QUANTITATIVE RESEARCH ON ECOLOGICAL COMPENSATION IN COASTAL AREAS BASED ON ECOLOGICAL FOOTPRINT

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Abstract. Environmental degradation has severely restricted the economic development of coastal beach areas. Quantitative analysis of ecological compensation in coastal beach areas will help to understand the current situation of local resources and environment. Therefore, this paper proposes a quantitative analysis method for coastal beach ecological compensation based on changes in ecological footprint. According to the ecological red line regional ecological compensation theory, the subject and object of ecological compensation are clarified, and the ecological footprint calculation model and ecological compensation sharing model are constructed. From the ecosystem service value, ecological footprint calculation, ecological carrying capacity and ecological footprint efficiency, direct income loss compensation, static from the perspectives of evaluation compensation and dynamic evaluation compensation, the quantitative analysis of ecological compensation in coastal beach areas has been realized. In this paper, a certain place is selected as the experimental area, and the principal component analysis method is used to evaluate the effect of local ecological compensation. The results show that the level of ecological surplus in 2020 has significantly increased compared to that of 2010; The ecological capacity per capita in the study area is lower than the national average; The ecological compensation effect after normalization treatment is obviously better than that before normalization.
Keywords: *changes in human ecological footprint, coastal areas, ecological compensation, Principal Component Analysis, ecological carrying capacity, evaluation*

Introduction

The ecological environment supports the survival and development of human society by providing ecological products and services to humans, but the value and characteristics of the ecological environment have not yet been fully reflected in social and economic activities. The external effects of use are significant, and protection and benefit are out of touch (Kosev and Vasileva, 2019). With the rapid development of society and economy, the destruction and pollution of the ecological environment are becoming more and more serious. As one of the effective ways to solve the problems of the ecological environment, ecological compensation has been paid more and more attention by people. In recent years, the ecological compensation mechanism has become a research hotspot in the academic circle. Scholars at home and abroad have conducted in-depth and extensive research on the scope of ecological compensation, compensation standards, compensation basis, compensation methods, etc. One such study involves the determination of ecological compensation standards. This is the focus and difficulty of whether the practice can be carried out (Itsukushima, 2019).

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In reference to the study by Wang et al. (2019), taking Changsha City, Hunan Province, China as an example, proposed a quantitative analysis method for ecological compensation based on the value of ecological services, using Swedish carbon tax law, industrial oxygen production cost method, and alternative cost method. Fully consider the beneficial value of the ecological services of cultivated land resources and the cost of environmental pollution control, construct and establish an accounting system for the ecological service value of cultivated land, and quantify the amount of ecological compensation. The results show that the value of ecological service benefits provided by cultivated land resources in Changsha city from 2011 to 2017 increased from 1.6867×10~(9)US dollars to 1.7447×10~(9)US dollars in 2017, while the cost of environmental pollution control increased from 9.7281×10~(8)US dollars reduced to 9.1891×10~(8) US dollars, the value of the ecological service benefits of cultivated land resources is far greater than the cost of environmental pollution control; the average value of ecological compensation for cultivated land in Changsha from 2011 to 2017 was 6.8688×10~(8) US dollars, and the ecological compensation amount of various districts and counties is quite different. Reference (Wang et al., 2020) takes Hubei province as an example, proposes research on ecological compensation methods from the perspective of the main function zone. From the perspective of the main function zone, on the basis of measuring the value of the ecosystem services in Hubei Province, define the ecological compensation and compensation payment subjects, to determine the level and order of ecological compensation and compensation payment. The results show that: (1) the spatial distribution of total value, market value and non-market value of ecosystem services in Hubei province is similar, showing a pattern of "high in the west, low in the east". High value areas are mostly concentrated in key ecological function areas and main agricultural product producing areas, while low value areas are mostly concentrated in key development areas; (2) The ecological compensation level of the 30 key ecological function areas can be divided into five levels, showing a spatial distribution pattern of "high in the west and low in the east"; (3) The ecological compensation priority of 29 main agricultural product producing areas is divided into five levels; (4) The compensation payment level of the 30 key development zones is divided into five levels, showing a spatial distribution pattern of "east first, west later". In the practice of ecological compensation payment, the national level key development zones should be prior to the provincial level key development zones. Reference (Nie and Cheng, 2019) proposed a regional horizontal forest ecological compensation method based on the marginal effect theory. Based on the marginal effect theory, taking 2016 as the time section, the marginal benefit of forest ecological construction was calculated, and the critical value of horizontal compensation was obtained. Combined with the unbalanced coordinated development of the region, the forest ecological compensation value was obtained according to the expert weighting method. The results show that in theory, Beijing should provide 814675375 US dollars / year to 1996419312.5 US dollars / year for forest ecological compensation in Zhangcheng area. In fact, in fact, the amount of ecological compensation for Zhangcheng covered areas in Beijing during the 13th Five Year Plan period is only 111250000 US dollars / year. Therefore, Beijing should increase the compensation for forest ecology in Zhangcheng area of Hebei province on the basis of existing compensation.

