Available online at: epubs.icar.org.in/index.php/IJF

The ecological footprint study of marine fisheries in Liaoning Province of China based on system dynamics

J. S. Yang[1,2], X. W. Pan[1], Z. Q. Yin[1*], J. R. Cui[1,2], P. Q. Sun[1,2], H. F. Gu[1], J. X. Li[1,2], Y. Wang[1] and M. Xu[3]

[1]College of Marine Science and Environment, Dalian Ocean University, Dalian - 116 023, China
[2]College of Fisheries and Life Science, Dalian Ocean University, Dalian - 116 023, China
[3]East China Sea Fisheries Research Institute, Chinese Academy of Fisheries Science, Shanghai - 200 090, China

Abstract

Since the end of the 20th century, with the rapid development of the marine economy, the marine environment of Liaoning Province in China was under tremendous pressure and the fishery resources have been in serious decline. The marine fishing output of Liaoning Province was reduced from 1.502×10^7 t in 2000 to 5.244×10^6 t in 2018. Using STELLA software as the modeling platform, we followed the basic steps of system dynamics modeling (SD model), combined with the principle of ecological footprint of fisheries to establish the SD model of ecological footprint of fisheries in Liaoning Province of China, and applied the fuzzy evaluation method to comprehensively evaluate the ecological carrying capacity of Liaoning marine area. The results show that marine fishery resources in Liaoning Province have been in ecological deficit and unsustainable development. The ecological footprint of fisheries in Liaoning Province has increased from 1.08×10^7 km^2 to 1.88×10^7 km^2 with an average value of 1.60×10^7 km^2 between 2000 and 2018, which is already higher than the ecological carrying capacity of 3.20×10^6 km^2 and about 5 times of the carrying capacity, which means that fishing pressure needs to be reduced to at least 20% of its current level for the ecological footprint of fisheries to rebound and for the ecological deficit to decrease steadily, thus preventing an ecosystem collapse.

*Correspondence e-mail:
zqyin@dlou.edu.cn

Keywords:
Ecological footprint of fisheries; Liaoning fishery resources; System dynamics; STELLA software

Received : 23.04.2023
Accepted : 12.12.2023

Introduction

The ocean is the source of life and has been known as the “natural breadbasket”, “blue oil field” and “treasure trove of resources” (Wang, 2000). Since 1950s, with the increasing exploitation of marine resources, the fishery resources and ecological environment of Liaoning, China, have been affected by the decline in biodiversity, primary productivity and biomass (Zhang *et al.,* 2010), leading to decline in marine fish production from from 1.502×10^7 t in 2000 to 5.244×10^6 t in 2018 (Zhang, 2019). Although several studies have been carried out related to fishery resources in Liaoning (Liu, 2006; Liu *et al.,* 2014), studies on the ecological footprint of fisheries in Liaoning have not been reported so far.

The main methods of ecological carrying capacity assessment are indicator system method, supply and demand balance method, system model method and environmental capacity method (Gao, 2001). At present, the fuzzy comprehensive evaluation method is the most practical in the evaluation of ecological carrying capacity (Wu and Hu, 2020). The ecological footprint was proposed by Canadian ecological economist William Rees in 1992 and after further research and improvement by Mathis Wackernagel, a perfect ecological footprint model was established which became a new method for measuring sustainable development (Rees, 1992). After the concept of ecological footprint was gradually improved, the concept was extended to various fields such as land, energy, transportation, trade and water resources (Rosenberg, 1997; Bicknell *et al.,* 1998; Vuuren and Smeets, 2000; Lenzen and Murray, 2001; Gossling *et al.,* 2002; Turner *et al.,* 2007). When the study of ecological footprint was applied to the field of marine fisheries, it was defined as the area of marine ecosystem occupied by humans to meet their own needs of seafood and marine products (Folke *et al.,* 1998).

System Dynamics (SD) is a discipline that specialises in the study of systems with dynamic complexity using computer simulation methods and is based on feedback control theory. The innovation of this study lies in linking system dynamics and ecological footprint, establishing the SD model of ecological footprint of marine fisheries, analysing and predicting the marine fishery resources and ecological footprint of fisheries and analysing the changes of ecological footprint of fisheries under different fishing pressure.

Materials and methods

Overview of the study area

Liaoning Province has a coastline of 2878.5 km, including 2178.3 km of mainland coastline and 700.2 km of island coastline. The total area of mudflats in Liaoning Province is about 1696 km^2, accounting for 9.7% of mudflats in China, ranking sixth in the country. Among them, the coastal mudflats in Liaodong Bay cover an area of 1,020 km^2, accounting for about 60% and the coastal mudflats in the northern part of the Yellow Sea cover an area of 676 km^2, accounting for about 40%. There are 506 islands, lagoons and reefs in Liaoning Province, including 205 islands with an area of 0.01 km^2 or more, with a total area of 189.21 km^2; the wetlands in the province cover an area of about 2,132 km^2 (Dai, 2007). Liaoning Province has a variety of marine life and rich resources, and there are more than 80 species with high economic value that have been exploited. The average marine fishing yield is about 1×10^6 t. However, since the 1950s, due to overfishing, the fishery resources have been declining over a period of time and the density and quantity of resources have been greatly reduced (Sun, 2011).

SD model construction of fishery ecological footprint

Using STELLA software as the modeling platform, we followed the basic steps of system dynamics modeling, combined with the principle of ecological footprint of fisheries to model and constructed the SD model of ecological footprint of fisheries in Liaoning marine area. The model analysed the changes of ecological footprint of fishery in Liaoning waters in recent years and predicted the development trend of ecological footprint of fishery in the coming years.

The model consists of four modules, which are fisheries resources module, bait module, fisheries ecological footprint module and benefits module. The model was constructed as shown in Fig. 1.

