological condition of Hunan is characterized by "overall improvement with localized severity." The overall ecological pressure and capital stock occupation in the province have significantly decreased, while ecological resource utilization efficiency and ecological diversity have shown notable improvements, leading to a marked enhancement in the overall ecological sustainable development level of Hunan. There are significant ecological disparities among the cities and prefectures, with Changsha experiencing the most substantial change. Changsha transitioned from a state of very unsustainability in 2010 to slight unsustainability in 2022, achieving remarkable progress. In contrast, Xiangtan, Yueyang, and Loudi face severe ecological challenges, with Xiangtan remaining in a state of extreme unsustainability for an extended period. Therefore, it is necessary to implement region-specific ecological protection policies tailored to local conditions, promote the restructuring of industrial policies in ecologically critical areas, strengthen the protection of ecological functional zones, and encourage the development of green industries.

(4) From 2010 to 2022, the ecological compensation area in Hunan expanded, while the total amount of ecological services decreased, and the disparities in ecological

compensation among cities and prefectures narrowed. Among them, Yueyang recorded the highest average ecological compensation payment, while Huaihua received the largest total amount of ecological compensation. Notably, during this period, Changsha transitioned from being an ecological payment zone to an ecological compensation zone.

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REFERENCES

[1] Anaafo, D., Nutsugbodo, R. Y., Adusu, D. (2023): Mining and sustainable development in the Asutifi North District, Ghana. – Resources Policy 80: 103171.
[2] Cai, J., He, Y., Xie, R., Liu, Y. (2020): A footprint-based water security assessment: An analysis of Hunan province in China. – Journal of Cleaner Production 245: 118485.
[3] Chen, X., Liu, Q., Fang, K., He, J., Chen, Y., Wang, T., Fang, C., Shen, Y. (2020): Tracking national sustainability of critical natural capital and the socioeconomic drivers in the context of the Belt and Road Initiative. – Ecological Indicators 114: 106315.
[4] Chen, W., Zeng, J., Zhong, M., Pan, S. (2021): Coupling Analysis of Ecosystem Services Value and Economic Development in the Yangtze River Economic Belt: A Case Study in Hunan Province, China. – Remote Sensing 13(8): 1552.
[5] Chen, Y., Lu, H., Yan, P., Qiao, Y., Xia, J. (2022): Spatial-temporal collaborative relation among ecological footprint depth/size and economic development in Chengyu urban agglomeration. – Science of The Total Environment 812: 151510.
[6] Chen, C., Nie, P., Huang, F., Fan, D., Xiang, L., Zeng, J., Chen, F., Hu, G. (2024): Evaluation and driving mechanism of eco-environmental quality based on improved RSEI model: a case study at Taojiang County, Hunan Province. – Bulletin of Soil and Water Conservation, pp. 159-170.
[7] Dai, J., Ouyang, Y., Hou, J., Cai, L. (2023): Long-time series assessment of the sustainable development of Xiamen City in China based on ecological footprint calculations. – Ecological Indicators 148: 110130.
[8] Du, H., Zhao, L., Zhang, P., Li, J., Yu, S. (2023): Ecological compensation in the Beijing-Tianjin-Hebei region based on ecosystem services flow. – Journal of Environmental Management 331: 117230.
[9] Fang, K., Li, H. (2012): Provincial Pattern of China's Natural Capital Use: A Modification and Application of Ecological Footprint Depth and Size. – Journal of Natural Resources 27(12): 1995-2005.
[10] Fang, K., Gao, K., Li, H. (2013): International comparison of natural capital use: A three-dimensional model optimization of ecological footprint. – Geographical Research 32(9): 1657-1667.
[11] Gong, J., Liu, C., Jiao, L., Wu, L., Xu, M. (2020): Study on the regional difference and influential factors of eco-compensation in Hunan Province. – Ecological Science 39(05): 211-219.
[12] Guo, J. (2022): Evaluation and Prediction of Ecological Sustainability in the Upper Reaches of the Yellow River Based on Improved Three-Dimensional Ecological Footprint Model. – International Journal of Environmental Research and Public Health 19(20): 13550.
[13] Jiang, Y., Guan, D., He, X., Yin, B., Zhou, L., Sun, L., Huang, D., Li, Z., Zhang, Y. (2022): Quantification of the coupling relationship between ecological compensation and

ecosystem services in the Yangtze River Economic Belt, China. – Land Use Policy 114: 105995.

[14] Kızılgöl, Ö., Öndes, H. (2022): Factors affecting the ecological footprint: A study on the OECD countries. – Science of The Total Environment 849: 157757.