Based on the above research results, in order to further improve the effect of ecological compensation analysis, this paper proposes a quantitative research method of

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ecological compensation in coastal beach area based on the change of ecological footprint.

Materials and methods

Quantitative analysis method of ecological compensation in beach areas based on changes in ecological footprint

Ecological compensation is a kind of public system which aims at protecting the ecological environment and promoting the harmonious development between human and nature. According to the value of ecosystem services, the cost of ecological protection and the cost of development opportunity, the government and the market are used to regulate the interest relationship among the stakeholders of ecological protection. The following is a quantitative analysis of ecological compensation in coastal beach areas from the aspects of ecological compensation theory, subject and object of ecological compensation, ecological footprint calculation model and ecological compensation sharing model (Salemi et al., 2019).

Theoretical basis of ecological compensation in the ecological red line area

The ecological red line was first applied in the process of urbanization, aiming to standardize the development space of the city, and then gradually extended to the ecological environment protection. The proposal of the ecological red line is based on the country's ecological security and sustainable economic and social development, and is to maintain the boundary line of the land and space through the implementation of the strictest control system. The "ecological red line" cannot be simply understood as a regional boundary. It is a hierarchical system that includes many ecological protections point sets, line clusters and locations (Smee, 2019). In short, point set is the layer of ecological red line area, on which there are many ecological value protection targets; Line cluster, with the connotation of dynamic change, mainly refers to the cluster close to sensitive protection point source in the belt area formed by rivers, lakes and swamps in the ecological red line area (Dong and Liu, 2020); Location, from the macro level, refers to those vulnerable areas with important or special ecological value or high ecological sensitivity.

According to the theory of ecological red line, the ecological compensation standard of coastal beach area is set:

Assuming that the ecological spillover value in year i is E_i ($i = 1, 2, ..., k$), and the construction period of the tidal flat area are N years, then the ecological spillover value before the tidal flat area is E_0, the ecological spillover value of the tidal flat area after reclamation, that is, the ecological spillover value at the end of year N is E_N. This article defines the ecological spillover value increment S_n in year n as follows:

$$S_n = E_0 - E_n \quad \text{(Eq.1)}$$

It can be seen from formula (*Eq.1*) that the increment of ecological spillover value in year n is relative to the initial value E_0, and the final value is subtracted from the initial

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value. The purpose is to make it non-negative under normal circumstances (Yang et al., 2019). The increment of ecological spillover value before and after reclamation is taken as the theoretical standard of ecological compensation, which is essentially based on the value of ecological damage as the basis for compensation.

Determination of the subject and object of ecological compensation

Definition of the subject of ecological compensation

The so-called subject of ecological compensation refers to "who will bear the responsibility of ecological compensation". The main body of ecological compensation in coastal wetland areas should include two parts: one is "who benefits, who compensates". The beneficiaries of wetland protection, including the international community, governments, enterprises and individuals, should give back to coastal wetland protectors; The second is "whoever destroys it, who is responsible." Any government, enterprise and individual that destroys the ecological environment of the wetland should pay economic compensation or even legal liability for the loss of the value of the ecological environment (Su et al., 2020).