Fisheries resources module

For the biomass of fishery resources, natural reproduction is its replenishment and natural mortality and fishing is its reduction. In the model, the state variable is fishery resource biomass and flow rate variables are natural increment, natural mortality and annual catch. In the simulation of the ecological footprint of fishery in the sea off Liaoning, the year 2000 was set as the initial year and with reference to the results of the analysis of fishery resources in Liaoning based on Bayes method by Li *et al.* (2012). The initial amount of fishery resources in 2000 was set to 3×10^9 kg, the natural reproduction rate was 0.6 and the natural mortality rate was 0.16. The maximum sustainable yield (MSY) of fishery resources in Liaoning is about 140×10^4 t and the fishing effort required to support MSY is about 817771 megawatt (MW), so the fishing effort in 1998 is set to 820 MW in this study, which is converted to fishing pressure 0.5 for the convenience of calculation (Li *et al.,* 2012). The application of the nutrient dynamic method to estimate the environmental holding capacity of fishery resources in Liaoning (Wang *et al.*, 2005) was calculated by using the formula:

$$P = P_0 E^n \qquad (1)$$

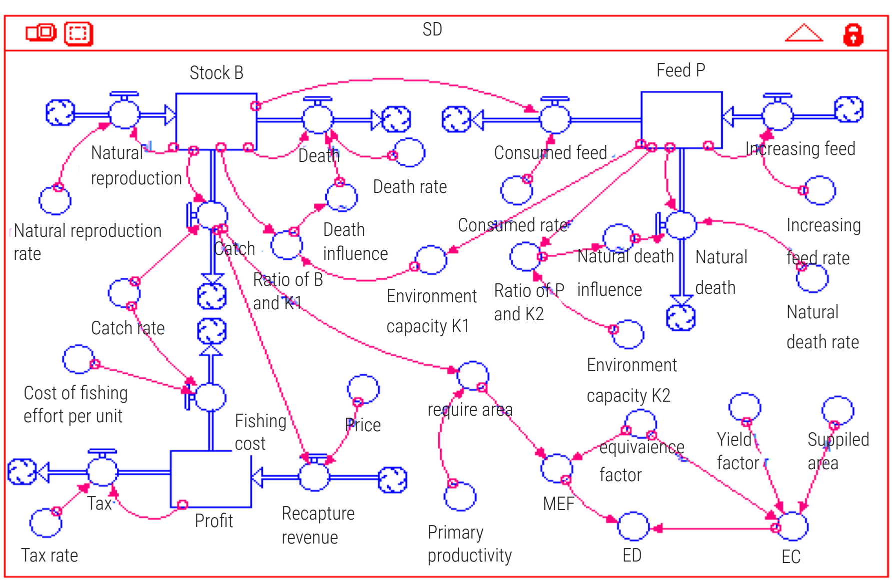

Fig.1. SD model of fishery ecological footprint in Liaoning marine area

where P denotes the biomass of fishery resources, P_0 denotes the phytoplankton production, E is the ecological efficiency, and n is the number of trophic level conversion levels under the same ecological efficiency.

The marine area near Liaoning is an inshore area, the eco-efficiency is taken as 15% and the trophic level conversion level of the estimation object is taken as 3 (Lu *et al.,* 2002). The environmental carrying capacity of fishery resources in the offshore Liaoning calculated by this method is about 6×10^9 kg, which is basically consistent with the results of Li *et al.* (2012).

Bait module

In the bait module, the state variable is the phytoplankton biomass, the replenishment is the natural reproduction of phytoplankton and the reduction is the natural mortality and predated fraction. Phytoplankton act as producers converting energy and nutrients into primary productivity and moving along food webs and food chains. According to the study of primary productivity in Liaoning from 2003 to 2016 by Li *et al.* (2017), the average annual primary productivity of Liaoning marine area is 2361 g C m^{-2} yr^{-1} and the area of Liaoning is 77.284 million km^2, so the annual primary carbon production of this marine area is about 1.83×10^{14} g. According to the conversion of 1 g carbon equivalent to 10 g fresh phytoplankton ratio (Liu *et al.,* 2015), the fresh weight of phytoplankton in this marine area is 1.83×10^{12} kg and the fresh weight of phytoplankton is set as the initial value of phytoplankton biomass. Combined with values from published literature on phytoplankton and the characteristics of phytoplankton in Liaoning waters, the values of natural growth rate and natural mortality of phytoplankton were set to 0.2 (Liu *et al.,* 2012). The average bait requirement of fishery resource to maturity is 0.15 (Shi and Xu, 2010) and so the average bait requirement of fishery resources was set at 0.15.

Income module

In the revenue module, revenue is set as the state variable and here the revenue is assumed to be the marine fishing output value in Liaoning waters and the rise and fall of revenue indicates the profit and loss of Liaoning fisheries economy. Fishing costs, re-capture income and taxes are used as flow rate variables, where fishing costs and taxes represent outflows, indicating a decrease in earnings and re-capture income represents inflows, indicating an accumulation and increase in earnings. In the model, the value of revenue A was arbitrarily set to 1.4×10^7 USD, the tax rate was set to 0.1, the average price of swimming organisms was set to 7.71 USD kg^{-1} (FFA-MoARA, 2020), the fishing catch rate was 0.5 and the variable cost per unit of fishing effort was set to 1.4×10^3 USD.

Ecological footprint module

In the ecological footprint of fisheries module, the equilibrium factor and the required area of fishery waters will directly affect the change in the ecological footprint of fisheries, and the required area of fishery waters will be directly affected by the total annual marine catch and primary productivity; The change of ecological deficit is determined by ecological carrying capacity and ecological footprint of fisheries and the supplied water area, yield factor and equilibrium will be directly related to the change of ecological carrying capacity. Also, for the consideration of ecological safety of fishery waters, 12% of the fishery water area reserved for marine biodiversity was subtracted (Wang and Chao, 2017) and EC was the ecological carrying capacity of fishery (km^2).

Calculation method of ecological footprint of marine fisheries

Marine capture production and mariculture production together constitute the demand for marine fishery resources, and in calculating the ecological footprint of marine fisheries, the area of marine capture (S1) and the area of mariculture (S2) are calculated separately and the area of marine capture and the area of mariculture are transformed into the ecological footprint area of marine fisheries consumption (km^2) by the equivalence factor (WF) (Zhao *et al.,* 2015). The formulae used are:

$$S = S_1 + S_2 \quad \text{.......(2)}$$

$$S_1 = (P_1 + I - E) / Y_1 \quad \text{.......(3)}$$

$$S_2 = (P_2 + I - E) / Y_2 \quad \text{.......(4)}$$

where P_1 = Annual marine capture production (kg), P_2 = Annual mariculture production (kg), I = Annual seafood import (kg), E = Annual seafood export (kg), Y_1 = Primary productivity of marine capture waters and Y_2 = Primary productivity of mariculture waters.

The ecological footprint of fisheries (km^2 $person^{-1}$) is calculated as:

$$EF = S \times WF / N \quad \text{.......(5)}$$

where S is the area of water required for ocean consumption; WF is the equivalence factor and N is the regional population.

Model validation

In this study, the annual marine catch of Liaoning from 2000-2018 was used as an example and the feasibility of the model was tested by applying the historical test method, inputting the parameters required for the model operation into the model, running the simulation with 1998 as the starting year, simulating the annual marine catch from 1998-2017 and comparing the simulated value with the actual value to calculate its deviation (Shi and Xu, 2010), calculated as follows:

$$D_t = \frac{X_t - X_t}{X_t} \times 100\% \quad \text{.......(6)}$$

where, D_t is the deviation; X_t' is the simulated value of catch in year t and X_t is the actual value of catch in year t.

