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Marine ecological security assessment from the perspective of emergy ecological footprint

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Introduction: Marine ecological security assessments are considered as a basis for coordinating marine economic development and ecological protection.

Methods: We propose an assessment method based on the emergy ecological footprint which first measures the emergy of the natural and economic elements of the marine ecosystem. Considering the role of economic, social and waste discharge factors in the marine ecosystem, an ecological security evaluation index is constructed, and a dynamic evaluation is conducted based on long time series data to characterize the change trend of ecological security.

Results: The Guangxi marine ecosystem was selected as the case study, and the ecological security dynamic evaluation was conducted by collecting data from 2008 to 2020. The results show that Guangxi's marine ecosystem has always been in an ecologically secure state, but since 2010, the emergy ecological footprint intensity has been increasing, indicating ecosystem deterioration. Therefore, some targeted suggestions are put forward.

Discussion: This method provides a new assessment tool for marine ecological security evaluation and offers guidance for the sustainable development and utilization of marine ecosystems.

KEYWORDS

ecological security, emergy, ecological footprint, marine economy, assessment

1 Introduction

In recent years, the total output value of the global marine industry has been increasing, and emerging marine industries have developed rapidly (Yin et al., 2022; Ye et al., 2022). The marine economy has become an important part of many national economies and an important contributor to the sustainable development of human society. With the rapid development of marine economy, the contradiction between marine resource development and ecological environment protection has become increasingly prominent (Samhouri et al., 2012; Thushari and Senevirathna, 2020), with negative factors including ocean warming (Gomiero et al., 2018), biodiversity loss (Xu et al., 2017), water and air pollution (Xu et al., 2022), resource depletion (Bax et al., 2021; La Daana et al., 2022), and overfishing (Sumaila and Tai, 2020). The second global marine comprehensive assessment report released by the United Nations in 2021 pointed out that the global ocean surface pH decreased by approximately 0.1 on average, and the acidity increased by approximately 30%. The number of "dead water areas" with extremely low oxygen content in the world's oceans increased from more than 400 in 2008 to nearly 700 in 2019. The annual economic losses caused by overfishing are as high as 88.9 billion dollars. The development of the marine economy has exerted increasing pressure on marine ecosystems, leading to their deterioration as well as threatening and restricting high-quality economic development and the pace of ecological and social transformation (Liu C. et al., 2021).

Global sustainable development goals, such as "carbon peaking" and "carbon neutralization," have imposed new requirements on marine industries, accelerating the transformation and upgradation of the marine economy. Effective use of marine resources, reducing pressure on the environment while maintaining the rapid growth of the marine economy, and improving marine ecological security are significant challenges in the development of the marine economy. As a result, there is an increasingly urgent need to propose a marine ecological security assessment model to support coordinated development of the marine economy, and to offer a theoretical basis for rational and orderly marine development and research. However, the energy flow and material flow involved in the marine ecosystem are various and of different types. How to deal with different flows and construct evaluation indicators to evaluate the marine ecological security scientifically and reasonably is a big challenge.

Since the concept of ecological security was initially put forward (Brown, 1977), an increasing number of scholars have given it attention. During the late 1990s Costanza (1999) developed the eco-economic value system to assess true values of global marine ecosystem services, which focused attention on rational use and protection of marine resources. Marine ecology and industry face many problems. Effective measures must be taken to coordinate the development of marine resources and the protection of the ecological environment to promote the sustainable development of the marine ecological economic system (Koulouri et al, 2022). On the basis of analyzing the ecological, economic and social importance of global coastal areas, Martínez et al. (2007) proposed that to achieve sustainable development of coastal areas, marine ecosystem assessment should be strengthened.

Effectively measuring marine ecological security is challenging, and scholars have adopted different methods to evaluate it. The driver pressure state impact response (DPSIR) and multi-criteria analysis methods are used to estimate the economic value of coastal and marine ecosystem services (Ghermandi et al., 2019). Combined with the technology environment resource economy model and layered DEMATEL method, DPSIR is also used to determine the key factors of marine ranch ecological security systems and conduct sustainability assessments (Du and Li, 2022). Emergy and eco-exergy methods have been proposed to calculate the stock value of natural capital in marine reserves and supplement the economic evaluation based on market standards (Buonocore et al., 2019). An integrated life cycle assessment analysis was used to assess the resource and environmental carrying capacity of China's marine ranches (Wang and Du, 2023). The AHP entropy-based TOPSIS method was used to conduct a dynamic analysis of the marine ecological carrying capacity of Shandong Province, China (Sun et al., 2022). Wang et al. (2021) built a dynamic model of a marine ecological security comprehensive multi-function composite system, conducted data simulations and predictions, and used the Lotka Volterra model to assess the marine ecological security system.

Rees, a Canadian ecologist, first proposed the ecological footprint method to measure ecological security and sustainable development (Rees, 1992), and this was gradually improved by his students Wackernagel and others (Wackernagel and Rees, 1997; Wackernagel and Yount, 1998). This method judges and analyzes the ecological status of a region or system by comparing its ecological footprint with its ecological carrying capacity. The calculation is simple, and the conclusions are easy to understand. It effectively reflects the regeneration and replaceability of natural resources, self-purification, and biodiversity conservation (Zhao et al., 2022), and simplifies and quantifies the complex problem of the interaction between human socio-economic activities and nature. As one of the most influential quantitative methods, this method has gained worldwide attention and application owing to its new perspective and good operability (Geng et al., 2014; Ahmed et al., 2022). In marine ecosystems, this method has been applied to the production of marine products (Folke et al., 1998), the impact of climate change on the ocean (Karani and Failler, 2020), marine fisheries (Lam and Pauly, 2019; Yıldırım et al., 2022), ocean ranches (Du et al., 2022), and ocean cities (Tang et al., 2022).

With the deepening of research, scholars noticed shortcomings in the ecological footprint model, which are mainly reflected in: (1) The parameters used in the ecological footprint method, such as the equivalence factor, yield factor, and global average productivity, are based on the assumption of substitutability between artificial and natural capital. The differences in ecological advantages and time perspective of each region have not been fully considered, resulting in unstable measurement results, which affect the credibility of the method as a standard for measurement and comparison. (2) The ecological footprint method focuses only on the material cycle in the ecosystem and does not consider the impact of intangible factors. It fails to take into account economic, technological, cultural, social, and other factors such as waste discharges, and additionally does not consider the positive feedback and impact of the progress of these factors on ecological carrying capacity. (3) Finally, this method was originally a static analysis method, which assumed that technology, population, material consumption level were all unchanged, it can only reflect the degree of sustainability and security at a certain time, but can not effectively reflect the changes and future trends of ecosystem occupancy over time.

Based on the above analysis, our study instead adopted the emergy ecological footprint method to evaluate marine ecological security. This method was first proposed by Zhao et al. (2005). It combines the emergy analysis theory (Odum, 1988) with the ecological footprint method, discarding the controversial production and equilibrium factors in the ecological footprint method, instead first converting different types and levels of energy into solar emergy values and then using the emergy density to convert each consumption item into a corresponding bio-productive land area, namely the emergy ecological footprint, so that products with different properties can be compared based on a unified unit. The emergy ecological footprint method has been rapidly adopted worldwide owing to its scientific and theoretical basis, strong operability, extensive practicability, and other advantages (Nakajima and Ortega, 2016). Such as industrial ecological footprint (Zadgaonkar and Mandavgane, 2020), regional sustainability (Liu et al., 2022), ecological safety assessment of agricultural ecosystem (Zadehdabagh et al., 2022), biological community (Santos et al., 2021), water resources (Liu Z. et al., 2021).