Definition of the object of ecological compensation

The object of ecological compensation refers to "who will receive ecological compensation". The object of ecological compensation in beach areas should also include two parts: one is to protect the coastal wetland resources, and the local residents whose income is damaged, and the employees of the wetland nature reserve who contribute to the protection of the wetland (Ferro-Azcona et al., 2019); Second, groups or individuals whose living environment is threatened and their economic income is damaged due to the destruction of the wetland ecological environment.

Ecological footprint calculation model

The calculation of the ecological footprint is based on the following two basic facts: one is that humans can determine most of the resources they consume and the amount of waste they produce; the other is that these resources and wastes can be converted into the corresponding ecologically productive land area. Assume that all types of material consumption, energy consumption and wastewater treatment require a certain amount of land area and water area (Stone et al., 2019). The calculation formula of ecological footprint is as follows:

$$EL = \sum_{j=1}^{n}\sum_{i=1}^{n}\beta_j\varphi_i\left(Z_j\right) + \sum_{s=1}^{n}a_{s,i}(t) \tag{Eq.2}$$

In the formula, i represents the type of consumption item; φ_i represents the per capita consumption of the i-th consumption item; represents the equilibrium factor; $a_{s,u}$ represents the ecologically productive land area converted by the i-th consumer product; Z_j represents the ecological footprint per capita; t represents the ecological footprint of the total population.

The calculation of ecological footprint mainly includes the consumption of biological resources and energy consumption. The consumption of biological resources mainly

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includes agricultural products, animal products, wood, aquatic products, etc. in the energy consumption part, the footprint of raw coal, coke, natural gas, crude oil, gasoline, kerosene, diesel oil, fuel oil, heat, electricity, etc. can be calculated according to the data (Boutahar et al., 2019). The calculation method of ecological footprint is to add up the area of land per capita ecological demand of biological resources and energy resources calculated above, and then allocate appropriate weight, namely, equilibrium factor, to obtain the ecological footprint of coastal beach area.

Construction of ecological compensation sharing model

This study combines the upstream and downstream water consumption and economic affordability of coastal beach areas to establish a regional and central ecological compensation cost allocation model, in order to provide scientific suggestions for the implementation of ecological compensation in coastal beach areas. The specific model is as follows:

$$W(x,y)=\frac{P(x\cap y)}{\min\left(P(x),P(y)\right)} \quad \text{(Eq.3)}$$

In the formula, $P(x)$ represents the amount of ecological compensation along the beach; $P(y)$ represents the amount of ecological compensation cost apportionment.

Considering that the value of model parameters is easily affected by the external environment, and has uncertainty. In this paper, Crystal Ball software is used to analyze the sensitivity of model parameters. Firstly, Monte Carlo simulation method is used to sample the probability distribution function of model parameters, and establish the distribution function of ecological compensation, so as to obtain important mathematical features in the model, such as mathematical expectation, variance, interval estimation, etc. (Park et al., 2019). On this basis, variance analysis is used to analyze the parameters, and the sensitivity of the parameters is determined according to the proportion of the normalized square of the rank correlation coefficient between the input and the output of ecological compensation. The specific formula is as follows:

$$P(x)=\log\frac{P_g(x,y)}{P_c(x,y)}\times 100\% \quad \text{(Eq.4)}$$

$$P(y)=\frac{P_g(x,y)}{P_c(x,y)P_g(x,y)}dxdy \quad \text{(Eq.5)}$$

In the formula, $P_g(x,y)$ represents the variance contribution rate of the parameter variable; $P_c(x,y)$ represents the correlation coefficient of the ecological compensation amount.

