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RESEARCH PAPER

Quantitative Analysis and Study on the Maximum Bearing Capacity of Global Ecosystem to Disposable Plastic Products

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Abstract

Disposable or disposable plastic products not only bring economic benefits, but also pose a great threat to the environment. In order to explore the environmental carrying capacity of plastic waste and solve the problem of environmental carrying capacity of plastic waste, a series of models was established to study the bearing capacity of global ecosystem to disposable plastic products. First of all, based on the experimental data, 12 indicators were evaluated through principal component analysis (PCA) algorithm, such as the source of waste, the severity of the current waste problem and the availability of resources for waste disposal. The K-means clustering analysis was carried out to the original data. Under the appropriate index system, combined with the index and its impact on the environment, a multivariate nonlinear regression model was established. It was estimated that the maximum amount of disposable or disposable plastic waste that can be safely reduced worldwide was 3.87bts. To define the level of environmental security, a new comprehensive environmental index model was generated by integrating Nemelo index method, Bonferroni operator testing, index compilation and other methods. Therefore, plastic waste must be reduced to 4.22 billion tons to achieve the level of environmental safety. Moreover, according to the theory of fuzzy mathematics, the qualitative indicators have been evaluated and explain the differences in the effectiveness of plastic restrictions between China and France.

Keywords Disposable plastic · Bearing capacity · Multiple nonlinear regression · Environmental index

1 Introduction

Disposable plastic products have a major impact on business activities and our lives and there is no doubt about their benefits. It is not only used widely in many aspects of life, but also easy to make because of its low cost and simple manufacturing process (Yuan 2009; Gautam et al. 2020). Although the rapid rise of the plastic industry has boosted economic development, it faces a variety of problems. On the one hand, a pile of disposable plastic products is hard to be resolved in nature, which results in the flooding of plastic waste (Lim et al. 2018; Plastics Europe 2019; Chen et al. 2021; Ranjan et al. 2021). Harmful plastic has blocked thousands of animals' airways and stomachs, which eventually delivered toxic chemicals to humans through the food chain (Rigamonti et al. 2014). An increasing number of people gradually become aware of the destruction of disposable plastic products to the ecological environment (UNEP 2016, 2017, 2019; Boucher et al. 2019). Therefore, how to control plastic waste and improve the management of plastic waste worth our consideration.

Resources are the basis of human survival, and human activities will cause changes in the ecological environment, resulting in certain pollution (Gautam and Caetano 2017). The use of resources and the carrying capacity of the environment have a certain limit, which is the mark of the environmental carrying capacity. Therefore, sustainable development must be built on the basis of environmental carrying capacity, and the study of environmental carrying capacity has important theoretical and practical significance.

The term "carrying capacity" is originally used to refer to the ability of ground strength to carry loads on buildings, a concept borrowed from geology. The concept of carrying capacity was first put forward in ecology by Parker and Burgess (1921) pointing out that ecological carrying capacity is

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the maximum number of a certain individual that can survive under certain specific environmental conditions (). In the second half of twentieth century, with the rapid development of national industry, there are many problems, such as the shortage of resources, the rapid growth of population and the deterioration of environment. Under the background of the research on the bearing capacity to become a hot spot in the research of various problems, at the same time related theory and research method of bearing capacity and get further development were evaluated.

Many scholars have explored the theory of carrying capacity, mainly focusing on resources and environment, and the connotation of carrying capacity has been gradually improved. Seid (1999) based on the theory of the logistic equation and Malthus' population bearing capacity of foundation pointed out the ecology of ecological carrying capacity is more focused on the system pressure and the corresponding population and application in the field of human activity in the bearing capacity is to be human values, ecosystem dynamics and management practices such as complex normative concept. Del Monte-Luna et al. (2004) proposed the definition of carrying capacity applicable to any level from population to biosphere, that is, carrying capacity is the limit of biological development or growth at each level determined by the dependence between the limited resources and the consumers of these resources. Graymore (2010) developed and tested a new method applicable to regional sustainability, proposed the sustaining human carrying capacity (SHCC), and evaluated the sustainability of the region by considering the pressure of human activities on the ecosystem of the region (Graymore et al. 2010). Lane (2010) compared a series of existing carrying capacity assessment methods by adopting system constraints, dynamic response, regional boundary demarcation and other criteria, combined the successful components of different authors and collected relevant data, aiming to propose a comprehensive model to evaluate population carrying capacity. Ati-Aoudia and Berezowska-Azzag (2016) defined water resource carrying capacity as the limit of human activities that can be sustained by available water resources according to the connotation of water resource carrying capacity, and evaluates the population that water resources can maintain in the domestic household consumption pattern in Algeria.