Comprehensive evaluation of fishery ecological carrying capacity

This part applies the fuzzy evaluation method of the plane summation method in the index system method to make a comprehensive evaluation of the ecological carrying capacity. Combining with the actual situation of the marine area near Liaoning, the annual marine fishing volume (u1), population density (u2), fishery employees (u3), total fishery output value (u4), Engel's coefficient (u5) and GDP per capita (u6) are selected as evaluation indicators. Through the collection of statistical data from Liaoning Bureau of Statistics, National Fishery Statistics Network and China Statistical Yearbook in previous years, the data of each indicator was statistically analysed and the raw data of each indicator is presented in Table 1.

Evaluation index selection and grading

According to Peng *et al*. (2019), Wang *et al.* (2020), Wu and Hu (2020) and Ying *et al.* (2022), the degree of influence of each evaluation index on the bearing capacity was divided into three levels, V1, V2 and V3 (Table 2). V1 is in poor condition, indicating that the ecological carrying capacity is close to saturation and the potential for further development is low, which is an unsustainable development state; V3 is in good condition, indicating that the ecological carrying capacity still has more room for development and the biological resources in the region have greater development potential and V2 is the state between V1 and V3, indicating that the exploitation of resources has reached a certain degree and although there is a certain potential for exploitation, the degree of sustainable utilisation is average and the biological resources in the region can meet the basic needs of fisheries development.

Determination of the fuzzy judging matrix R and the set of weights A

The fuzzy matrix R represents the degree of attribution of each indicator to the judging level, *i.e.*, the matrix composed of the affiliation of each indicator (u_i) to the judging level v_j. In this study, the median method was used to calculate the affiliation (Wang, 2011). The values of the affiliation function are fuzzified between the judging levels, k_1 is the critical value of V_1 and V_2; k_3 is the critical value of V_2 and V_3; k_2 is the median value of V_2; $k_2 = (k_1+k_3)/2$ and the critical values of each evaluation index to the judging levels are shown in Table 3.

The formula for the affiliation function of the set of rubrics for evaluation indicators u_1, u_2 and u_5 is as follows (Wu and Hu, 2020):

$$U_{v_1}(u_i) = \begin{cases} 0.5\left(1+\frac{u_i-k_1}{u_i-k_2}\right), & u_i \geq k_1 \\ 0.5\left(1-\frac{k_1-u_i}{k_1-k_2}\right), & k_2 < u_i < k_1 \\ 0, & u_i \leq k_2 \end{cases} \quad \text{.......................................(7)}$$

Table 1. Comprehensive evaluation index of ecological carrying capacity of Liaoning marine area

Year	Marine fishing volume u_1 (t^{-1})	Population density u_2 (person km^{-2})	Fishery employees u_3 ($person^{-1}$)	Total fishery output value u_4 (USD)	Engel's coefficient u_5	GDP per capita u_6 (USD $person^{-1}$)
2000	1501887	286.3514	367198	2476266480	44.25	22868.65
2001	1496053	283.3784	382669	2660511921	42.95	24910.22
2002	1488365	283.9865	427322	2948235624	41.95	26956.52
2003	1479639	284.4595	486604	3389572230	41.35	29595.47
2004	1491192	284.9324	493222	3918088359	42.45	32841.63
2005	1520371	285.2027	504377	4377085554	41.1	39573.53
2006	1481696	284.9324	525190	4821047686	39.4	45799.69
2007	1024408	283.6486	517593	5344460028	39.7	55202.82
2008	1028217	291.5541	712907	5885412342	40.8	65752.88
2009	995312	293.3108	582872	6869244039	38.75	72741.57
2010	1007398	295.6081	566324	7931767181	38.4	87571.26
2011	1061607	296.1486	741995	8971680224	38.35	105262.99
2012	1079288	296.5541	587600	10057089762	37.75	117508.85
2013	1079259	296.6216	592040	11159970547	33.69	128673.06
2014	1076005	296.6892	564931	11667099579	28.35	135325.05
2015	1107857	296.0811	543727	10979044881	28.24	135804.03
2016	553000	295.8108	542554	11753720898	27.49	105478.98
2017	552000	297.027	529930	9420265077	27.39	110535.51
2018	524394	294.527	527043	9147586255	26.77	120550.56

Table 2. Grading value of evaluation index

Evaluation Indicators	V_1	V_2	V_3
u_1 (t^{-1})	>1520371	524394-1520371	<5243094
u_2 (person km^{-2})	>297.03	283.38-297.03	<283.38
u_3 ($person^{-1}$)	<367198	367198-741995	>741995
u_4 (USD)	<2476266478	2476266478-11753720898	>11753720898
u_5	>44.25	26.77-44.25	<26.77
u_6 (USD $person^{-1}$)	<22875.18	22875.18-135806.45	>135806.45

Table 3. Critical value of evaluation index to evaluation grade

Evaluation Indicators	k_1	k_2	k_3
u_1 (t^{-1})	1520371	1022382.5	524394
u_2 (person km^{-2})	297.03	290.205	283.38
u_3 ($person^{-1}$)	367198	554596.5	741995
u_4 (USD)	2476266478	7114993688	11753720898
u_5	44.25	35.51	26.77
u_6 (USD $person^{-1}$)	22875.18	79340.82	135806.45

$$U_{v_3}(u_i)=\begin{cases}0.5\left(1-\frac{u_i-k_3}{k_2-k_3}\right), & k_3<u_i\le k_2\\ 0.5\left(1+\frac{k_3-u_i}{k_2-u_i}\right), & u_i\le k_3\\ 0, & u_i>k_2\end{cases} \quad (8)$$

$$U_{v_2}(u_i)=\begin{cases}0.5\left(1-\frac{u_i-k_1}{u_i-k_2}\right), & u_i>k_1\\ 0.5\left(1+\frac{k_1-u_i}{k_1-k_2}\right), & k_2<u_i\le k_1\\ 0.5\left(1+\frac{u_i-k_3}{k_2-k_3}\right), & k_3<u_i\le k_2\\ 0.5\left(1-\frac{k_3-u_i}{k_2-u_i}\right), & u_i\le k_3\end{cases} \quad (10)$$

The formulae for the affiliation function of the set of evaluation indicators u_3, u_4 and u_6 rubrics is as follows.