[15] Lemke, C., Bastini, K. (2020): Embracing multiple perspectives of sustainable development in a composite measure: The Multilevel Sustainable Development Index. – Journal of Cleaner Production 246: 118884.

[16] Li, M., Zhou, Y., Wang, Y., Singh, V. P., Li, Z., Li, Y. (2020): An ecological footprint approach for cropland use sustainability based on multi-objective optimization modelling. – Journal of Environmental Management 273: 111147.

[17] Li, D., Zhang, J. (2022): Measurement and analysis of ecological pressure due to industrial development in the Yangtze River economic belt from 2010 to 2018. – Journal of Cleaner Production 353: 131614.

[18] Li, J., Peng, H., Chen, Y., Zhang, S., He, P., Yang, L., Si, M., Yang, Y. (2024): Dynamic evolution of urban resilience and its coupling mechanism with EF3D-driven natural capital utilization: Case study in three typical urban agglomerations of China. – Environmental Impact Assessment Review 106: 107518.

[19] Liu, Y., Zhang, X., Deng, H. (2024): Construction and Influencing Factors of Voluntary Compensation Subjects for Herders—From the Perspective of Sustainable Utilization of Grassland Resources. – Sustainability 16(6): 2576.

[20] Lo-Iacono-Ferreira, V. G., Torregrosa-López, J. I., Capuz-Rizo, S. F. (2016): Use of Life Cycle Assessment methodology in the analysis of Ecological Footprint Assessment results to evaluate the environmental performance of universities. – Journal of Cleaner Production 133: 43-53.

[21] Mamghaderi, M., Mamkhezri, J., Khezri, M. (2023): Assessing the environmental efficiency of OECD countries through the lens of ecological footprint indices. – Journal of Environmental Management 338: 117796.

[22] Niccolucci, V., Bastianoni, S., Tiezzi, E. B. P., Wackernagel, M., Marchettini, N. (2009): How deep is the footprint? A 3D representation. – Ecological Modelling 220(20): 2819-2823.

[23] Niu, J., Mao, C., Xiang, J. (2024): Based on ecological footprint and ecosystem service value, research on ecological compensation in Anhui Province, China. – Ecological Indicators 158: 111341.

[24] Pan, Y., Zhang, B., Wu, Y., Tian, Y. (2021): Sustainability assessment of urban ecological-economic systems based on emergy analysis: A case study in Simao, China. – Ecological Indicators 121: 107157.

[25] Rees, W. E. (1992): Ecological Footprints and Appropriated Carrying Capacity: What Urban Economics Leaves Out. – Environment and Urbanization 4(2): 121-130.

[26] Shabir, M., Pazienza, P., De Lucia, C. (2023): Energy innovation and ecological footprint: Evidence from OECD countries during 1990–2018. – Technological Forecasting and Social Change 196: 122836.

[27] Sun, X., An, H. (2018): Emergy network analysis of Chinese sectoral ecological sustainability. – Journal of Cleaner Production 174: 548-559.

[28] Tan, J., Dong, L., Zhou, W., Tan, X., Liu, P. (2020): Regional differences of Hunan sustainable agricultural development based on combination evaluation. – Ecological Science 39(01): 110-117.

[29] Wackernagel, M., Onisto, L., Bello, P., Callejas Linares, A., Susana López Falfán, I., Méndez García, J., Isabel Suárez Guerrero, A., Guadalupe Suárez Guerrero, M. (1999): National natural capital accounting with the ecological footprint concept. – Ecological Economics 29(3): 375-390.

[30] Wang, H., Huang, J., Zhou, H., Deng, C., Fang, C. (2020): Analysis of sustainable utilization of water resources based on the improved water resources ecological footprint

model: A case study of Hubei Province, China. – Journal of Environmental Management 262: 110331.

[31] Wang, B., He, W., An, M., Fang, X., Ramsey, T. S. (2024a): Natural capital accounting of land resources based on ecological footprint and ecosystem services value. – Science of The Total Environment 914: 170051.

[32] Wang, Z.-L., Tao, F., Leng, H.-J., Wang, Y.-H., Zhou, T. (2024b): Multi-scale analysis on sustainability and driving factors based on three-dimensional ecological footprint: A case study of the Yangtze River Delta region, China. – Journal of Cleaner Production 436: 140596.

[33] WCED (1987): Our common future. – Report of the World Commission on Environment and Development.

[34] Wei, Y., Song, B., Wang, Y. (2022): Designing cross-region ecological compensation scheme by integrating habitat maintenance services production and consumption: A case study of Jing-Jin-Ji region. – Journal of Environmental Management 311: 114820.