In our study, when applying the emergy ecological footprint method to evaluate marine ecological security, we considered the role of economic, social, and waste discharge factors in the marine ecosystem and performed a dynamic evaluation based on long time series data. On the one hand, emergy ecological footprint analysis of marine ecosystems enriches relevant research on marine ecological security. On the other hand, it scientifically reveals the operational status, emergy structure characteristics, and ecological security status of marine ecosystems and provides appropriate suggestions for promoting the effective utilization of marine natural resources and the sustainable development of the marine economy.

The following research framework was applied to achieve the objectives of this study: Section 2 introduces the research methods, including the marine emergy ecological carrying capacity (MEEC), marine emergy ecological footprint (MEEF), and marine ecological security assessment indicators. Section 3 uses the Guangxi marine ecosystem as an example for applying this method in practice. Section 4 provides a summary of this paper and discusses the main contents and shortcomings of this study.

2 Research methods

Based on the research of the traditional ecological footprint model, this study proposes an emergy ecological footprint method to evaluate marine ecological security. This method is a combination of ecological footprint and emergy theory. It first uses the emergy conversion rate to convert different types and levels of energy in the ecosystem into comparable emergy standards, namely solaremergy, then introduces the concepts of global energy density and regional energy density, estimating the ecological space required by various natural environmental resources and wastes produced by human beings, and converted it into the area of bio productive land. By comparing the relationship between MEEC and MEEF, it can measure the regional ecological pressure and sustainable development capacity.

This method uses the global emergy baseline of 12.00 E+24 Sej y-1 (Brown and Ulgiati, 2016) to calculate the MEEC and MEEF of the analyzed regional ocean. The calculation of MEEC is based on the traditional calculation of emergy ecological carrying capacity of the natural environment, considering the positive role of human beings in improving regional resources and environmental carrying capacity (Peng et al., 2018) which has increased the socio-economic emergy ecological carrying capacity. MEEF mainly consists of two parts: the marine consumption resource footprint and marine pollution footprint (Xie et al., 2022). By measuring the ratio and difference between the MEEC and MEEF, the impact of human activity intensity on the marine ecosystem can be measured in order to determine the ecological security status of the marine ecosystem. The overall concept of the research method is shown in Figure 1.

2.1 Marine emergy ecological carrying capacity

MEEC refers to the calculation of the sea area from which natural resources can be drawn without degrading its ecological function, it reflects the ability of the natural environment to supply resources and support social development (Hu et al., 2019). Owing to the depletion of non-renewable resources in the process of economic and social development, only renewable natural resources are considered when measuring the emergy ecological carrying capacity. Therefore, the MEEC consists of the emergy ecological carrying capacity of renewable resources ($MEEC_R$) and the emergy ecological carrying capacity of

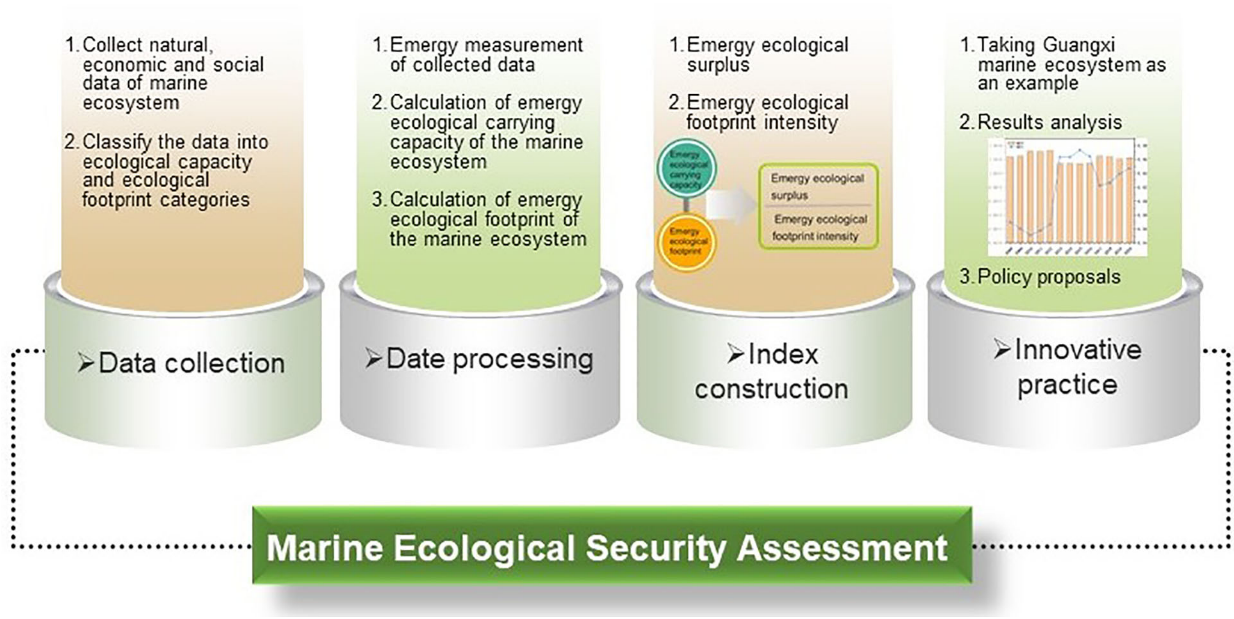

FIGURE 1
Method flow chart.

socio-economic resources ($MEEC_S$). The calculation formula is as follows:

$$MEEC = MEEC_R + MEEC_S \tag{1}$$

2.1.1 Ecological carrying capacity of renewable resources

Renewable natural resources in the marine ecosystem include solar energy, rainwater chemical energy, rainwater potential energy, wind energy, earth rotation energy, tidal energy, and wave energy. The emergy ecological carrying capacity of these renewable resources can be expressed as:

$$MEEC_R = \sum_{i=1}^{n}(R_i/p) \times (1 - 12\,\%) \tag{2}$$

where R_i represents the solar emergy of the i^{th} renewable resource provided by natural resources and p represents the global average emergy density. According to the new Earth biosphere emergy baseline (Campbell, 2016), the global emergy density is 2.35E+14 sej/ha (Pan et al, 2019), while a report of the World Commission on Environment and Development (WCED) recommends that 12% of the ecological capacity should be deducted when calculating the ecological carrying capacity to protect biodiversity.

2.1.2 Emergy ecological carrying capacity of social economic resources

In addition to renewable resources, emergy ecological carrying capacity is also affected by the social economy, science, and technology, mainly referring to the impact of labor input, economy, and technology, namely purchased renewable resources. The $MEEC_S$ reflects the role of human activities in the socio-economic ecosystem, which increase the ecological supply capacity and are considered as components of the marine ecosystem carrying capacity. The formula is:

$$MEEC_S = \sum_{i=1}^{n}(S_i/p) \times (1 - 12\,\%) \tag{3}$$

Here, S_i refers to the emergy value of the i^{th} purchased socioeconomic resource. This emergy can be used to improve the efficiency of resource utilization and plays an important role in marine ecological environment restoration and resource protection.