$$U_{v_1}(u_i)=\begin{cases}0.5\left(1+\frac{u_i-k_1}{k_i-k_2}\right), & u_i\le k_1\\ 0.5\left(1-\frac{k_1-u_i}{k_1-k_2}\right), & k_2>u_i>k_1\\ 0, & u_i\ge k_2\end{cases} \quad (11)$$

$$U_{v_2}(u_i)=\begin{cases}0.5\left(1-\frac{u_i-k_1}{u_i-k_2}\right), & u_i<k_1\\ 0.5\left(1+\frac{k_1-u_i}{k_1-k_2}\right), & k_2>u_i\ge k_1\\ 0.5\left(1+\frac{u_i-k_3}{k_2-k_3}\right), & k_3>u_i\ge k_2\\ 0.5\left(1-\frac{k_3-u_i}{k_2-u_i}\right), & u_i\ge k_3\end{cases} \quad (12)$$

$$U_{v_3}(u_i)=\begin{cases}0.5\left(1-\frac{u_i-k_3}{k_2-k_3}\right), & k_3>u_i\ge k_2\\ 0.5\left(1+\frac{k_3-u_i}{k_2-u_i}\right), & u_i\ge k_3\\ 0, & u_i<k_2\end{cases} \quad (13)$$

The degree of attribution of each evaluation index to the judging level r_{ij} is derived from the above affiliation formula, *i.e.*, the comprehensive evaluation matrix R is as follows:

$$R=\begin{Bmatrix} r_{11} & r_{12} & \cdots & r_{1n}\\ r_{21} & r_{22} & \cdots & r_{2n}\\ \cdots & \cdots & \cdots & \cdots\\ r_{m1} & r_{m2} & \cdots & r_{mn}\end{Bmatrix} \quad (14)$$

Since the relationship between the indicators is not equally weighted and they have different degrees of influence on the ecological carrying capacity, it is necessary to determine the weights of the indicators and the set of weights is denoted by A (Wu and Hu, 2020; Ying *et al.*, 2022).

$A = \{a_1, a_2, \ldots a_j\}, (a_1 + a_2 + \ldots + a_j = 1, 0 \le a_i \le 1)$ .... (15)

According to the magnitude of the influence of each evaluation index on the ecological carrying capacity of Liaoning marine area, the influence of each evaluation factor on the ecological carrying capacity is assigned with the weight matrix A = (0.3, 0.1, 0.1, 0.2, 0.1, 0.2) with reference to the national ecological carrying capacity evaluation standard.

The evaluation results are represented by vector B, which is the synthesis of the set of weights A and the fuzzy evaluation matrix R. The formula used for calculation is as follows:

$B = A \cdot R = (b_1, b_2, \ldots b_j, \ldots, b_m)$ .... (16)

The formula for calculating the composite score value is:

$$a=\frac{\sum_{j=1}^{3} b_j^k a_j}{\sum_{j=1}^{3} b_j^k} \quad (17)$$

where, a is the comprehensive score value of matrix B. The larger the value of a, the greater the regional ecological carrying capacity, k highlights the role of the dominant grade, which is determined as 1 here.

Results

Current status of ecological footprint of marine fisheries in Liaoning

The estimated ecological footprint of fisheries in Liaoning (Table 4, Fig. 2) shows that the average value of ecological footprint of fisheries in Liaoning over the past 20 years was 1.60×10^5 km^{-2}. The average ecological carrying capacity was 3.20×10^4 km^{-2}, the average ecological deficit was 1.27×10^5 km^{-2} and the average per capita deficit was 0.02970 km^{-2} when 12% of area for biodiversity conservation is deducted. The ecological footprint of fisheries is about 5 times the ecological carrying capacity. The results show that since 2000, the ecological footprint of fisheries in Liaoning Province has been higher than the ecological carrying capacity of the sea and the sea has been in ecological deficit, and the exploitation of fishery resources in Liaoning has exceeded its carrying capacity and the fishery resources are in an unsustainable state.

System dynamics model simulation results

STELLA software was applied to simulate the historical data of marine catch in Liaoning from 2000 to 2017 and the actual and simulated values were brought into Equation (6) and the calculation results are shown in Table 5 and Fig. 3. The deviation between the simulated and real values of annual marine catch in Liaoning waters is small, and the deviation was in the range of -0.18 to 0.15%, which is consistent with the 95% confidence interval.

Simulation of ecological footprint of fisheries under different fishing pressure

In order to understand the influence of the factors in the model on the ecological footprint of the fishery, a sensitivity analysis was done on the factors in the model using STELLA software and it was found that fishing pressure had a greater influence on the ecological footprint of the fishery. Therefore, in this study, fishing pressure was used as a decision variable and the impact of its variation on fishery biomass, fishery ecological footprint and ecological deficit were simulated for four scenarios of 0.2, 0.4, 0.6 and 0.8, respectively. With 2000 as the simulation base year and 2024 as the simulation report year, the length of the simulation time series was 25 years and the model was run and the results are depicted. In Fig. 4. The

Table 4. Ecological footprint of Liaoning fishery in 1998-2017

Year	Marine fishing yield ($x10^7$ kg)	Mariculture yield ($x10^7$ kg)	Fishery ecological footprints ($x10^5 km^{-2}$)	Ecological carrying capacity ($x10^4 km^{-2}$)	Ecological deficits ($x10^4 km^{-2}$)	Deficits per capita (km^{-2})
2000	150.1887	152.1197	1.84812	2.5387	15.9425	0.0381
2001	149.6053	160.887	1.84312	2.5578	15.8734	0.03785
2002	148.8365	178.2422	1.83789	2.6217	15.7573	0.03749
2003	147.9639	182.8818	1.82844	2.8237	15.4607	0.03672
2004	149.1192	197.0379	1.84569	2.8755	15.5814	0.03695
2005	152.0371	212.1253	1.88443	2.9582	15.8861	0.03764
2006	118.3523	177.6384	1.46984	2.8466	11.8518	0.02775
2007	116.6194	185.5365	1.45077	2.8507	11.6569	0.02712
2008	114.0353	202.098	1.42344	2.8838	11.3507	0.02631
2009	113.212	214.3168	1.41636	3.3158	10.8478	0.02499
2010	118.2672	231.4694	1.48137	3.5767	11.237	0.02568
2011	122.2774	243.5184	1.53258	3.5537	11.7722	0.02686
2012	125.7664	263.5627	1.57937	3.6752	12.1185	0.02761
2013	128.3693	282.7609	1.61526	3.9295	12.2231	0.02784
2014	140.63	289.0525	1.7647	3.9028	13.7443	0.0313
2015	137.7857	294.1965	1.73158	3.9118	13.404	0.03059
2016	83.8495	308.55	1.08397	3.4492	7.3905	0.01688
2017	83.74	308.1374	1.08255	3.4492	7.3763	0.01688