[35] Wei, Z., Jian, Z., Sun, Y., Pan, F., Han, H., Liu, Q., Mei, Y. (2023): Ecological sustainability and high-quality development of the Yellow River Delta in China based on the improved ecological footprint model. – Scientific Reports 13(1): 3821.

[36] Wu, Y., Zhang, T., Zhang, H., Pan, T., Ni, X., Grydehøj, A., Zhang, J. (2020): Factors influencing the ecological security of island cities: A neighborhood-scale study of Zhoushan Island, China. – Sustainable Cities and Society 55: 102029.

[37] Wu, C., Lu, R., Zhang, P., Dai, E. (2024): Multilevel ecological compensation policy design based on ecosystem service flow: A case study of carbon sequestration services in the Qinghai-Tibet Plateau. – Science of The Total Environment 921: 171093.

[38] Xiao, J., Yu, L., Chen, W., Shen, C. (2017): Hunan Regional Ecological Compensation Accounting-Based on the Method of Ecological Footprint. – Journal of Central South University of Forestry & Technology (Social Sciences) 11(01): 27-33+39.

[39] Xiong, Y., Ai, G., Zhou, C., Yao, Y., Xie, Q. (2022): Temporal and spatial evolution of ecological sustainability in Dongting Lake area based on the improved three-dimensional ecological footprint model. – Acta Ecologica Sinica 42(03): 1165-1179.

[40] Yang, J., Huang, X. (2021): The 30 m annual land cover dataset and its dynamics in China from 1990 to 2019. – Earth System Science Data 13(8): 3907-3925.

[41] Yang, Y., Lu, H., Liang, D., Chen, Y., Tian, P., Xia, J., Wang, H., Lei, X. (2022a): Ecological sustainability and its driving factor of urban agglomerations in the Yangtze River Economic Belt based on three-dimensional ecological footprint analysis. – Journal of Cleaner Production 330: 129802.

[42] Yang, Y., Zhang, Y., Yang, H., Yang, F. (2022b): Horizontal ecological compensation as a tool for sustainable development of urban agglomerations: Exploration of the realization mechanism of Guanzhong Plain urban agglomeration in China. – Environmental Science & Policy 137: 301-313.

[43] Yu, G., Liu, D., Liao, X., Wang, T., Tian, Q., Liao, Y. (2017): Quantitative Research on Regional Ecological Compensation from the Perspective of Carbon-Neutral: The Case of Hunan Province, China. – Sustainability 9(7): 1095.

[44] Yu, J., Yi, L., Xie, B., Li, X., Li, J., Xiao, J., Zhang, L. (2023): Matching and coupling coordination between the supply and demand for ecosystem services in Hunan Province, China. – Ecological Indicators 157: 111303.

[45] Zhang, Y.-J., Hao, J.-F. (2016): The evaluation of environmental capacity: Evidence in Hunan province of China. – Ecological Indicators 60: 514-523.

[46] Zhang, R., Li, P., Xu, L. (2022): Evaluation and analysis of ecological security based on the improved three-dimensional ecological footprint in Shaanxi Province, China. – Ecological Indicators 144: 109483.

[47] Zhang, D., Wu, L., Niu, X., Guo, Z., Zhang, Z., Li, S., Zhang, G., Ahmad, F., Shang, Z., Xu, H. (2022): Looking for ecological sustainability: A dynamic evaluation and prediction

on the ecological environment of the belt and road region. – Sustainable Production and Consumption 32: 851-862.

[48] Zhang, J., Hao, X., Li, X., Fan, X., Zhang, S. (2024): Evaluation and regulation strategy for ecological security in the Tarim River Basin based on the ecological footprint. – Journal of Cleaner Production 435: 140488.

[49] Zhao, H., Liu, X., Wang, C. (2022): Spatio-temporal information entropy for the analysis of ecological sustainability and its application in the Yanhe watershed. – Acta Ecologica Sinica 42(9): 3749-3758.

[50] Zhao, Y., Li, T., Qi, Z., Li, S., Ge, J. (2022): Payments of ecosystem services allocation in Hunan province based on the value of ecosystem services and human well-being. – Journal of Shaanxi Normal University (Natural Science Edition) 50(04): 103-114.

[51] Zhou, T., Wang, Y., Gong, J., Wang, F., Feng, Y. (2015): Ecological footprint model modification and method improvement. – Acta Ecologica Sinica 35(14): 4592-4603.