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Quantitative analysis of ecological compensation based on ecological footprint

The determination of ecological compensation standards is generally based on three aspects: determination based on the standard of ecosystem service value evaluation; determination based on the standard of protection cost; determination based on the standard of protection loss (Sun and Wang, 2018). Domestic and foreign studies generally use service value evaluation as the basis for determining compensation standards. Based on the existing theoretical methods, this paper analyzes the dynamic changes of ecological footprints along beaches, and finally quantitatively analyzes the ecological compensation standards according to the efficiency of ecological footprints. The calculation steps are as follows:

(1) Ecosystem service value

In this paper, emergy analysis method is applied to the evaluation of ecosystem service function in coastal beach area. The environmental energy input of ecosystem is mainly considered. The renewable resource input includes solar energy, wind energy, rain energy, tidal energy and evapotranspiration energy, which are converted into solar energy through the corresponding emergy conversion rate, on this basis, the natural production value of different types of ecosystems was calculated (Zeng et al., 2020). In order to make the calculation of renewable resources input scientific and reasonable, emergy experts put forward different calculation methods from the aspects of completeness of calculation, avoiding repeated calculation and consistency with reality. In this paper, using evapotranspiration as renewable resources input can not only improve the estimation accuracy of renewable resources input, but also avoid the impact of time scale on renewable resources input to a large extent. According to the principle of emergy analysis, the emergy of environmental input and the calculation formula of each index are as follows:

$$\begin{aligned} EL_1 &= K_{TV1} \times u_1 \\ EL_2 &= K_{TV2} \times u_2 \times u_1 \\ EL_3 &= K_{TV3} \times u_3 \times u_2 \times u_1 \\ EL_4 &= K_{TV4} \times u_4 \times u_3 \times u_2 \times u_1 \\ EL_5 &= K_{TV5} \times u_5 \times u_4 \times u_3 \times u_2 \times u_1 \\ EL_6 &= K_{TV6} \times u_6 \times u_5 \times u_4 \times u_3 \times u_2 \times u_1 \end{aligned} \tag{Eq.6}$$

$$EL_{total} = \sum_{i=6}^{n} \left(EL_1 + EL_2 + EL_3 + EL_4 + EL_5 + EL_6 \right) \tag{Eq.7}$$

In the formula, EL_1, EL_2, EL_3, EL_4, EL_5 and EL_6 respectively represent solar energy, surface wind energy, rainwater chemical energy, tidal energy, evapotranspiration energy and soil organic matter loss energy.

(2) Calculate ecological footprint, ecological carrying capacity and ecological footprint efficiency. Among them, the ecological footprint efficiency refers to the output of a unit of ecological footprint, which is a method for quantitative analysis and comparison of resource utilization efficiency and capacity differences in different regions (Yang et al., 2019). Because the ecological compensation of nature reserves is

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mostly aimed at the farmers in the surrounding communities, the efficiency analysis of agricultural ecological footprint can also be used. Calculation method is:

$$ED = \sigma_i(t) - \frac{\alpha_i - \alpha_i^*}{EL_{total}} \quad \text{(Eq.8)}$$

In the formula, $\sigma_i(t)$ represents the ecological footprint efficiency; α_i represents the total ecological footprint; α_i^* represents the agricultural ecological footprint efficiency.

(3) Compensation for direct income loss caused by returning farmland to forests and lakes: compensation for direct income loss caused by returning farmland to forests, returning farmland to lakes and banning fishing in lakes is based on compensation for loss of cultivated land and lake surface, and is the lowest compensation standard to protect residents' rights and interests. Calculation method is:

$$EU = M_q\left(N_g \times N_q \times N_t\right) \quad \text{(Eq.9)}$$

In the formula, M_q represents the minimum ecological compensation value; N_g the area of returning farmland to forests and lakes; N_q represents the adjustment coefficient of cultivated land compensation, which can be determined according to the level of regional social and economic development.

(4) Static evaluation and compensation based on ecological carrying capacity: compare the ecological carrying capacity of the protected area and the area in the same year, and take the difference as the basis for compensation, which objectively increases the resettlement subsidy for the value of ecosystem services. Calculation method is:

$$EA = \frac{1}{2}\sum_{i=1}^{n}\left\|a^i - a^l\right\|^2 + a^d \times a^z \quad \text{(Eq.10)}$$

In the formula, a^i represents the static evaluation compensation value; a^l represents the total ecological carrying capacity of the beach area; a^d represents the area of the beach area; a^z represents the static ecological compensation adjustment coefficient, which can be adjusted according to the relevant regulations and the level of regional social and economic development. The value of a^z is 1.