2.2 Marine emergy ecological footprint

The MEEF of a specific sea area refers to the balance of resources converted from various marine sources and products extracted by human beings in the region, as well as wastes generated by production activities, to which emergy value can be added or subtracted according to the corresponding conversion rate and a calculation of the total amount of emergy performed after the introduction of emergy density (Chen et al., 2018). The consumption items of the MEEF include two categories. The emergy ecological footprint of consumption resource ($MEEF_R$) includes marine fishing, mariculture, marine power, marine crude oil, sea salt, marine chemical industry, marine biomedicine, marine mining, and others, while the emergy ecological footprint of pollution ($MEEF_W$) mainly refers to the wastewater and solid waste discharged into the marine environment.

The calculation formula is as follows:

$$MEEF = MEEF_R + MEEF_W = \sum_{i=1}^{n}(C_i/p) \quad 4$$

where C_i is the solar energy value for the i^{th} type of resource consumption. p represents the global average emergy density. MEEF reflects the regional ecological and economic characteristics, indicating the load intensity of human activities to the natural resources and environment.

2.3 Ecological security assessment

2.3.1 Marine emergy ecological surplus calculation

The difference between MEEC and MEEF is the emergy ecological surplus (Zhao et al., 2005), and the formula is as follows:

$$MEES = MEEC - MEEF \quad (5)$$

The MEES can indicate marine ecological pressure and sustainable development status. When MEES ≥ 0, i this indicates a surplus or balanced state, with no excessive negative ecological pressure. When MEES< 0, it means that the pressures on marine ecological resources are greater than the ecological adaptive capacity, indicating ecological overload. The greater the negative value, the greater the ecological pressure, indicating that the ecological environment is seriously degraded and is in an unsustainable state.

2.3.2 Calculation of the marine emergy footprint intensity

To measure the marine ecological surplus, the marine emergy ecological footprint intensity index was established, and the marine ecological security status evaluated by analyzing the pressure on the ecological capacity of the ecosystem. MEES is an evaluation method based on absolute value change points, which is simple and intuitive to show the ecological sustainable development status of the study area. Compared with MEES, EFI is based on relative values, reflecting the pressure on the unit ecological capacity of the ecosystem. The calculation formula is as follows:

$$MEFI = MEEF/MEEC \quad (6)$$

When MEFI<1, it is an ecological security state. When MEFI=1, the system is in a balanced state. When MEFI>1, the pressure on the marine ecosystem is greater than the ecological capacity and ecological security cannot be achieved. It can be seen that the larger the MEFI, the worse the marine ecological security status.

3 Case study

3.1 Study area

The coastal area of Guangxi is located at the southernmost end of mainland China, facing Southeast Asia and backed by southwest China. It is the most convenient passage to the sea in southwest China, with apparent regional advantages and a prominent strategic position. The marine functional area covers approximately 7000 km^2, with 1628.6 km of mainland shoreline and 643 islands. The coastline is tortuous, with rich bays and waterways and good natural barriers. There are many kinds of marine biological and rich marine mineral resources, mainly including port resources, marine biological resources, coastal tourism resources, marine oil and gas resources, mineral resources, wind energy, and tidal energy. Thus, the development potential of the marine economy is therefore significant. The geographical location and structure of Guangxi are shown in Figure 2.

Guangxi can not only enjoy the western development policy, but also has the regional advantage of opening up the eastern coast, as well as a flexible investment environment. The development of the marine economy takes place under highly favorable basic conditions and has maintained rapid growth. In 2020, the gross marine product of Guangxi was 165.1 billion yuan, accounting for 7.5% of the total regional Gross Domestic Product and becoming an important engine for sustained and rapid economic growth in the region., and the added value of the tertiary industry increased by more than 15%, making the marine industrial economic structure more significant. With much of Guangxi's economic development focused on the sea, it is important to understand the carrying capacity of the marine environment in order to ensure sustainable development of the ecological and economic system,

3.2 Data sources

To conduct a dynamic assessment of marine ecological security in Guangxi based on the emergy ecological footprint, this study collected original data from 2008 to 2020. Raw meteorological data, such as sunshine, annual mean precipitation, and annual mean wind speed, were obtained from the China Meteorological Data Service Center (https://data.cma.cn/en). Raw socio-economic data were derived from The China statistical yearbook (2009–2020) (http://www.stats.gov.cn), The China marine statistical yearbook (2009–2020, the Guangxi statistical yearbook (2009–2021) (http://tjj.gxzf.gov.cn/tjsj/tjnj/),the Statistical Bulletin of Guangxi Marine Economy (2010–2021) (http://hyj.gxzf.gov.cn/zwgk_66846/hygb_66897/

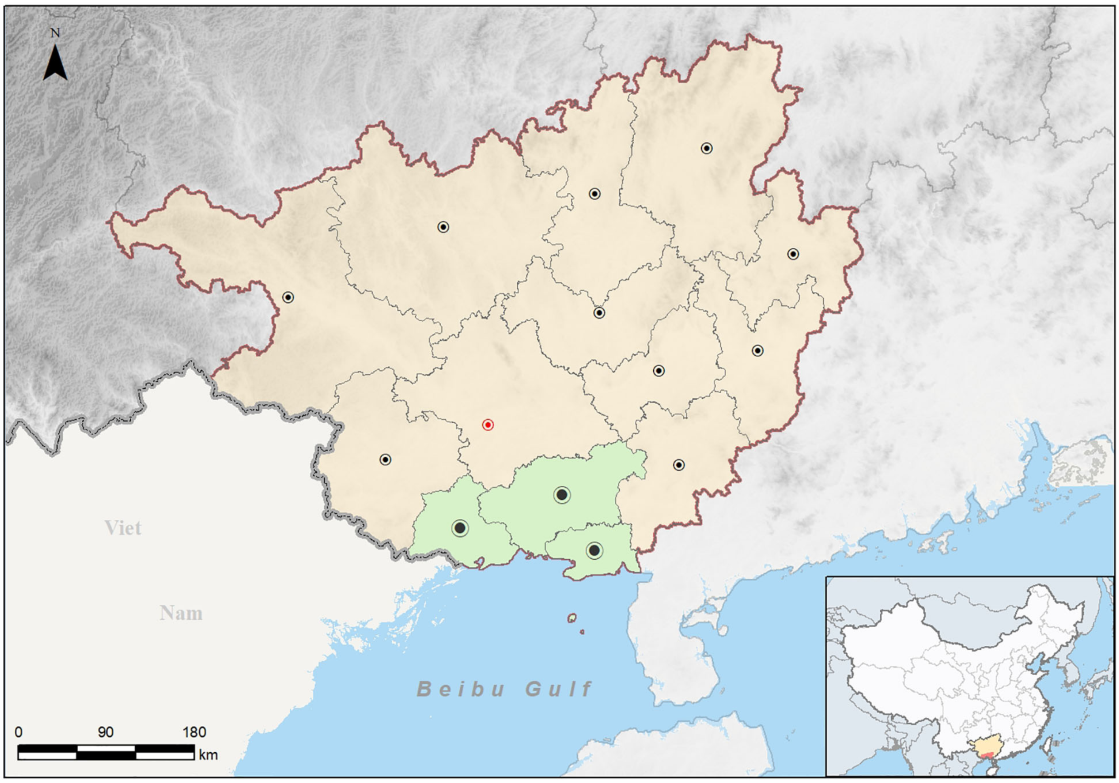

FIGURE 2
Study area.

hyjjtjgb/), and the Guangxi Water Resources Bulletin (2009–2021) (http://slt.gxzf.gov.cn/zwgk/jbgb/gxszygb/).