[52] Zhu, P., Wang, X., Xie, Y., Wen, N., Zhang, W. (2023): Evolution of supply and demand relationship of ecosystem services in Hu' nan Province based on main function zoning. – Acta Ecologica Sinica 43(15): 6182-6193.

APPENDICES

Appendix A. *Parameter factor calculation result*

Equivalence factor	**Cropland**	**Forest**	**Grassland**	**Water**	**Building land**
2010	2.52	0.17	3.26	0.71	2.52
2011	2.51	0.18	3.22	0.71	2.51
2012	2.53	0.17	3.58	0.76	2.53
2013	2.49	0.19	3.72	0.76	2.49
2014	2.48	0.19	3.87	0.78	2.48
2015	2.56	0.15	3.97	0.83	2.56
2016	2.49	0.18	4.16	0.88	2.49
2017	2.46	0.21	4.39	0.83	2.46
2018	2.43	0.22	4.52	0.93	2.43
2019	2.39	0.25	4.80	1	2.39
2020	2.35	0.26	5.83	0.98	2.35
2021	2.32	0.28	5.48	0.94	2.32
2022	2.34	0.28	7.35	1.05	2.34

Yield factor	**Cropland**			**Forest**			**Grassland**			**Water**			**Building land**		
Year	**2010**	**2016**	**2022**	**2010**	**2016**	**2022**	**2010**	**2016**	**2022**	**2010**	**2016**	**2022**	**2010**	**2016**	**2022**
Changsha	1.20	1.13	0.95	1.16	1.20	0.69	4.55	3.04	2.51	1.36	0.90	1.07	1.20	1.13	0.95
Zhuzhou	1.26	1.13	1.05	0.90	1.20	1.77	2.32	1.75	1.87	1.25	1.19	1.19	1.26	1.13	1.05
Xiangtan	1.38	1.34	1.07	0.45	0.45	1.16	1.31	0.82	1.27	1.26	1.44	1.36	1.38	1.34	1.07
Hengyang	1.00	1.02	0.98	1.25	1.91	2.43	3.22	2.74	2.82	1.89	1.79	1.64	1.00	1.02	0.98
Shaoyang	1.03	1.04	1.08	1.11	1.02	0.79	0.36	0.40	0.40	1.53	1.45	1.27	1.03	1.04	1.08
Yueyang	0.93	0.97	0.89	1.20	3.04	2.86	1.05	1.32	1.54	0.79	0.76	0.83	0.93	0.97	0.89
Changde	1.03	1.02	1.01	1.13	1.61	1.05	13.78	8.68	7.85	0.83	0.93	0.90	1.03	1.02	1.01
Zhangjiajie	0.75	0.71	0.91	0.40	0.22	0.24	2.15	1.12	1.36	0.38	0.49	0.20	0.75	0.71	0.91
Yiyang	1.08	1.08	1.01	1.83	2.34	1.95	5.16	6.62	3.67	0.89	1.00	1.17	1.08	1.08	1.01
Chenzhou	0.96	0.98	1.14	1.05	0.56	0.68	0.20	0.22	0.22	1.04	1.08	0.90	0.96	0.98	1.14
Yongzhou	0.9	0.95	0.99	1.17	0.94	0.82	0.62	1.23	1.60	1.64	1.67	1.54	0.9	0.95	0.99
Huaihua	0.84	0.81	1.07	1.13	0.64	0.89	1.05	0.81	1.26	0.43	0.48	0.39	0.84	0.81	1.07
Loudi	1.1	1.11	1.07	0.48	0.24	0.39	1.23	1.05	0.76	2.16	2.08	2.06	1.1	1.11	1.07
Xiangxi	0.59	0.55	0.71	0.31	0.32	0.19	1.24	0.78	0.62	0.64	0.55	0.33	0.59	0.55	0.71

Note: Due to space constraints, only the 2010, 2016, and 2022 yield factor calculations are shown in the table

***Appendix B.** Evaluation indicators for ecologically sustainable development*

Evaluation indicators	Formula	Description
EPI	$\mathrm{E}PI = \frac{\mathrm{e}f}{ec}$ (11)	ef and ec same as formula (3)(4).
EUE	$\mathrm{EUE} = \frac{EF}{GDP}$ (12)	EUE is the EF of 10^4 RMB of GDP.
R_{flow}^{stock}	$R_{flow}^{stock} = EF_{depth} - 1$ (13)	EF_{depth} same as formula (1).
ECC	$ECC = \frac{EF + EC}{\sqrt{EF^2 + EC^2}}$ (14)	EF and EC same as formula (3)(4).
EFDI	$EFDI = -\sum(P_i \times lnP_i)$ (15)	P_i represents the ratio of EF of the ith land type relative to the overall EF.
CIESD	$CIESD = a_1 \times EPI + a_2 \times EUE + a_3 \times ECC + a_4 \times R_{flow}^{stock} + a_5 \times EFDI$ (16)	a_1, a_2, a_3, a_4, a_5 are the weights of the indicators.