(5) Dynamic evaluation and compensation based on ecological carrying capacity: comparing the changes of ecological carrying capacity of coastal beach areas in different years, and taking the difference as the basis of compensation, it is the evaluation of the degree of residents' cooperation with the ecological construction of the reserve and the work efficiency of the management department of coastal beach areas, as well as the ecological compensation and subsidies for the work and the work of the management department of coastal beach areas. Calculation method is:

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$$ER = \sum_{i=1}^{n} \left[d_i(n) \times h_i(n) \times f_i(n) \right] \quad \text{(Eq.11)}$$

In the formula, $d_i(n)$ represents the dynamic evaluation compensation value; $h_i(n)$ represents the total ecological carrying capacity of the beach area in different years; $f_i(n)$ represents the dynamic ecological compensation adjustment coefficient, which can be adjusted according to the relevant regulations and the level of regional social and economic development (Yang et al., 2019). The value of $f_i(n)$ is 1 in this article.

Results and discussion

Select the experimental area, and use the quantitative analysis method of ecological compensation for coastal beach areas designed in this paper based on the ecological footprint changes to quantitatively analyze the area.

Overview of the study area

The experimental research area is located in Taizhou City, Zhejiang Province, China, on the southern edge of the northern subtropical zone. It has a maritime monsoon climate with four distinct seasons. The total area of reclamation is 25 374 hm^2, which is located in the geometric center of the metropolis and the geographical position is superior. The annual sunshine duration is 2048.4 hours, the total annual solar radiation is 468 608 J/cm^2, the average temperature is 16°C, and the frost-free period is 244 days. The annual precipitation is 1272.8 mm, and the average annual runoff is 5.122×108 m^3. East to southeast wind prevails in summer and northwest to north wind prevails in winter. The east wind prevails throughout the year. The average wind speed is 3 m/s and the annual windy day is 9.6 days. The planning and construction period of the new area is from 2010 to 2030. Before the start of development in 2010, there is a vast tidal flat with an average tidal range of 2.1 m over the years. The construction of the area will be completed in 2030. The topographic map is shown in the figure (*Fig. 1*) below:

Figure 1. *The topography of the study area*

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Data sources

Data sources: (*Eq.1*) the results of the Eighth National Forest Inventory (*Eq.2*) According to the first-hand data obtained from the interview, investigation and field investigation of the Landscaping Bureau, bureau of statistics, forest construction ecological zone, public welfare forest protection zone and relevant forestry experts in the study area, the current situation of ecological compensation in the study area is obtained according to the above data sources, as shown in *Table 1*.

Table 1. *Current status of ecological compensation in the study area*

Project	Current status of ecological compensation
Total forest area	258.37 million hm^2
Forest conservation investment	An average of 9.35 US dollars/hm^2, most of the investment is national investment, a small part is provincial public welfare forest investment
Natural forest	754,100 hm^2, with an investment of 15.40 million US dollars
Forest land not listed as public welfare forest	132.59hm^2
Other inputs	3.86 million US dollars

According to the forest resource inventory data released by the State Forestry Administration, the forest area of the study area is 2,583,700 hm^2, including 1,984,400 hm^2 collective forests and 597,700 hm^2 state-owned forests.

According to formula (*Eq.6*) and formula (*Eq.7*), the value of the ecosystem service function of the study area is obtained, as shown in *Table 2*.