4 Results and discussions

Based on the emergy ecological footprint model built above, the raw data of the Guangxi marine ecological indicators were collated, and evaluations of Guangxi marine emergy ecological carrying capacity, emergy ecological footprint, and emergy ecological security were derived.

4.1 Results of MEEC

Using 2020 as an example, the calculation results of the Guangxi MEEC account are listed in Table 1.

The same method was used to calculate the MEEC of the Guangxi marine ecosystem from 2008 to 2020 (Appendix Table S1-S3); with the results shown in Figure 3. From the general trend, $MEEC_R$ showed high volatility during the study period, and the supply of natural resources was unstable. It can be seen from Table S1 that $MEEC_R$ fluctuates mainly due to the influence of precipitation, resulting in a change in emergy of renewable environmental resources. The $MEEC_S$ mainly considers two indicators: Guangxi's sea-related employment of the labor force and scientific and technological investment. During the study period, the emergy of social and economic investment steadily increased from 3.26E+22 to 3.85E+22, driving the improvement in Guangxi's total marine ecological carrying capacity (from 1.96E+08 in 2008 to 2.21E+08 in 2020).

4.2 Results of MEEF

Combined with the characteristics of Guangxi's marine ecosystem and the availability of index data and considering the ecological impact of marine consumption activities on the marine ecosystem when calculating its MEEF, the consumption resource footprint calculation uses marine fishing, mariculture, marine electricity, sea salt, and marine minerals as inputs. It is difficult to measure the exhaust gas in the discharge of pollutants from the marine ecosystem and this is thought to have little impact on the results. As a result, the pollution footprint is mainly based on the wastewater discharged into the sea by maritime economic activity. Taking 2020 as an example, Table 2 shows the calculation results for Guangxi MEEF.

The results of the MEEF (Appendix Tab. S4-S6) of the Guangxi marine ecosystem from 2008 to 2020 are shown in Figure 4. We can

TABLE 1 Emergy ecological carrying capacity of Guangxi Marine in 2020.

Emergy Item	Basic data	Unit	Transformity	Emergy (sej)	MEEC
Solar radiant energy	3.56E+19	J	1	3.56E+19	1.51E+05
Wind energy	5.43E+16	J	2.45E+03	1.33E+20	5.66E+05
Rainwater chemical energ	5.78E+16	J	3.05E+04	1.76E+21	7.50E+06
Rain, potential	1.37E+16	J	4.70E+04	6.44E+20	2.74E+06
Earth's rotational energy	1.01E+16	J	5.80E+04	5.89E+20	2.50E+06
Tidal energy	1.24E+17	J	7.39E+04	9.13E+21	3.88E+07
Wave energy	3.57E+16	J	3.00E+04	1.07E+21	4.55E+06
Sea related labor force	1.23E+06	J	3.10E+16	3.82E+22	1.63E+08
Science and technology investment	4.24E+08	CNY	8.11E+11	3.44E+20	1.46E+06

The final emergy was calculated according to each emergy transformation (Odum, 1996; Odum, 2000).
J, Joule; CNY, RMB unit; sej, emergy unit; MEEC, marine emergy ecological carrying capacity; g, gram.

see that the MEEF of Guangxi's marine ecosystem was unevenly distributed. Mariculture and marine fishing make a large contribution to Guangxi's MEEF in 2020, accounting for 68.7% and 22.9% of the total MEEF, respectively. The development of Guangxi's marine economy depends heavily on mariculture and fishing. The MEEF of mariculture changed from 3.49E+07 in 2008 to 6.80E+07 in 2020, showing a rapid upward trend. However, due to environmental problems such as sea water pollution and the reduction of marine biological species caused by marine overfishing, the government has regulated the behavior of the fishing industry,

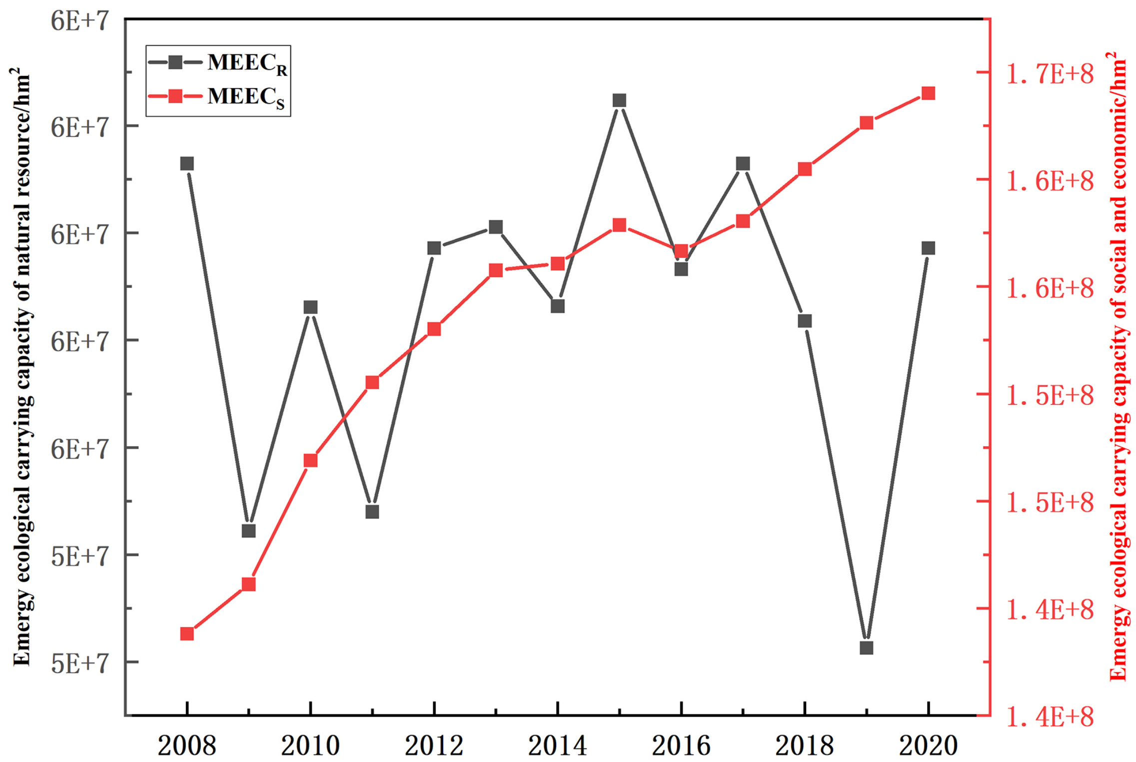

FIGURE 3
Emergy ecological carrying capacity of Guangxi Marine.

TABLE 2 Emergy ecological footprint of Guangxi Marine in 2020.