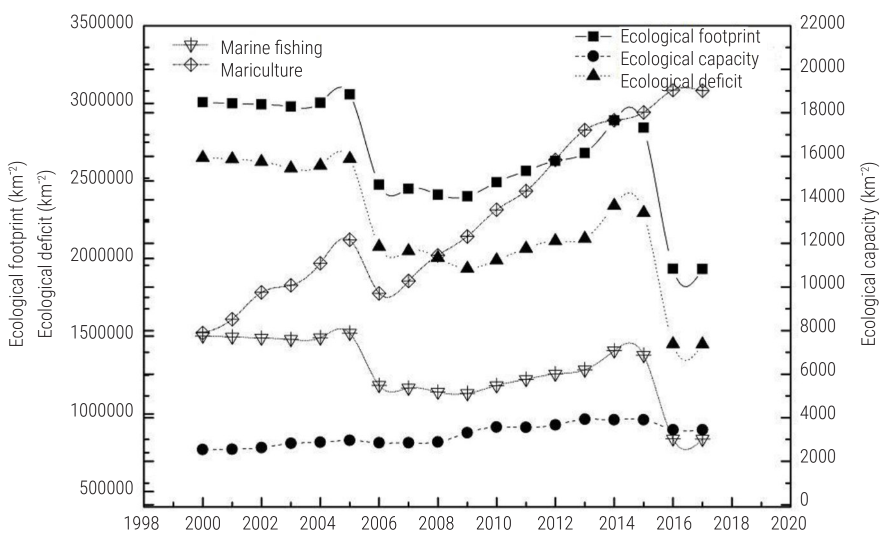

Fig. 2. Changes of fishery ecological footprint and ecological deficit in Liaoning Province

curves 1, 2, 3 and 4 in Fig. 4 indicate the changes of each variable when the fishing pressure changes from small to large, respectively.

Through the model debugging simulation, the current fishing pressure is about 0.47. Under such fishing pressure, the variables are bounded to change between curve 2 and curve 3 and the variables will maintain a relatively stable state for a short period of time, but with the passage of time, the biomass of fishery resources and the ecological footprint of fishery will show a decreasing trend, which is not conducive to the sustainable development of marine resources.

Fuzzy evaluation results of ecological carrying capacity of fishery in Liaoning

The calculation results of the correlation degree matrix R of each index from 2000 to 2018 are as follows:

$$R_{2000} = \begin{bmatrix} 0.519 & 0.418 & 0 \\ 0 & 0.718 & 0.282 \\ 0.5 & 0.5 & 0 \\ 0.5 & 0.5 & 0 \\ 0.5 & 0.5 & 0 \\ 0.5 & 0.5 & 0 \end{bmatrix} \quad R_{2001} = \begin{bmatrix} 0.476 & 0.418 & 0 \\ 0 & 0.5 & 0.5 \\ 0.5 & 0.5 & 0 \\ 0.5 & 0.5 & 0 \\ 0.5 & 0.5 & 0 \\ 0.5 & 0.5 & 0 \end{bmatrix}$$

$$R_{2002}=\begin{bmatrix}0.468 & 0.524 & 0\\ 0 & 0.544 & 0.465\\ 0.5 & 0.5 & 0\\ 0.5 & 0.5 & 0\\ 0.5 & 0.5 & 0\\ 0.5 & 0.5 & 0\end{bmatrix}\quad R_{2003}=\begin{bmatrix}0.459 & 0.541 & 0\\ 0 & 0.579 & 0.421\\ 0.181 & 0.819 & 0\\ 0.402 & 0.598 & 0\\ 0.334 & 0.666 & 0\\ 0.440 & 0.560 & 0\end{bmatrix}\quad R_{2004}=\begin{bmatrix}0.471 & 0.529 & 0\\ 0 & 0.614 & 0.386\\ 0.164 & 0.836 & 0\\ 0.345 & 0.655 & 0\\ 0.397 & 0.603 & 0\\ 0.412 & 0.588 & 0\end{bmatrix}\quad R_{2005}=\begin{bmatrix}0.5 & 0.5 & 0\\ 0 & 0.634 & 0.366\\ 0.134 & 0.866 & 0\\ 0.295 & 0.705 & 0\\ 0.320 & 0.680 & 0\\ 0.352 & 0.648 & 0\end{bmatrix}$$

$$R_{2006}=\begin{bmatrix}0.461 & 0.539 & 0\\ 0 & 0.614 & 0.386\\ 0.078 & 0.922 & 0\\ 0.247 & 0.753 & 0\\ 0.223 & 0.777 & 0\\ 0.297 & 0.703 & 0\end{bmatrix}\quad R_{2007}=\begin{bmatrix}0.002 & 0.998 & 0\\ 0 & 0.520 & 0.480\\ 0.099 & 0.901 & 0\\ 0.191 & 0.809 & 0\\ 0.240 & 0.760 & 0\\ 0.214 & 0.786 & 0\end{bmatrix}\quad R_{2008}=\begin{bmatrix}0.006 & 0.994 & 0\\ 0.099 & 0.901 & 0\\ 0 & 0.578 & 0.422\\ 0.133 & 0.867 & 0\\ 0.303 & 0.697 & 0\\ 0.120 & 0.880 & 0\end{bmatrix}\quad R_{2009}=\begin{bmatrix}0 & 0.973 & 0.027\\ 0.228 & 0.772 & 0\\ 0 & 0.925 & 0.075\\ 0.026 & 0.974 & 0\\ 0.185 & 0.815 & 0\\ 0.058 & 0.942 & 0\end{bmatrix}$$

$$R_{2010}=\begin{bmatrix}0 & 0.985 & 0.015\\ 0.396 & 0.604 & 0\\ 0 & 0.969 & 0.031\\ 0 & 0.912 & 0.088\\ 0.165 & 0.835 & 0\\ 0 & 0.927 & 0.073\end{bmatrix}\quad R_{2011}=\begin{bmatrix}0.039 & 0.961 & 0\\ 0.435 & 0.565 & 0\\ 0 & 0.5 & 0.5\\ 0 & 0.8 & 0.2\\ 0.162 & 0.838 & 0\\ 0 & 0.770 & 0.230\end{bmatrix}\quad R_{2012}=\begin{bmatrix}0.057 & 0.943 & 0\\ 0.465 & 0.535 & 0\\ 0 & 0.912 & 0.088\\ 0 & 0.683 & 0.317\\ 0.128 & 0.872 & 0\\ 0 & 0.662 & 0.338\end{bmatrix}\quad R_{2013}=\begin{bmatrix}0.057 & 0.943 & 0\\ 0.470 & 0.530 & 0\\ 0 & 0.9 & 0.1\\ 0 & 0.564 & 0.436\\ 0 & 0.896 & 0.104\\ 0 & 0.563 & 0.437\end{bmatrix}$$