Table 2. *The value of ecosystem services in the study area*

Energy category	Quantity/J	Emergy conversion rate	Emergy
Tidal energy	1.08×10^{18}	1093	1.08×10^{20}
Surface wind energy	1.35×10^{18}	3964	2.03×10^{17}
Solar energy	1.67×10^{14}	54128	1.94×10^{20}
Surface wind energy	4.59×10^{17}	3654	7.24×10^{19}
Rainwater chemical energy	3.21×10^{14}	7892	4.17×10^{18}
Evapotranspiration	1.09×10^{17}	11258	1.53×10^{18}
Organic matter loss energy	8.52×10^{15}	2648	2.57×10^{20}

Evaluation of the effectiveness of ecological compensation in beach areas

In the quantitative analysis of the effectiveness of ecological compensation system at the county (District) level, the first thing to do is to choose the analysis method. The appropriate analysis method will often achieve twice the result with half the effort. At present, there are many methods to evaluate the effect in academic circles, such as factor analysis, analytic hierarchy process, principal component analysis, fuzzy comprehensive evaluation, regression analysis, etc. Ecological compensation system is a system involving multiple interest groups such as government, social organizations and farmers. It is an important part of ecological protection mechanism with ecological resources, environment and economic benefits as the main content, relevance among

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interest groups as the link, and complex index system as the evaluation scale. In order to evaluate the effect of ecological compensation, it is necessary to clarify the contribution value of each index of ecological compensation system to ecological protection. In order to facilitate in-depth study, this paper uses the principal component analysis method to analyze the effect of ecological compensation in coastal beach area.

If there are A samples and select B indicators ($B<a$), each indicator can be understood as a variable, that is, b indicators. In fact, there are b variables in the evaluation model, and the set of variables can be expressed as $B=\{b_1,b_2,...,b_n\}$, the principal component analysis method is to combine b indicators into a linear distribution to generate a new evaluation indicator system, denoted as $F=\{f_1, f_2,.., f_n\}$. This newly generated indicator system can retain most of the original information, and the indicators are independent of each other. The specific steps for evaluating the effect of ecological compensation in beach areas are as follows:

(1) Simplify the initial data according to standardization requirements. The purpose is to eliminate the dimensional problem, which can be expressed by formula (*Eq.12*):

$$m_i = \sum_{i=1}^{n} r_i \eta_i \tag{Eq.12}$$

In the formula, m_i represents the standardized value; r_i represents the initial data; η_i represents the average value of the sample.

(2) Using the correlation system matrix κ of the standardized data to find the eigenvectors and eigenvalues, the eigenvectors and eigenvalues can be obtained from equation $(\kappa - m_i)^2 = 0$.

(3) Determine the number of principal components to be evaluated, and then obtain the variance contribution rate and the cumulative contribution rate.

If the t-th component is V_t, its variance contribution rate is the ratio of its variance to the variance of all components. It can be seen that the greater the contribution value, the greater the amount of information. The cumulative contribution rate refers to the ratio of the variance of the first t principal components to the variance of the principal components, and its calculation formula is:

$$T_Q = \frac{\sum_{i=1}^{n} t_{ci}}{\sum_{i=1}^{n} g_i} \tag{Eq.13}$$

The formula (*Eq.13*) expresses the size of the amount of information contained in the first t principal components. Under normal circumstances, the number of principal components is determined based on the amount of information of the first t principal components. In actual calculations, the evaluation basis is the cumulative contribution rate of the first t principal components. This formula can be understood as the first t

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principal components only occupy a part of the amount of information. The first t principal components can be determined by formula (*Eq.14*):

$$\eta_t = a \times h \times P + b \times C + c \times B \qquad \text{(Eq.14)}$$

It can be concluded that the cumulative evaluation index is:

$$T_{zi} = \sum_{i=1}^{n} t_{zi}(\eta_t) \qquad \text{(Eq.15)}$$

(4) After the weighted average of t principal components is processed, the comprehensive evaluation score can be obtained. In order to make the score more intuitive, the comprehensive evaluation data can be normalized.

Quantitative analysis of ecological compensation in beach areas

Based on the evaluation process of the effect of ecological compensation in the coastal area, a quantitative analysis of the effect of ecological compensation in the coastal area is carried out. The specific results are as follows.