Emergy Item	Basic data	Unit	Transformity	Reference	Emergy (sej)	Ecological footprint
Marine fishing	2.72E+15	J	1.96E+06	Odum (1996)	5.32E+21	2.26E+07
Mariculture	8.15E+15	J	1.96E+06	Odum (1996)	1.60E+22	6.80E+07
Marine electricity	3.01E+14	J	1.47E+05	Brown and Ulgiati (2016)	4.43E+19	1.88E+05
Sea salt	0.00E+00	g	1.00E+09	Odum (1996)	0.00E+00	0.00E+00
Marine minerals	1.70E+12	g	1.00E+09	Odum (1996)	1.70E+21	7.23E+06
Wastewater into the sea	2.26E+14	J	6.66E+05	Kampeng et al. (2016)	1.50E+20	6.39E+05

J, Joule; CNY, RMB unit; sej, emergy unit; MEEC, marine emergy ecological carrying capacity; g, gram .

using management techniques such as the implementation of a fishing moratorium and fishing boat scrapping system. The contribution of marine fishing is slowly declining. In addition, marine mineral resource use changed greatly, with significant growth in 2013 and a significant decline in 2017. Other factors accounted for a small proportion of MEEF, with sea salt production having been stopped since 2017.

4.3 Results of ecological security assessment

Analyzing the results of the MEES and MEFI of Guangxi's marine ecosystem from 2008 to 2020 (Figure 5), it can be seen that its MEEC is greater than its MEEF, which indicates a surplus state. MEFI<1, which indicates that the ecological state

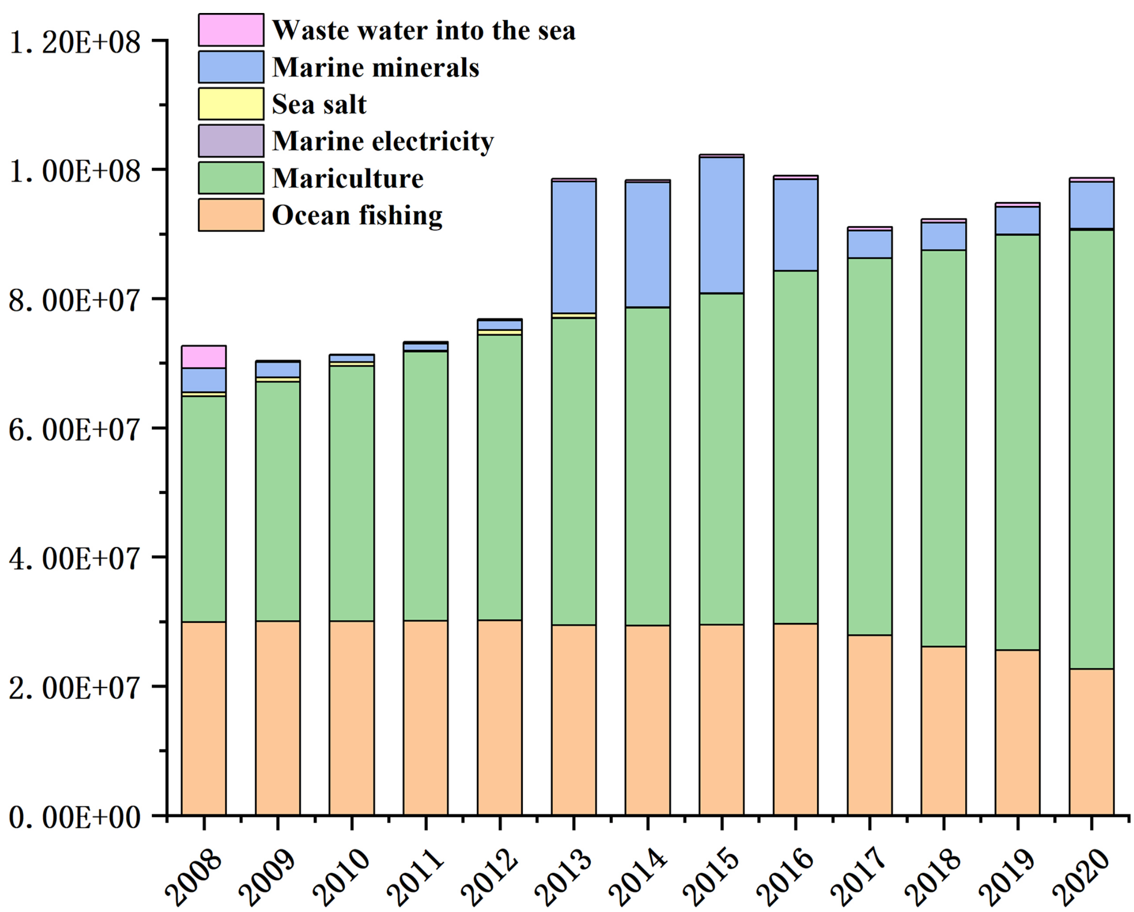

FIGURE 4
Composition of Guangxi marine ecological footprint.

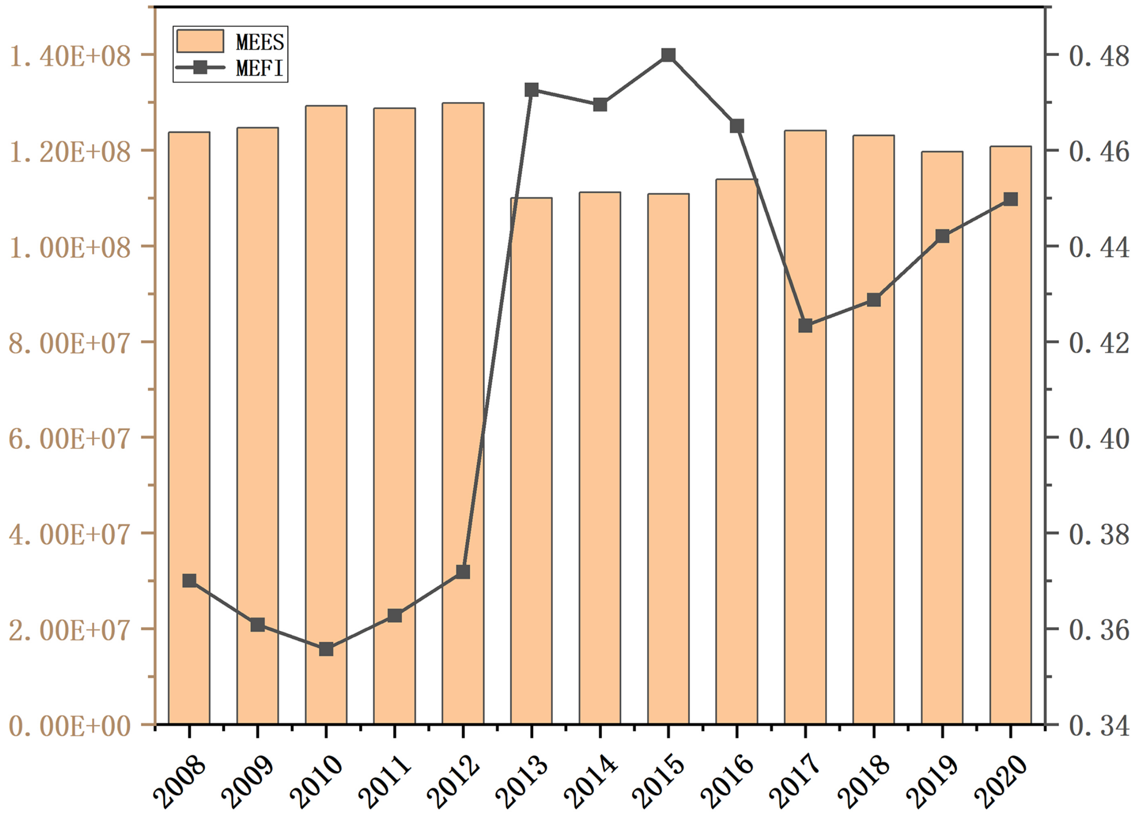

FIGURE 5
Emergy ecological security of Guangxi Marine.

is secure and that Guangxi's marine ecological economy is free of excess ecological pressure and that development can be considered sustainable. However, MEES generally declined, and MEFI began to increase in 2010. In 2012, this indicator showed a large increase. Although it declined in 2016, MEFI increased from 0.37 to 0.45 during the study period, reflecting the deterioration of the marine eco-system.