In this paper, a try has been made to establish a series of models to study the bearing capacity of global ecosystem to disposable plastic products with taking to account the following assumptions and justification. People all over the world support the policy of reducing plastic waste and actively cooperate. All countries are willing to assume their responsibilities on a fair basis. In short term, the garbage treatment policies of various countries will not change. The garbage data published by various countries are true and effective and there is no concealment.

2 Maximum Environmental Carrying Capacity Model

2.1 Construction of Index System and Data Processing

2.1.1 Index System

First, 57 initial indicators were selected to measure the environmental carrying capacity. Because there are too many related indicators, which is not conducive to further analysis, the principal component analysis method was used to reduce the number of indicators and avoid information loss as much as possible. The selection of indicators is based on the following four aspects:

(1) Existing damage speed

In the process of burning waste plastic, a large number of harmful gases enter the air and pollute the atmosphere. Therefore, air quality was considered as an indicator to measure the degree of air pollution. Micro-plastics mainly refer to plastic particles with particle sizes less than 5 mm. They have small size, strong hydrophobicity, relatively stable properties and can exist in the environment for a long time. According to many previous studies, the impact of micro-plastics on water resources and soil could be evaluated using its amount.

(2) Causing damage

Waste plastics is easy to release a variety of greenhouse gases and the longer the exposure time is, the more gases will be released. Besides, the process will not stop once triggered. Although the waste plastics does not release CO2, it still has a fatal impact on the greenhouse effect due to the amount plastics waste. EASTEWASTE model based on LCA was implemented to simulate the landfill and burning of waste plastics, so that the impact of waste plastics on human toxicity was considered via water and human toxicity via soil.

(3) Local restraint

It is known that waste plastics are harmful to the atmosphere, water resources and soil. Therefore, the required indicators could be considered in reverse according to the above ideas. In the government's measures to improve air quality, expanding green area is the most common one. Moreover, it can be easily observe the air quality according to the green area of urban built-up areas. Hence, the sewage treatment capacity and land reclamation area can be very intuitive to see the government measures to help the environment.

(4) Natural recovery speed
The environment itself has some kind of ability to repair for the damage that has been caused. Therefore, in this study the purification capacities of air, soil and water were used as the measurement indicators.

2.2 Data Sources and Processing

Collecting sufficient and effective data is the basis for developing a complete indicator system. The China Statistics Bureau, National Data Network and OEDC data, were searched and found 12 indicators to measure the environmental carrying capacity and plastic pollution. SPSS was applied to cluster the data.

Data availability is a very important issue. No measure can provide an effective assessment if it is based on unreliable data. However, some data is inevitably lost because not all data is fully provided by the official website. Therefore, to improve this situation, the following methods were proposed to improve the existing data: (I) Delete data with obvious deviations or too many missing parts; (II) if the data of the preceding and following items can be obtained, take the average and fill in the missing part; (III) if the two sets of data are highly similar, take the data in one set and replace the missing data in the other set; and (IV) use interpolation in other cases.

Due to the different dimensions of these indicators, data comparison cannot be carried out directly. Hence, all data are converted to numbers between 0 and 1 through a dimensionless transformation to standardize the information. Through the investigation, the indicators can be divided into three categories: cost indicators, benefit indicators and moderate indicators. Among these three types of indicators, the smaller the cost indicator, the better; the benefit indicators are just the opposite; and the moderate indicators are better if they are closer to a specific value. Based on this, normalize the three types of data in the following different ways.