(1) Ecological footprint status of coastal areas

According to the above calculation formulas of ecological footprint and ecological carrying capacity and the evaluation process of ecological compensation effect in beach areas, and using the data sources in section 3.2 to calculate the ecological footprint of the study area from 2010 to 2020, the results are shown in *Table 3*.

Table 3. *Ecological footprint of coastal areas*

Years	Ecological footprint per capita hm^2/person	Per capita ecological carrying capacity hm^2/person	Ecological surplus	Amount to GDP ratio/%
2010	752.3	4.01	-2017.2	0.19
2011	683.1	3.95	-1954.3	0.23
2012	701.5	4.13	-954.5	0.24
2013	699.3	3.69	-1028.7	0.21
2014	671.5	4.28	-1596.3	0.18
2015	652.8	3.71	-1254.3	0.15
2016	720.8	3.64	-947.2	0.17
2017	741.8	3.32	-984.0	0.20
2018	690.5	4.15	-856.9	0.19
2019	715.0	3.67	-847.1	0.19
2020	726.3	4.08	-1010.8	0.17

According to *Table 3*, the ecological footprint per capita in the study area in 2010 is 752.3 hm^2, the per capita ecological capacity is 4.01 hm^2, and the per capita ecological surplus is -2017.2. From the horizontal comparison, the per capita ecological footprint

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and ecological surplus level are higher than the average level of the western provinces in China, while the per capita ecological footprint is lower than that of the western provinces in China; From the vertical comparison, the level of ecological surplus in 2020 is significantly increased compared with that of 2010.

(2) The ecological carrying capacity of the study area

Fig. 2 shows the ecological carrying capacity of the study area from 2010 to 2020.

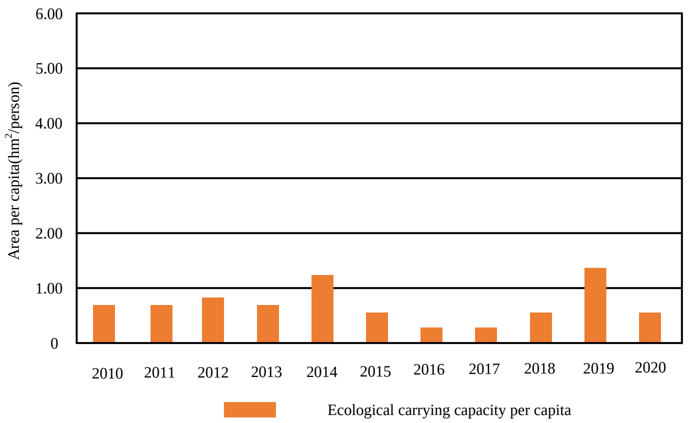

Figure 2. *The ecological carrying capacity of the study area from 2010 to 2020*

It can be seen from *Fig. 2* that the per capita ecological carrying capacity of the study area is lower than the national average, which shows that the region needs to rely on the ecological carrying capacity of economically underdeveloped regions to support the local consumption load.

(3) Comprehensive evaluation of the effect of ecological compensation in the study area

The comprehensive score of the actual effect of ecological compensation in the study area from 2010 to 2020 can be calculated by using the evaluation method of ecological compensation effect in coastal beach area. See *Table 4* for specific data. In order to facilitate comparison, we should normalize the data, and convert all the comprehensive scores into the values between 0-1. The closer the score is to 0, the worse the ecological compensation effect is, and the closer to 1, the better the ecological compensation effect is.

Table 4. *Comprehensive evaluation of ecological compensation effect in the study area*

Years	Before normalization	After normalization
2010	0.23	0.78
2011	0.31	0.80
2012	0.35	0.83
2013	0.38	0.85
2014	0.40	0.86
2015	0.41	0.86
2016	0.43	0.91
2017	0.43	0.94
2018	0.49	0.95
2019	0.51	0.96
2020	0.53	1.00

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The results show that the effect of ecological compensation after normalization is better than that before normalization. It is worth mentioning that this score is relative, not absolute. The above analysis of the actual effect of ecological compensation in the study area also reflects the effect of the implementation of ecological compensation policy in the study area since 2010 to a certain extent. According to the scores in *Table 4*, the development track of ecological compensation effect can also be predicted, and the results are shown in *Fig. 3*.