4.4 Suggestion

It can be seen from our results that Guangxi's marine ecology was in a secure state during the period 2008–2020, but due to increasing economic and environmental pressure, the marine eco-system has since deteriorated. Therefore, we propose the following suggestions for managing Guangxi's marine ecological security.

1. Make efficient use of natural resources and increase the use of renewable resources

The MEEC of the Guangxi marine ecosystem has always been greater than MEEF, which indicates an ecological surplus state because Guangxi has rich marine resources. The available renewable energy of the system has a large emergy value, and Guangxi Province has invested significant labor, scientific, and technological resources to develop the marine economy (Figure 3), giving the region a high ecological carrying capacity. From the MEEF, we can see that Guangxi lacks exploitation of marine crude oil and marine natural gas while MEEF values for marine electricity and sea salt were considerably low. Sea salt production ceased in 2017 (Figure 4) as mentioned above. The utilization rate of marine renewable resources is considerably low, and the ecosystem is in a safe state. Given this, greater use should be made of Guangxi's superior natural conditions, particularly the utilization of renewable resources. Research and development should be focused on renewable resources such as tidal energy, wind energy, and wave energy, and give more emphasis to the advantages of marine energy in island cities.

2. Increase investment in marine scientific research

It can be seen from the results of the MEEC (Figure 3) that labor, science, and technology investment have greatly increased the MEEC of Guangxi's marine ecosystem. Science and technology are important factors that affect the development efficiency of marine ecological economic systems and are the key to transforming the development mode of the marine economy as well as improving the breadth and depth of resource utilization. The rapid development of marine science and technology has not only brought about economic development but has also brought about the expansion of marine ecological capacity and the improvement of marine ecological environment quality. However, according to the second Global Marine Science Report released by UNESCO on December 14 (Isensee, 2020), the average proportion of marine science funds in the total scientific research investment in the world is only 1.7%, which is far lower than that in other major scientific fields. There is also a gap between the development level of marine science and technology in Guangxi Province and that of the rest of the world. Although investment in science and technology increased from 2016 to 2020, it has decreased considerably compared to previous years. Development momentum has slowed down due to unfavorable conditions, such as insufficient investment in marine scientific research funds and slow growth of marine scientific research personnel. Therefore, the government should increase investments in marine scientific research to ensure the stability and health of Guangxi's marine ecology.

3. Further adjust and optimize the industrial structure and develop ecological mariculture

As shown in Figure 4, fishery is the main part of Guangxi's marine industrial structure. The proportion of marine fishing in the MEEF decreased from 41.21% in 2008 to 22.95% in 2020, and the proportion of mariculture increased from 48.09% to 68.88%. The MEEF of marine mining fluctuated greatly, reaching 20.77% of the total MEEF at its peak and 7.33% in 2020. The marine industrial structure of Guangxi needs to be further optimized. First of all, with green development as the core, we should adopt "undersea forest" and "marine ranching" and other aquaculture methods to develop ecological mariculture, minimize the impact of human activities on the marine natural ecosystem, and ensure the stability and sustainable growth of aquatic resources. Secondly, the development potential of traditional industries is gradually decreasing, and new marine industries offer alternatives. Guangxi can vigorously develop new marine industries, such as clean energy, marine biological medicine, seawater utilization, and marine exploration to maximize the value of marine resources.

4.5 Discussion

This study used the emergy ecological footprint to evaluate marine ecosystems. Compared with other marine ecological security assessment methods (Todd et al., 2019; Zhao et al., 2020; Gao et al., 2022), this method has the following advantages: (1) conversion of different types and levels of energy into solar emergy values, introduction of global emergy density, and conversion of each consumption item into a corresponding bio-productive land area to enable products of different natures to be compared based on a unified unit; (2) the calculation of carrying capacity and ecological footprint takes into account economic, social, and other factors and waste emissions, fully reflecting the role of human activities in the marine ecosystem; (3) dynamic evaluation of marine ecological security based on long time series data can reflect the changing trends of ecological security.

This research has led to the following insights.

(1) Marine ecosystems are unique composite systems. The emergy ecological footprint reveals the complexity, particularity, and sustainability of the marine ecosystem by studying the flows of materials, energy, and other factors between the system and the environment. It can simply and scientifically evaluate marine ecological security. The evaluation results help us better protect the marine ecological economic system and guide the scientific development of the marine ecological economic system.

(2) In an ecological security assessment, social, economic, scientific, and technological factors have significant impacts on the improvement of carrying capacity. On one hand, these factors can directly enhance the ecological carrying capacity of the system; while on the other hand, they can indirectly enhance the ecological carrying capacity of the system by improving the ecological capacity of natural resources.

(3) To reduce the pressure on marine ecological security, we should improve the level of science and technology, optimize the marine industrial structure, and protect the environment. This requires not only making full use of regional advantages to develop marine industries according to local conditions, but also giving full play to the role of science and technology in improving the ecological carrying capacity and reducing ecological impacts. Simultaneously, in the process of development, it is necessary to simultaneously improve the efficiency of use of natural resources, control pollutant emissions, and achieve sustainable development of marine ecology.

Conclusion

A healthy marine ecological environment is a precondition for the survival of marine organisms. Once changes in the ecosystem and biological resources exceed the tolerance of the biological community, the balance of the ecosystem will be disturbed, which will damage the stability of marine ecology and threaten human development. An ecological security assessment can objectively assess the current marine ecological situation and provide suggestions for the sustainable development of the marine industry.

In this study, the emergy ecological footprint model was applied for the assessment of marine ecological security to provide an effective theoretical method for the study of sustainable development of the marine economy. The main contributions of this study are as follows: (i) The emergy method is used to measure the input and output elements of the marine ecosystem. It unifies the measurement standards to make the use of natural and human resources more comparable. (ii) An emergy ecological footprint model is established to evaluate the security of marine ecosystems, and long time series data are used for dynamic evaluation to characterize the change trend of ecological security. (iii) The emergy ecological footprint method is applied to the assessment of marine ecological security in Guangxi from 2008 to 2020, to reveal the current situation and dynamic change characteristics of marine ecological security in Guangxi and verify the effectiveness of the method. The results show that the marine system in this area is in a secure state, but with a trend towards deterioration. Based on this, corresponding management countermeasures for marine ecological security are proposed. This research provides theoretical support for the utilization of the ocean and the coordinated development of economy, society, and ecology, and is helpful to managers responsible for sustainable ecological security management of regional oceans.