$$R_{2014}=\begin{bmatrix}0.054 & 0.946 & 0\\ 0.475 & 0.525 & 0\\ 0 & 0.972 & 0.028\\ 0 & 0.509 & 0.491\\ 0 & 0.590 & 0.410\\ 0 & 0.504 & 0.496\end{bmatrix}\quad R_{2015}=\begin{bmatrix}0.086 & 0.914 & 0\\ 0.430 & 0.570 & 0\\ 0.029 & 0.971 & 0\\ 0 & 0.584 & 0.416\\ 0 & 0.580 & 0.420\\ 0 & 0.5 & 0.5\end{bmatrix}\quad R_{2016}=\begin{bmatrix}0 & 0.528 & 0.472\\ 0.411 & 0.589 & 0\\ 0.032 & 0.968 & 0\\ 0 & 0.5 & 0.5\\ 0 & 0.459 & 0.541\\ 0 & 0.769 & 0.231\end{bmatrix}\quad R_{2017}=\begin{bmatrix}0.5 & 0.5 & 0\\ 0.5 & 0.5 & 0\\ 0.066 & 0.934 & 0\\ 0 & 0.752 & 0.248\\ 0 & 0.535 & 0.465\\ 0 & 0.724 & 0.276\end{bmatrix}$$

$$R_{2018}=\begin{bmatrix}0 & 0.5 & 0.5\\ 0.317 & 0.683 & 0\\ 0.074 & 0.926 & 0\\ 0 & 0.781 & 0.219\\ 0 & 0.5 & 0.5\\ 0 & 0.635 & 0.365\end{bmatrix}$$

Table 5. Comparison of annual simulated and actual values

Year	Actual value (kg)	Simulated output (kg)	Deviation
2000	1501887000	1467804000.00	-0.022693452
2001	1496053000	1423769880.00	-0.048315882
2002	1488365000	1381056783.60	-0.072098051
2003	1479639000	1339625080.09	-0.094627081
2004	1491192000	1299436327.69	-0.128592208
2005	1520371000	1260453237.86	-0.170956801
2006	1183523000	1222639640.72	0.033051019
2007	1166194000	1185960451.50	0.01694954
2008	1140353000	1150381637.96	0.008794328
2009	1132120000	1115870188.82	-0.014353435
2010	1182672000	1082394083.15	-0.084789288
2011	1222774000	1049922260.66	-0.141360333
2012	1257664000	1018424592.84	-0.190225217
2013	1283693000	987871855.05	-0.230445399
2014	1406300000	958235699.40	-0.318612174
2015	1377857000	929488628.42	-0.325409946
2016	838495000	901603969.57	0.075264575
2017	837400000	874555850.48	0.044370493
2018	790300000	814911280.19	0.031141693

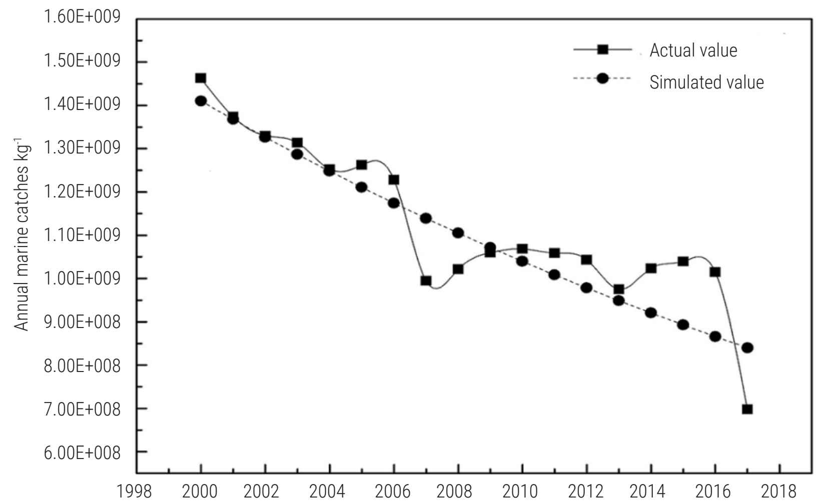

Fig. 3. Deviation of the real value from the simulated value

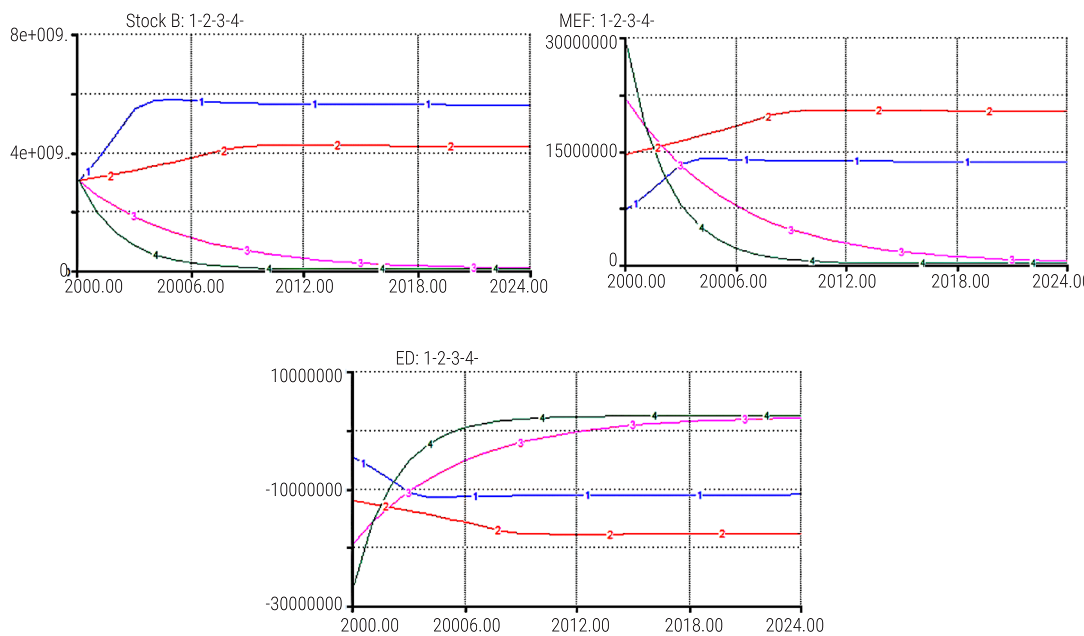

Fig. 4. Effects of different catch rates on fishery biomass, marine ecological footprint (MEF) and ecological deficit (ED). The catch rate is 0.2 for curve 1, 0.4 for curve 2, 0.6 for curve 3 and 0.8 for curve 4