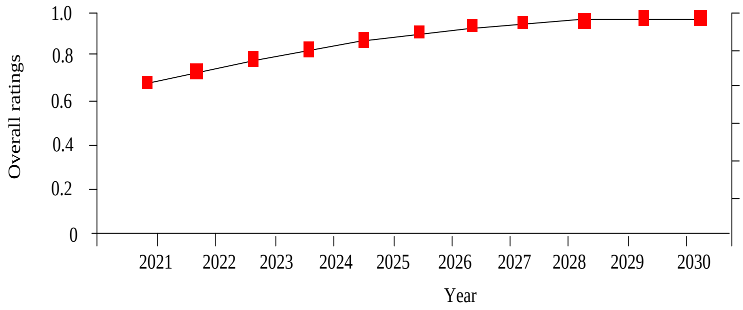

Figure 3. *Forecast of ecological compensation effect*

(4) Calculation results of ecological footprint per capita

Fig. 4 shows the calculation results of the ecological footprint per capita in the study area.

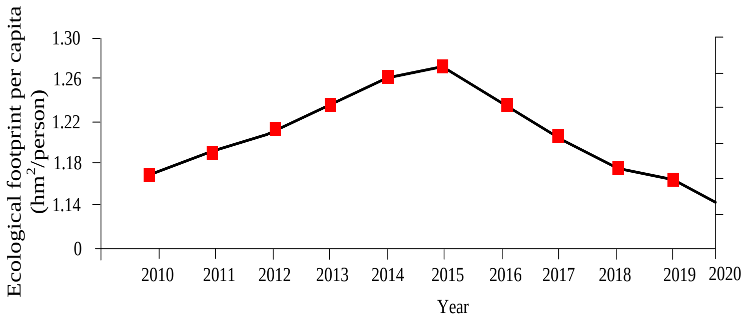

Figure 4. *Ecological footprint per capita in the study area*

According to *Fig. 4*, the per capita ecological footprint of the study area showed an upward trend from 2011 to 2015, and a downward trend from 2016 to 2018. On the one hand, over the past five years, with the development of social economy, people's production and life style and consumption structure are changing. The demand of residents in the study area for meat, aquatic products and milk is gradually increasing. The demand for pork increases from 32 Kg per capita to 35.7 Kg per year, and the demand for aquatic products increases from 5.4 Kg to 7.1 Kg per year. The demand for food crops has changed little, and the demand for other consumer goods has also changed to varying degrees, resulting in changes in the ecological footprint. On the other hand, since 2016, the government has strengthened the protection of resources and environment, people's awareness of resource conservation has gradually improved, some consumer goods have been intensively used, and the per capita consumption has

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decreased. The most obvious performance is the demand for raw coal, which has decreased from 1.39Kg per capita to 1.09 Kg per year, leading to a significant decline in per capita ecological footprint.

Conclusion

On the basis of absorbing the existing research results, this paper proposes a quantitative analysis method of ecological compensation in coastal beach areas based on changes in ecological footprint. The research results show that this method has the characteristics of strong practical pertinence. This paper takes the ecological red line layout along the beach area as a breakthrough point in the research, upholds the concept of environmental sustainable development, and aims to improve the ecological compensation mechanism to evaluate the effectiveness of the ecological red line regional ecological compensation in the study area. The results show that the ecological surplus in the study area in 2020 has a substantial increase compared with the per capita ecological surplus in the study area in 2010; the per capita ecological carrying capacity of the study area is lower than the national average; the effect of ecological compensation after normalization is obviously better the effect of ecological compensation before normalization. It shows that this method can realize the accurate analysis of the study area and provide a reference for the ecological development path of the area. Although the evaluation method in this article can realize the evaluation of the local human ecological footprint, it has not yet considered the impact of the development of industrial manufacturing on the data. This aspect will be studied in the future and a more accurate evaluation model will be proposed.

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