Owing to the complexity of the marine ecosystem itself, many factors affect its ecological security, and these problems are complex. Moreover, it is difficult to collect all necessary data. Noting these data gaps, we have to give up after balancing, which may lead to a slight deviation between the research results and the actual situation. In addition, this study only considers the situation from 2008 to 2020 and analyzes the changes in this period but was unable to predict the future ecological security of the region. These limitations will be addressed in future work.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding authors.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by CW, AL, and CL. The first draft of the manuscript was written by CW and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.1090965/full#supplementary-material

References

Ahmed, Z., Caglar, A. E., and Murshed, M. (2022). A path towards environmental sustainability: The role of clean energy and democracy in ecological footprint of Pakistan. *J. Cleaner Production* 358, 132007. doi: 10.1016/j.jclepro.2022.132007

Bax, N., Novaglio, C., Maxwell, K. H., Meyers, K., McCann, J., Jennings, S., et al. (2021). Ocean resource use: building the coastal blue economy. *Rev. Fish Biol. Fish.* 32 (1), 189–207. doi: 10.1007/s11160-021-09636-0

Brown, L. R. (1977). *In: Redefining national security* (Washington DC: World Watch Institute), 40–41.

Brown, M. T., and Ulgiati, S. (2016). Emergy assessment of global renewable sources. *Ecol. Model.* 339, 148–156. doi: 10.1016/j.ecolmodel.2016.03.010

Buonocore, E., Picone, F., Donnarumma, L., Russo, G. F., and Franzese, P. P. (2019). Modeling matter and energy flows in marine ecosystems using emergy and eco-exergy methods to account for natural capital value. *Ecol. Model.* 392, 137–146. doi: 10.1016/j.ecolmodel.2018.11.018

Campbell, D. E. (2016). Emergy baseline for the earth: a historical review of the science and a new calculation. *Ecol. Model.* 339, 96–125. doi: 10.1016/j.ecolmodel.2015.12.010

Chen, W., Geng, Y., Dong, H. J., Tian, X., Zhong, S. Z., Wu, Q., et al. (2018). An emergy accounting based regional sustainability evaluation: a case of qinghai in China. *Ecol. Indicat.* 88, 152–160. doi: 10.1016/j.ecolind.2017.12.06

Costanza, R. (1999). The ecological, economic, and social importance of the oceans. *Ecol. Econ.* 31 (2), 199–213. doi: 10.1016/S0921-8009(99)00079-8

Du, Y. W., and Li, X. X. (2022). Critical factor identification of marine ranching ecological security with hierarchical DEMATEL. *Mar. Policy* 138, 104982. doi: 10.1016/j.marpol.2022.104982

Du, Y. W., Wang, Y. C., and Li, W. S. (2022). Emergy ecological footprint method considering uncertainty and its application in evaluating marine ranching resources and environmental carrying capacity. *J. Cleaner Production* 336, 130363. doi: 10.1016/j.jclepro.2022.130363

Folke, C., Kautsky, N., Berg, H., Jansson, Å., and Troell, M. (1998). The ecological footprint concept for sustainable seafood production: a review. *Ecol. Appl.* 8 (sp1), S63–S71. doi: 10.1890/1051-0761(1998)8[S63:TEFCFS]2.0.CO;2

Gao, L. H., Ning, J., Yan, A., and Yin, Q. R. (2022). A study on the marine ecological security assessment of guangdong-Hong Kong-Macao great bay area. *Mar. pollut. Bull.* 176, 113416. doi: 10.1016/j.marpolbul.2022.113416

Geng, Y., Zhang, L., Chen, X., Xue, B., Fujita, T., and Dong, H. (2014). Urban ecologicalfootprint analysis: a comparative study between shenyang in China and Kawasaki in Japan. *J. Clean. Prod.* 75 (14), 130–142. doi: 10.1016/j.jclepro.2014.03.082

Ghermandi, A., Obura, D., Knudsen, C., and Nunes, P. A. (2019). Marine ecosystem services in the northern Mozambique channel: A geospatial and socio-economic analysis for policy support. *Ecosystem Serv.* 35, 1–12. doi: 10.1016/j.ecoser.2018.10.009

Gomiero, A., Bellerby, R. G. J., Manca Zeichen, M., Babbini, L., and Viarengo, A. (2018). Biological responses of two marine organisms of ecological relevance to on-going ocean acidification and global warming. *Environ. pollut.* 236, 60–70. doi: 10.1016/j.envpol.2018.01.063

Hu, W., Hu, Y., Hu, Z., Huang, Y., Zhao, Y., and Ren, M. (2019). Emergy-based sustainability evaluation of china's marine eco-economic system during 2006–2015. *Ocean & coastal management. 179* (6), 104811. doi: 10.1016/j.ocecoaman.2019.05.013

Isensee, K. (2020). Intergovernmental Oceanographic Commission. *Global Ocean Science Report: Charting Capacity for Ocean Sustainability* (Vol. 2020). Unesco Publishing.

Kampeng, L., Lu, L., Dan, H., and Inchio, L. (2016). Mass, energy, and emergy analysis of the metabolism of Macao. *J. Clean. Prod.* 114, 160–170. doi: 10.1016/j.jclepro.2015.05.099

Karani, P., and Failler, P. (2020). Comparative coastal and marine tourism, climate change, and the blue economy in African Large marine ecosystems. *Environ. Dev.* 36, 100572. doi: 10.1016/j.envdev.2020.100572

Koulouri, P., Mogias, A., and Gerovasileiou, V. (2022). Ocean literacy across the Mediterranean Sea region in the era of 2030 agenda and the decade of ocean science for sustainable development 2021-2030). *Mediterr. Mar. Sci.* 23 (2). doi: 10.3389/fmars.2021.829610

La Daana, K. K., Asmath, H., and Gobin, J. F. (2022). The status of marine debris/litter and plastic pollution in the Caribbean Large marine ecosystem (CLME): 1980–2020. *Environ. pollut.* 300, 118919.

Lam, V. W., and Pauly, D. (2019). Status of fisheries in 13 Asian large marine ecosystems. *Deep Sea Res. Part II: Topical Stud. Oceanography* 163, 57–64. doi: 10.1016/j.dsr2.2018.09.002

Liu, C., Cai, W., Zhai, M., Zhu, G., Zhang, C., and Jiang, Z. (2021). Decoupling of wastewater eco-environmental damage and china's economic development. *Sci. Total Environ.* 789, 147980. doi: 10.1016/j.scitotenv.2021.147980

Liu, Z., Li, B., Chen, M., and Li, T. (2021). Evaluation on sustainability of water resource in karst area based on the emergy ecological footprint model and analysis of its driving factors: a case study of guiyang city, China. *Environ. Sci. pollut. Res.* 28 (35), 49232–49243. doi: 10.1007/s11356-021-14162-4

Liu, Y., Qu, Y., Cang, Y., and Ding, X. (2022). Ecological security assessment for megacities in the Yangtze river basin: Applying improved emergy-ecological footprint and DEA-SBM model. *Ecol. Indic.* ,134, 108481. doi: 10.1016/j.ecolind.2021.108481

Martínez, M. L., Intralawan, A., Vázquez, G., Pérez-Maqueo, O., Sutton, P., and Landgrave, R. (2007). The coasts of our world: Ecological, economic and social importance. *Ecol. economics* ,63 (2-3), 254–272. doi: 10.1016/j.ecolecon.2006.10.022

Nakajima, E. S., and Ortega, E. (2016). Carrying capacity using emergy and a new calculation of the ecological footprint. *Ecol. Indic.* 60, 1200–1207. doi: 10.1016/j.ecolind.2015.08.054

Odum, H. T. (1988). Self-organization, transformity, and information. *Science* 242 (4882), 1132–1139. doi: 10.1126/science.242.4882.1132

Odum, H. T. (1996). *Environmental accounting: Emergy and environmental decision making* (New York. USA: John Wiley & Sons).