Cost indicators:

$$x_{ij} = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}} \tag{1}$$

Benefit indicators:

$$x_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}} \tag{2}$$

Moderate indicators:

$$x_{ij} = \begin{cases} 1 - \frac{c - x_{ij}}{\max\left\{c - x_j^{\min}, x_j^{\max} - c\right\}} & x_{ij} < c \\ 1 & x_{ij} = c \\ 1 - \frac{x_{ij} - c}{\max\left\{c - x_j^{\min}, x_j^{\max} - c\right\}} & x_{ij} > c \end{cases} \tag{3}$$

2.3 Maximum Environmental Carrying Capacity Model

2.3.1 Model Establishment

Environmental carrying capacity is an important indicator used to estimate the maximum amount of single-use or disposable plastic products that can be safely reduced, which is related to the combined effects of existing damage, ongoing damage, local intervention, natural recovery speed and other factors. There are complex interactions among various environmental factors, which make it difficult to analyze the environmental carrying capacity. Many scholars use neural networks to predict it, but neural networks cannot obtain the explicit expressions of the models during the process of prediction. This practical application brings inconvenience. Therefore, the relevant analytical models are necessary.

Multivariate nonlinear theory can better handle the nonlinear relationship between the dependent variable and their respective variable. A nonlinear function relationship can be established according to mathematical statistics. The most commonly used parameter estimation method is the nonlinear least square method, which uses the linear function to approximate the nonlinear function, and obtains the optimal solution of the parameters by iterating this process continuously.

The formal description of the multiple nonlinear regression analysis model is:

$$Y = f(X, \beta) + \varepsilon \tag{4}$$

whereβ is a constant term, which represents the estimated value of the overall average value of Y when all independent variables are 0, and n in $\beta_1, \beta_2, \ldots, \beta_n$ represents regression coefficients.

The function of the sum of residual squared is:

$$S(\beta) = \sum_{i}^{n} \left[Y_i - f\left(X_i, \beta\right)\right]^2 \tag{5}$$

Using the first-order Taylor expansion approximation gets:

$$S(\beta) = \sum_{i=1}^{n} \left[Y_i - f\left(X_i, \beta\right) - \overline{X}_i\left(\beta_l\right)\left(\beta - \beta_1\right)\right]^2 \tag{6}$$

$$\overline{X}_i(\beta_1) = \frac{df(X_i, \beta)}{d\beta} | \beta_i \tag{7}$$

For a given initial value, $\overline{X}_i(\beta_l)$ is definitely computable, so the sum of the residuals squared of the formal linear regression is expressed by $S(\beta)$. The recurrence relation is obtained from the least squares estimate:

$$\beta_{n+1} = \beta_n + \left[\overline{X}(\beta_n)'\overline{X}(\beta_1)\right]^{-1}\overline{X}(\beta_n)'\left[Y - f(X_n, \beta)\right] \tag{8}$$

According to the scatter diagram and the related references, the correlation analysis is carried out with SPSS, and the impact of environmental factors is appropriately added. However, in some models, due to the weak correlation, the environmental factors were eliminated. The final fitted models are shown in Table 1.

In the above equations, the coefficients are determined. Finally, the analytical formula for the maximum environmental load model was obtained:

$$C = \frac{e^{\lambda_0 + \sum_{i=1}^{4} \lambda_i x_i}}{1 + e^{\lambda_0 + \sum_{i=1}^{4} \lambda_i x_i}} \tag{13}$$

2.3.2 Model Inspection

Coefficient of determination (R^2), root mean square error (RMSE) and relative error (RE) tests evaluated the fitting effect on the environmental carrying capacity model.

$$R^2 = \frac{\sum_{i=1}^{n} (\hat{y}_i - \overline{y})^2}{\sum_{i=1}^{n} (y_i - \overline{y})^2} \tag{14}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (\hat{y}_i - y_i)^2}{n}} \tag{15}$$

$$RE = \frac{RMSE}{\overline{h}} \times 100 \tag{16}$$

where $\hat{y}$. = the predicted value of each indicator, $\overline{y}$ = the average of each indicator, n = the sample size (Yang 2018).