The results of the ecological carrying capacity evaluation of fisheries in Liaoning from 2000-2018 are shown in Table 6. As can be seen from Table 6 and Fig. 5, the mean values of the ecological carrying capacity of Liaoning marine area to V_1, V_2 and V_3 affiliation from 2000-2018 are 0.267416, 0.496995 and 0.235611, respectively and the affiliation to V_2 is significantly greater than that of V_1 and V_3, indicating that the exploitation of fishery resources in Liaoning marine area has reached a certain scale and although the current resources can meet the needs of economic development, the potential for further development is small and the sustainable development capacity of the resources is average. The changes in the affiliation of the ecological carrying capacity of fisheries in Liaoning to V_1, V_2 and V_3 during the period from 2000 to 2018 can be divided into 2 stages. The first stage is 2000-2006, and the affiliation degree of this stage to V_1, V_2 and V_3 remains stable, and the values of V_1 and V_2 are around 0.4 and the value of V_3 is smaller, indicating that the ecological carrying capacity of Liaoning marine area has been in a critical state during this period, which is not conducive to sustainable development. During this period, Liaoning's marine economy is in a sustained growth phase and the leading marine industries are evolving. The second stage of growth rate is 2006-2018 and the affiliation to V_2 in this period is significantly larger than that of V_1 and V_3 and the decreasing trend of V_1 i and the increasing trend of V_3 is obvious, which indicates that the carrying capacity of Liaoning marine area has turned better in this period, but the comprehensive score value is low indicating that Liaoning marine area is still in the over-exploitation state.

Table 6. Comprehensive assessment of Liaoning's fishery ecological carrying capacity in 2000-2018

Year	V1	V2	V3	Overall rating value
2000	0.4008	0.4325	0.1667	0.605345
2001	0.3967	0.4367	0.1667	0.60349
2002	0.39	0.4433	0.1667	0.600485
2003	0.3825	0.4508	0.1667	0.59711
2004	0.3925	0.4408	0.1667	0.60161
2005	0.4167	0.4167	0.1667	0.612489
2006	0.3842	0.4492	0.1667	0.597865
2007	0.2308	0.5769	0.1923	0.517325
2008	0.2325	0.4605	0.307	0.466475
2009	0.2286	0.6857	0.0857	0.564305
2010	0.2252	0.6757	0.0991	0.556745
2011	0.1667	0.5	0.3333	0.42503
2012	0.2	0.6	0.2	0.5
2013	0.2	0.6	0.2	0.5
2014	0.1667	0.5	0.3333	0.42503
2015	0.1667	0.5	0.3333	0.42503
2016	0.1669	0.4407	0.3923	0.39856
2017	0.1667	0.4167	0.4167	0.387511
2018	0.1667	0.4167	0.4167	0.387511
Average	0.267416	0.496995	0.235611	0.514311

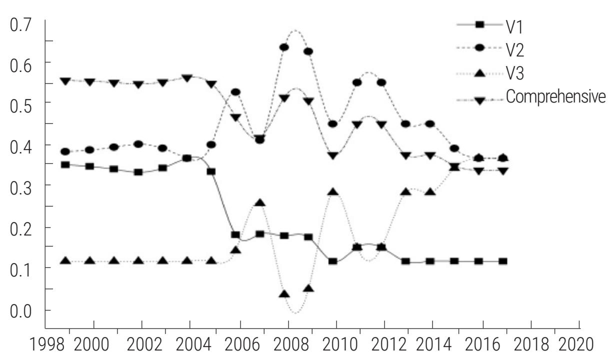

Fig. 5. Comprehensive evaluation of fishery ecological carrying capacity in Liaoning during 2000-2018

Discussion

In this study an ecological footprint prediction model based on back propagation (BP) neural network was constructed for Liaoning using the method detailed by Li *et al.* (2007). The results showed that the relative error between the ecological footprint results predicted by the BP neural network and the actual ecological footprint values was 0.69%, and the accuracy of the model prediction was more accurate than the traditional multiple regression statistical model (Li and Zhou, 2007). The results of this study are consistent with the development trend of the national ecological deficit investigated by Chen *et al***.** (2006). Based on the current research, the change trend of the ecological footprint in the offshore waters is in an inverted U-shaped parabolic shape, which may be related to the "zero growth policy" and fishing boat repurchase measures implemented across the country at that time (Zhu *et al*., 2007). These studies prove that the fishery ecological footprint model can quantify the effect of human activities on the degree of ecological interference.

Unlike earlier studies which carried out static analysis of fishery ecological footprint, this study combines System Dynamics future fishery ecological footprint trend simulation and Liaoning fishery simulation for better outputs which can be used by fisheries management and environmental protection agencies of the region.

The calculation results of the ecological footprint of marine fishery in Liaoning Province from 2000 - 2018 showed that the marine fishery resources in Liaoning Province have been in a state of ecological deficit, and the fishery resources are in a state of unsustainable development. The extremely high fishing pressure will reduce the biomass of fishery resources, increase the fishery ecological footprint and finally cause the collapse of fishery ecosystem. The existing fishing pressure is at higher side which would imbalance the sustainable development of Liaoning fishery resources, and should be reduced to at least 20% of the current fishing pressure, so as to reduce the ecological deficit.

The affiliation of ecological carrying capacity of Liaoning marine area to V_2 is obviously larger than that of V_1 and V_3, and the comprehensive score value keeps decreasing. The exploitation of fishery resources in Liaoning marine area has reached a certain scale, and although the resources can meet the needs of current economic development, the potential for further development is small, and the resources are in an unsustainable development state. In order to realise the sustainable development of Liaoning sea resources, relevant departments should take active measures to govern the sea and develop and utilise marine resources scientifically and reasonably.

The study of ecological footprint of marine fisheries involves many disciplines such as resources, environment and human systems, and its research also integrates the methods and approaches of many disciplines. In future research, it is necessary to strengthen the cross-integration research between fisheries ecological footprint and marine economy, marine management and other disciplines, to realise the dynamic monitoring, data collection and analysis of marine ecological environment, and to improve the accuracy of research results (Jin, 2000).

This investigation was an exploratory study of applying a system dynamics model to the ecological footprint of marine fisheries in Liaoning Province, China. The model only considered the factors related to the four modules of fishery resources, bait, income and ecological footprint, which have a greater impact on the marine fishery ecosystem and some of the parameters were estimated. However, the actual ecological footprint of marine fisheries is much more complex than the model established in this study. The above deficiencies may lead to certain errors in the simulation results of the model. Therefore, we will continue to enrich data and improve model parameters by strengthening social survey and field investigation in the future, so as to make the model more realistic and provide theoretical reference for future management of marine fisheries.

References

Bicknell, Ball, R. J., Cullen, R. and Bigsby, H. R. 1998. New methodology for the ecological footprint with an application to the New Zealand economy. *Ecol. Econ.,* 27: 149-160.

Chen, D. J., Li, P. Y., Du, J., Liu, Y. L. and Xu, X. Y. 2006. The evaluation of sustainable development based on ecological footprint and human development indexment basof marine fishery resources utilisation in China. *Chin. Soft. Sci.,* 5:96-103.

Dai, X. S. 2007. Analysis of marine resources present situation and marine industry development trend in Liaoning Province. Ocean. *Dev. Manage.,* 24(2): 129-134.