Odum, H. T. (2000). Emergy evaluation of an OTEC electrical power system. *Energy* 25 (4), 389–393. doi: 10.1016/S0360-5442(99)00076-6

Pan, H., Zhuang, M., Geng, Y., Wu, F., and Dong, H. (2019). Emergy-based ecological footprint analysis for a mega-city: the dynamic changes of shanghai. *J. Clean. Prod.* 210, 552–562. doi: 10.1016/j.jclepro.2018.11.064

Peng, W., Wang, X., Li, X., and He, C. (2018). Sustainability evaluation based on the emergy ecological footprint method: A case study of qingdao, China, from 2004 to 2014. *Ecol. Indic.* 85, 1249–1261. doi: 10.1016/j.ecolind.2017.12.020

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

Samhouri, J. F., Lester, S. E., Selig, E. R., Halpern, B. S., Fogarty, M. J., Longo, C., et al. (2012). Sea Sick? setting targets to assess ocean health and ecosystem services. *Ecosphere* 3 (5), 1–18. doi: 10.1890/ES11-00366.1

Santos, W. A. D., Erthal Junior, M., and Barcellos, R. G. S. (2021). Biocapacity of Brazilian biomes using emergy ecological footprint concepts. *Ambiente Sociedade* 2021, 24. doi: 10.1590/1809-4422asoc20180134r2vu2021L5AO

Sumaila, U. R., and Tai, T. C. (2020). End overfishing and increase the resilience of the ocean to climate change. *Front. Mar. Sci.* 7. doi: 10.3389/fmars.2020.00523

Sun, J., Miao, J., Mu, H., Xu, J., and Zhai, N. (2022). Sustainable development in marine economy: Assessing carrying capacity of Shandong province in China. *Ocean Coast. Manage.* 216, 105981. doi: 10.1016/j.ocecoaman.2021.105981

Tang, Y., Wang, M., Liu, Q., Hu, Z., Zhang, J., Shi, T., et al. (2022). Ecological carrying capacity and sustainability assessment for coastal zones: A novel framework based on spatial scene and three-dimensional ecological footprint model. *Ecol. Model.* 466, 109881. doi: 10.1016/j.ecolmodel.2022.109881

Thushari, G. G. N., and Senevirathna, J. D. M. (2020). Plastic pollution in the marine environment. *Heliyon* 6 (8), e04709.

Todd, P. A., Heery, E. C., Loke, L. H., Thurstan, R. H., Kotze, D. J., and Swan, C. (2019). Towards an urban marine ecology: characterizing the drivers, patterns and processes of marine ecosystems in coastal cities. *Oikos* 128 (9), 1215–1242. doi: 10.1111/oik.05946

Wackernagel, M., and Rees, W. E. (1997). Perceptual and structural barriers to investing in natural capital: Economics from an ecological footprint perspective. *Ecol. Econ.* 20 (1), 3–24. doi: 10.1016/S0921-8009(96)00077-8

Wackernagel, M., and Yount, J. D. (1998). The ecological footprint: an indicator of progress toward regional sustainability. *Environ. Monit. Assess.* 51, 511–529. doi: 10.1007/978-94-011-4976-1_40

Wang, S., Chen, S., Zhang, H., and Song, M. (2021). The model of early warning for china's marine ecology-economy symbiosis security. *Mar. Policy* 128, 104476. doi: 10.1016/j.marpol.2021.104476

Wang, Y. C., and Du, Y. W. (2023). Evaluation of resources and environmental carrying capacity of marine ranching in China: An integrated life cycle assessment-emergy analysis. *Sci. Total Environ.* 856, 159102. doi: 10.1016/j.scitotenv.2022.159102

Xie, B., Zhang, X., Lu, J., Liu, F., and Fan, Y. (2022). Research on ecological evaluation of shanghai port logistics based on emergy ecological footprint models. *Ecol. Indic.* 139, 108916. doi: 10.1016/j.ecolind.2022.108916

Xu, W., Xiao, Y., Zhang, J., Yang, W., Zhang, L., Hull, V., et al. (2017). Strengthening protected areas for biodiversity and ecosystem services in China. *Proc. Natl. Acad. Sci. U. S. A.* 114, 201620503. doi: 10.1073/pnas.1620503114

Xu, L., Zhao, X., and Chen, J. (2022). Exploring the governance dilemma of nuclear wastewater in fukushima: A tripartite evolutionary game model. *Ocean Coast. Manage.* 225, 106220. doi: 10.1016/j.ocecoaman.2022.106220

Ye, F., He, Y., Yi, Y., Quan, Y., and Deng, Y. (2022). Promotion of environmental regulation on the decoupling of marine economic growth from marine environmental pollution–based on interprovincial data in China. *J. Environ. Plann. Manage.* 65 (8), 1456–1482. doi: 10.1080/09640568.2021.1932771

Yin, K., Zhang, K., and Huang, C. (2022). Institutional supply, market cultivation, and the development of marine strategic emerging industries. *Mar. Policy* 139, 105045. doi: 10.1016/j.marpol.2022.105045

Yıldırım, D. Ç., Yıldırım, S., Bostancı, S. H., and Turan, T. (2022). The nexus between human development and fishing footprint among mediterranean countries. *Mar. pollut. Bull.* 176, 113426. doi: 10.1016/j.marpolbul.2022.113426

Zadehdabagh, N., Monavari, S. M., Kargari, N., Taghavi, L., and Pirasteh, S. (2022). Sustainability of agroecosystems by indices: A comparative study between indicators of ecological footprint sustainability and emergy analysis; a case study in dez catchment, Iran. *Ecol. Model.* 474, 110165. doi: 10.1016/j.ecolmodel.2022.110165

Zadgaonkar, L. A., and Mandavgane, S. A. (2020). Framework for calculating ecological footprint of process industries in local hectares using emergy and LCA approach. *Clean Technol. Environ. Policy* 22 (10), 2207–2221. doi: 10.1007/s10098-020-01970-4

Zhao, H., Li, Y., Hao, F., and Ajaz, T. (2022). Role of green energy technology on ecological footprint in China: Evidence from Beijing-Tianjin-Hebei region. *Front. Environ. Sci.* 10, 965679. doi: 10.3389/fenvs.2022.965679

Zhao, S., Li, Z., and Li, W. (2005). A modified method of ecological footprint calculation and its application. *Ecol. Model.* 185 (1), 65–75. doi: 10.1016/j.ecolmodel.2004.11.016

Zhao, W., Zhao, G., Yang, J., Xu, M., and Kou, J. (2020). Assessment of the ecological security of the coastal zone of the Guangdong/Hong Kong/Macao greater bay area. *J. Coast. Res.* 102 (SI), 287–295. doi: 10.2112/SI102-035.1