Table 1 Fitted models for environmental factors

Models	Function	Eqs
Existing damage	$x_1 = \frac{k}{1+ae^{-bx_{11}-cx_{12}-dx_{13}}}$	(9)
Causing damage	$x_2 = e^{ax_{21}^2+bx_{22}+cx_{23}+d} + g$	(10)
Local intervention	$x_3 = ax_{31}^3 + bx_{32}^2 + cx_{33}^2 + d$	(11)
Natural recovery	$x_4 = a + b\ln(cx_{41} + dx_{41} + gx_{41} + h$	(12)

3 Result and Discussion

3.1 Definition of Environmentally Safe Level

First, the environmentally safe level should be defined before discussing to what extent plastic waste. Nemelo comprehensive environmental index (NCEI) was used to rate the environmental situation and then use the model in the first question to compute the specific amount of waste plastic that should be reduced. NCEI is a combination of normal distribution properties and Nemelo index (NI), Bonferroni mean operator (BMO) and index compiling method (ICM), and is a new improved definition method.

Based on the standardized data, the property was used that the data obey the normal distribution to construct the environmental carrying capacity index (ECCI) of a single indicator. $P_i = S_i / \sum S_i$ satisfy $P_i \sim N(\mu, \sigma^2)$ where S_i is the real data of a single indicator, and μ and σ are their mathematical expectations and standard deviations.

As it often appears in actual research, some countries or regions perform poorly on a particular indicator, but the average level of various indicators is below the safe line. This problem was solved well by using the NI. The following is the calculation formula:

$$P_s = \sqrt{\frac{\overline{P}_i^2 + P_{i\max}^2}{2}} \tag{17}$$

where $P_s, \overline{P}_i, P_{i\max}$ are the comprehensive environmental indexes, the average value of a single environmental index and the maximum value of single environmental index, respectively. This method combines the mean value with the maximum value and can highlight the role of a poor indicator.

However, due to the difference between social environment and natural environment, different indicators have different impacts in different countries or regions. Here the Bonferroni operator was introduced for weighting. This operator can better eliminate the mutual influence and dependence between indicators. Besides, let the results be fairer and more objective. What is more, it has a good application in group decision-making. The following is the calculation formula:

$$y_i = \left(\frac{\sum_{k,l=1,k\neq l}^{m} (w_k x_{ik})^p \cdot (w_l x_{il})^q}{\sum_{k,l=1,k\neq l}^{m} (w_k)^p \cdot (w_l)^q} \right)^{\frac{1}{p+q}} \tag{18}$$

Finally, the improved formula was obtained as follows:

$$\hat{P} = \frac{\sum_{i=1}^{n} y_i P_s}{\sum_{i=1}^{n} y_i} \tag{19}$$

Table 2 Five states of global plastic waste

Rating	Score	Plastic waste
	%	billion tons
Excellent	99.7	2.33
Good	95.4	2.46
Safe	84.2	2.69
Bad	61.8	3.02
Terrible	51.3	3.61

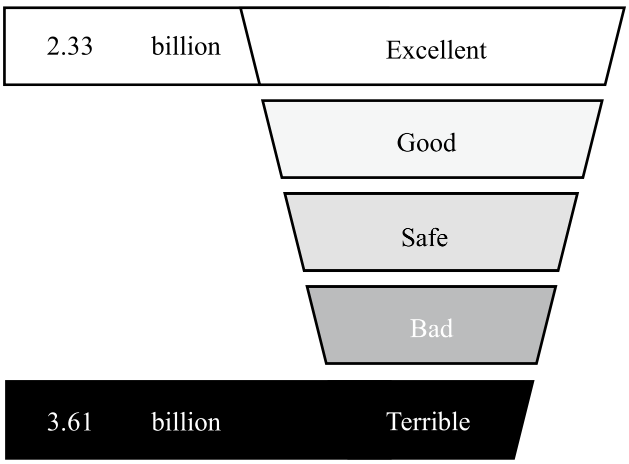

Fig. 1 Different levels of global plastic waste

MATLAB programming was used to solve the above model, and then, the waste amount of disposable plastic products was deduced by substituting the model. The results are shown in Table 2 in the form of percentage:

According to the developed model, the amount of plastic waste allowed by the environmentally safe level is 69.51% of the maximum environmental carrying capacity of the earth. In terms of current global plastic waste, it would at least reduce 4.22 billion tons to achieve an environmentally safe level (Fig. 1).