Folke, C., Kautsky, N., Berg, H., Jansson, A. and Troell, M. 1998. The ecological footprint concept for sustainable seafood production: A review. *Ecol. Appl.,* 8(1): S63–S71.

FFA-MoARA 2020. Fisheries and Fishery Administration of Ministry of Agriculture and Rural Affairs of China. *China fisheries yearbook.* China Agricultural Press, Beijing, China, pp. 24-34.

Gao, J. X. 2001. *Exploration of sustainable development theory: Theory, methodology and application of ecological carrying capacity.* China Building Materials Industry Press, Beijing, China, 63 p.

Gossling, S., Hansson, C., Hörstmeier, O. and Saggel, S. 2002. Ecological footprint analysis as a tool to assess tourism sustainability. *Ecol. Econ.,* 43: 199-211. https://doi.org/10.1016/S0921-8009(02)00211-2.

Jin, X. S. 2000. The dynamics of major fishery resources in the Bohai Sea. *J. Fish. Sci. Chin.,* 07(04): 22-26.

Liu, J. 2006. On the sustainable development of fishery in Liaoning. *J. DL. Mar. Uni:* Soc. Sci. Ed., 5(3): 42-46.

Liu, X. Z., Dong, J., Yu, X. G., Sun, M., Wang, B. and Wang, X. L. 2014. Structure of fishery resources in coastal waters of Liaoning Province. *Mar. Fish.,* 36(04): 289-299.

Lenzen, M. and Murray, S. A. 2001. A modified ecological footprint method and its application to Australia. *Ecol. Econ.,* 37: 229-255. https://doi.org/10.1016/S0921-8009(00)00275-5.

Li, J. Q., Nie, X. J., Ye, C. C. and Yin, Z. Q. 2012. A review of the dynamics of fishery resources in the Bohai Sea based on Bayes' method. *J. Nat. Resour.,* 27(04): 643-649.

Li, X, M. and Zhou, J. X. 2007. Forecasting of urban total ecological footprint based on BP Neural Network-A case study of Wuhan. *Environ. Sci. Technol.,* 08: 68-70+119.

Li, X. X., Yuan, J. G. Liu, X. J. and Li, Z. Y. 2017. Spatial and temporal variation of net primary productivity in the Bohai Sea based on MODIS data. *Ecol. Env.. Sci.,* 26(05): 785-793.

Liu, L. L., Wan, R., Wang, X. J., Wang, S. J. and Wang, Y. Z. 2012. Analysis of the effect of fishery resources proliferation and release based on system dynamics model. *S. Chin. Fish. Sci.,* 08(01): 16-23.

Liu, J., Yu, Z. G., Zang, J. Y., Sun, T., Zhao, C. Y. and Ran, X. B. 2015. Distribution characteristics and income and expenditure assessment of organic carbon in the Yellow Bohai Sea. *Adv. Earth. Sci.,* 30(05): 564-578. https://doi.org/10.11867/j.issn.1001-8166.2015.05.564

Lu, Z. B., Dai, Q. S. and Yan, Y. M. 2002. Productivity and maximum sustainable yield of fishery resources in Taiwan Strait and its adjacent waters. *J. Fish. Sci. Chin.,* 09(02):28-32.

Peng, B., Li, Y., Elahi, E. and Wei, G. 2019. Dynamic evolution of ecological carrying capacity based on the ecological footprint theory: A case study of Jiangsu *Province. Ecol. Indic.,* 99: 19-26. https://doi.org/10.1016/j.ecolind.2018.12.009.

Rees, W. E. 1992. Ecological footprints and appropriated carrying capacity: What urban economics leaves out. *Environ. Urban.,* 4(2): 121-130. https://doi.org/10.1177/095624789200400212

Rosenberg, J. 1997. Ecological Footprint. *Science,* 275: 1049 - 1053.

Shi, M. J. and Xu, Z. M. 2010. An analysis of the sustainable development in Zhangye Municipality based on SD model. *J. Glaciol. Geocryol.,* 32(4): 851-859.

Sun, J. F. 2011. Countermeasures for the development of Liaoning fishery economy. *LN Econ.,* 3:75-77.

Turner, K., Lenzen, M., Wiedmann, T. O. and Barrett, J. 2007. Examining the global environmental impact of regional consumption activities -Part 1: A technical note on combining input-output and ecological footprint analysis. *Ecol. Econ.,* 62: 37-44. https://doi.org/10.1016/j.ecolecon.2006.12.002.

Vuuren, D. P. and Smeets, E. 2000. Ecological footprints of Benin, Bhutan, Costa Rica and the Netherlands. *Ecol. Econ.,* 34: 115-130.

Wang, Y. H. 2000. The natural protein "granary" of the ocean in the 21st century. *Meat. Hyg.,* 11: 35-36.

Wang, Z. H., Li, C. H. and Jia, X. P. 2005. Application of primary productivity to estimate fishery resources in the northern South China Sea. *Prog. Fish. Sci.,* 26(03): 9-15.

Wang, Z. C. and Chao, M. 2017. Simulation of the marine ecological footprint of Jiangsu coastal waters using STELLA model. *J. Fish. Sci. Chin.,* 24(03): 5765-5786. https://doi.org/10.3724/SP.J.1118.2017.16224

Wang, Y., Zhou, Q. and Wang, H. 2020. Assessing ecological carrying capacity in the Guangdong-Hong Kong-Macao Greater Bay area based on a three-dimensional ecological footprint model. *Sustainability,* 12(22): 9705. https://doi.org/10.3390/su12229705

Wu, X. and Hu, F. 2020. Analysis of ecological carrying capacity using a fuzzy comprehensive evaluation method. *Ecol. Indic.,* 113: 106243. https://doi.org/10.1016/j.ecolind.2020.106243

Ying, H., Chen, S. and Mao, Y. 2022. Research on marine ecological carrying capacity of Ningbo City in China based on system dynamics. *Sustainability*, 14(8): 4568 https://doi.org/10.3390/su14084568

Zhang, X. L., 2019. *China fisheries yearbook 2019.* China Agriculture Press, Beijing, China, pp.50-55.

Zhang, Y. G., Han, Z. L., Liu, K. and Liu, G. C. 2010. Research on the development and utilisation of marine resources--Liaoning Province as an example. *J. Nat. Resour.,* 25(5):785-794.

Zhao, Y. T., Xu, S. N., Qi, Z. H. and Li, C. H. 2015. Review on ecological footprint of fisheries. *Fish. Moder.,* 42(02): 71-75.

Zhu, Y. G., Wan, Rong. and Mu,. Y. T. 2007. The regulations of fishing capacity: traditional methods and substitutional scheme. *Chin. Fish. Econ.,* 5:21-24.