***Appendix C.** Formula for calculating ecological compensation*

$$C_m = V_m - F_m$$

$$V_m = R \times \frac{EC_m}{\sum_{m=1}^{n} EC}$$

$$F_m = R \times \frac{EF_m \times M_{ec_m}}{\sum_{m=1}^{n}(EF_m \times M_{ec_m})}$$

$$M_{ec_m} = \frac{U_m \times W_m}{U \times W}, U_m = \frac{ef_m}{Y_m}, W_m = \frac{Y_m \times l_m}{Y}, l_m = \frac{1}{1 + e^{-t}}, t = \frac{I_m}{I}, I = \frac{A \times a + B \times b}{a + b}$$

where C_m is the amount of eco-compensation in the m-area, $C_m > 0$ when the m-area should get the amount of eco-compensation C_m, $C_m < 0$ when the m-area should be given the amount of eco-compensation $|C_m|$; V_m represents the supply of ecological services in zone m; R represents the volume of ecological services in Hunan Province (proxied by investment in environmental pollution management); F_m represents the consumption of ecological services in zone m; M_{ec_m} is the composite correction coefficient for region m; U_m is the EF of 10^4 RMB GDP for region m; W_m is the willingness to pay for region m; U is the average of the EF of 10^4 RMB GDP for all regions; W is the average of the willingness to pay for all regions; Y_m is the GDP per capita for region m; Y is the GDP per capita for all regions; l_m is the development stage coefficient of region m; I is the per capita income of all regions; a and b are the urban and rural populations of the region, respectively; A and B denote the per capita disposable incomes for urban and rural areas of the region, respectively.

Appendix D. *Ecological compensation amounts for each city and prefecture in Hunan Province from 2010 to 2022(×107CNY)*

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Changsha	-2.3	-1.4	-2.1	-2.4	-1.1	-0.4	0.9	2.0	1.7	1.6	1.2	3.7	1.5
Zhuzhou	1.6	1.0	2.2	2.9	2.3	4.4	2.2	1.1	0.7	1.1	0.7	2.1	1.0
Xiangtan	-9.1	-6.8	-11.1	-13.8	-10.2	-13.4	-6.4	-3.6	-3.2	-1.8	-1.3	-4.2	-2.3
Hengyang	-8.2	-5.6	-8.2	-9.5	-6.0	-8.4	-4.0	-1.4	-1.4	-1.0	-0.6	-1.7	-0.6
Shaoyang	5.1	3.9	6.5	7.8	5.5	8.4	4.5	1.0	3.3	2.8	1.9	5.4	2.5
Yueyang	-11.1	-8.7	-18.1	-22.4	-15.9	-28.2	-14.2	-9.7	-9.3	-8.6	-5.6	-15.0	-6.9
Changde	-3.0	-1.8	-3.9	-6.9	-5.8	-9.5	-5.0	-3.4	-3.4	-3.4	-2.4	-7.4	-3.2
Zhangjiajie	4.8	3.4	6.5	8.6	6.4	9.7	4.8	3.3	2.8	2.3	1.5	4.6	2.0
Yiyang	-1.8	-1.4	-3.4	-5.0	-4.3	-7.9	-4.3	-3.0	-3.4	-3.1	-2.0	-6.4	-2.6
Chenzhou	3.8	2.6	5.0	7.0	5.2	8.9	4.2	2.9	2.4	2.1	1.3	3.2	1.5
Yongzhou	2.2	1.8	3.6	5.0	3.4	4.3	1.6	0.7	0.2	0.3	0.6	0.9	0.3
Huaihua	14.8	10.5	19.2	26.0	19.1	28.8	14.2	9.0	7.5	6.1	3.9	11.8	5.4
Loudi	-4.9	-3.6	-7.5	-12.2	-9.6	-13.6	-6.7	-4.5	-2.8	-2.2	-1.5	-4.3	-2.0
Xiangxi	8.3	5.9	11.2	14.8	11.1	16.8	8.2	5.5	4.6	3.7	2.3	7.2	3.2
Total	137.9	97.0	179.6	233.7	173.4	261.4	127.0	86.1	70.5	54.8	33.5	105.6	44.3

Note: The ‘Total’ column in the table refers to the total ecological services in Hunan