3.2 Quantification of Qualitative Indicators

According to the developed model, the amount of plastic waste allowed by the environmentally safe level is 69.51% of the maximum environmental carrying capacity of the earth. In terms of current global plastic waste, it would at least reduce 4.22 billion tons to achieve an environmentally safe level.

In this model, U was used to represent the factor set to measure the comprehensive environmental index obtained in the previous question and recorded as:

$$U = \{u_1, u_2, \dots, u_p\} \tag{20}$$

Due to the different levels of index evaluation, V was considered to represent the factor set to measure the comprehensive environmental index obtained in the previous question. It is recorded as:

$$V = \{v_1, v_2, \dots, v_q\} \tag{21}$$

In general, the role of the comprehensive environmental index in the overall assessment varies from country to country. The evaluation results not only are related to the comprehensive environment index of each country, but also depend on the social environment and natural environment of each country to a large extent. Therefore, it is necessary to determine the weight distribution among various factors, which is a fuzzy vector on U, it is recorded as

$$A = [a_1, a_2, \dots, a_n] \tag{22}$$

a_i express $i-th$ country weight, and it meet $\sum_{i=1}^{n} a_i = 1$.

For the index of u_i, the evaluation grade is a fuzzy subset of V. The evaluation of the index u_i recorded as:

$$R_i = [r_{i1}, r_{i2}, \dots, r_{im}] \tag{23}$$

It is a U to V fuzzy relation matrix

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \tag{24}$$

R was incorporated to get the fuzzy transformation:

$$T_R : F(U) \to F(V) \tag{25}$$

Through this transformation, the overall evaluation results can be obtained $B = A \cdot R$ The comprehensive evaluation can be regarded as the fuzzy vector on V

$$B = [b_1, b_2, \dots, b_n] \tag{26}$$

3.3 Determine Weights

Here, the entropy weight method was used to determine the weights between the indicators and use the order relation analysis method to analyze the relationship between the indicators and ratings. For the related data that have been normalized, the following matrix is obtained:

$$X_{ij} = \begin{array}{c} index1 \\ index2 \\ \vdots \\ \vdots \\ indexM \end{array} \begin{bmatrix} X_{11} & X_{12} & \cdots & \cdots & X_{1m} \\ X_{21} & X_{22} & \cdots & \cdots & X_{2m} \\ \vdots & \vdots & \ddots & & \vdots \\ \vdots & \vdots & & \ddots & \vdots \\ X_{n1} & X_{n2} & \cdots & \cdots & X_{nm} \end{bmatrix} \tag{27}$$

At this time, r_j has information entropy

$$e_j = -\sum_{i=1}^{m}\left[\left(\frac{X_{ij}}{\sum_{i=1}^{m} X_{ij}}\right)\cdot \ln\left(\frac{X_{ij}}{\sum_{i=1}^{m} X_{ij}}\right)\right] \tag{28}$$

Obviously, the smaller the entropy value of an index is, the more information it provides; the greater the role it plays in the comprehensive evaluation, the greater its weight. On the contrary, the larger the entropy, the smaller the weight. Then do normalization processing: $e_j' = -e_j/\ln m$.

Then the normalization treatment is performed:

$$r(E,S) = \frac{\sum_{i=1}^{n}\left(e_i' - \overline{e}\right)\left(s_i - \overline{s}\right)}{\sqrt{\sum_{i=1}^{n}\left(e_i' - \overline{e}\right)^2}\cdot\sqrt{\sum_{i=1}^{n}\left(s_i - \overline{s}\right)^2}} \tag{29}$$

S is a standard index entropy obtained by clustering analysis of a large number of data. Finally, an optimization model was used to determine the entropy weight:

$$\begin{aligned} max &= \sum_{k=1}^{m} r_k W_k \\ &\sum_{k=1}^{m} W_k = 1 \\ W_k &\geq 0, k = 1, 2, \ldots, m \end{aligned} \tag{30}$$

According to the above optimization model, the final weight W_k。 was estimated.

Order relation analysis is an improved analytical hierarchy process. Compared with the analytical hierarchy process, this method is not only simpler to in calculation, but it also does not need a consistency test. The basic principle is to rank the importance of evaluation indexes, then judge the importance of adjacent indexes according to the ranking results and finally get the weight of evaluation indexes. The calculation formula is as follows:

$$\overline{w}_m = \left(1 + \sum_{l=2}^{m}\prod_{k=l}^{m} r_k\right)^{-1} \quad \overline{w}_{j-1} = r_j\overline{w}_j \tag{31}$$

M is the number of indicators, and r_j refers to the indicator of $j-1$ compared with indicator.

3.4 Results of Important Indicators

The importance ratings of various indicators were obtained using MATLAB programming. The most important of these is the promulgation of policies. Due to the limited space, there are some important indicators below (Table 3).

Table 3 Result of important indicators

Index	Importance score	Importance rank
Policy promulgation	0.1096	Most important
Availability of plastic alternatives	0.0845	Important
Waste resource availability	0.0801	Important
Impact on citizen life	0.0773	Less important
Effect on environment	0.0771	Less important
Severity of current waste	0.0721	Less important
Source of waste	0.0592	General

3.5 Analysis of Policy Effectiveness Differences

At present, more than 40 countries and regions around the world have stipulated the use of plastic bags, including three policies: banned, partially banned and restricted use. France and China have selected from developed countries and developing countries. Their policies are analyzed and compared as follows:

As early as 1975, France began to implement a "restriction order for plastics," which has been modified and improved many times since then, and now, it has become matured. These measures are very effective. As of 2017, the use of disposable plastic products has been reduced by 50%; as of 2019, the use of disposable plastic products was reduced by 80%.

Compared to France, “plastic restriction order” in China started many years later. It has also made a significant impact. Before 2007, the consumption of plastic bags in China was as high as 1 million tons. After 2015, the number has decreased to about 700,000 tons.

Although both of them aim to reduce the amount of plastics, the "restriction orders" formulated by China and France are still very different. For example, France has banned using single-use or disposable plastic bags completely since 2016, while China only requires shopping malls to charge extra fee for plastic bags. Since white pollution has seriously endangered environmental quality, why cannot China implement the same policy as France? After conducting an analysis based on China’s national conditions, we found that if China also implements this measure, it will cause a lot of inconvenience to the people’s production and life, and may even cause a series of economic fluctuations.

France’s "plastic limit order" is about 30 years earlier than China. In these 30 years, France has developed many alternatives to plastic bags. However, in China, although domestic biodegradable plastic technologies have made breakthroughs recently, the related physical characteristics and production costs of the product are still far behind the traditional plastic bags. Therefore, it is difficult to completely replace them.

4 Conclusion

To understand the relationship between single-use or disposable plastic products and the ecological environment, it is necessary to establish a maximum environmental carrying capacity model to determine the maximum levels of single-use or disposable plastic product waste. By selecting appropriate indicators, a complete maximum environmental carrying capacity indicator system was established. Subsequently, the established model was applied to solve the problems and propose modifications to improve it. The maximum environmental carrying capacity model was established and the principal component analysis method was used to screen out 12 indicators. Then, the impact of each indicator on the maximum environmental carrying capacity and use multiple nonlinear regression analysis to obtain the maximum environmental carrying capacity model were analyzed. A maximum environmental carrying capacity evaluation model was constructed in this study. The modified Nemelo index was implemented to define the environmental safety level and improve the maximum environmental carrying capacity index to 15. The entropy weight method (EWM) and the order relationship analysis method were used to weight the level. Eventually, the differences in effectiveness of the same policies between France and China were analyzed. According to the solution of the model, the maximum level of single-use or disposable plastic product waste is 3.87 billion tons. However, 6.9 billion tons of plastic waste has been produced globally by the end of 2019, which has already exceeded the maximum environment carrying capacity. Therefore, it should minimize the use of single-use or disposable plastics in all aspects of daily life and production to achieve a safe level in environment.

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