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# The land-sea system dynamics model with shared socioeconomic pathways can identify the gaps in achieving Sustainable Development Goal 14

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ABSTRACT

Sustainable Development Goal 14 (SDG14) identifies development targets directly related to oceans; however, the gaps in achieving SDG14 remain unclear, understanding these gaps is essential in promoting sustainable management of coastal resources. We use the integrated land-sea system dynamics model to explore whether China's coastal area development, resources and ecology are capable of achieving SDG14 under different shared socioeconomic pathways, shock detection is then carried out to find management interventions that potentially contribute to SDG14. We find that SDG14.1, 14.3 and 14.7 can be achieved, but the expansion of mariculture in China's coastal area prevents the realization of SDG14.5 and 14.A unbalanced development of the marine industry will contribute to failing to achieve SDG14.2. Marine fishery is the primary factor in the decoupling between marine industries, and the shocks of SDG14 were mainly caused by changes in fisheries policies and natural disasters. Insights from this research can inform essential information for SDG14 from resilience thinking.

## 1. Introduction

Oceans and coastal zones can provide a variety of ecosystem services for human beings. The sustainable development of oceans and coastal zones has been formally integrated into the United Nations Sustainable Development Goals (SDGs) (United Nations (UN), 2015, 2017). The SDGs establish a systematic framework with 17 goals. Management objectives related to ocean and coastal conservation and exploitation, are linked, in particular, to SDG 14: "Conserve and Sustainably use the oceans, seas and marine resources for sustainable development". Population growth, economic development, increasing demand and competition for resources are putting various pressures on coastal ecosystems and their ability to provide sustainable resources for future generations.

Under these circumstances, enormous challenges are posed to sustainable development in ocean and coastal regions (Cinner et al., 2018), for instance, improvement of socioeconomic welfare, reduction of negative impact induced by rising human activities and effective conservation of marine ecosystems (Lu et al., 2019). Integrated land-sea management offers an opportunity to address these challenges (Winther et al., 2020), which considers land and sea as a complex non-linear system of dynamic evolution. However, as it is difficult to accurately describe the interactions between society, economy and the environment due to the non-linear relationship among the elements in the land-sea system, we need to analyze the SDG14 from a more systematic perspective (Fu et al., 2020; Lubchenco et al., 2016; Nash et al., 2020; Singh et al., 2018).

System Dynamics (SD) assesses the structure of a system by modelling the system with a series of interconnected variables that interact and feedback with each other, which can study the system's past and future. Compared to other models, SD can capture and reproduce the endogenous dynamics of complex system elements (Boons et al., 2021; Jiang et al., 2021; Papachristos, 2019). In addition, SD can provide a flexible simulation on the internal connection of multiple subsystems, enabling cross-system simulation and prediction. In 2010, the IPCC proposed the shared socioeconomic pathways (SSPs) by designing five scenarios of socioeconomic development that describe the possible consequences of different climate policies by characterizing the relationship between radiative forcing and socioeconomic development till 2100 SSPs is a critical tool and linked to SD, provide a more reliable prediction for future social, economic, and environmental changes (O'Neill et al., 2014, 2017).

More recently increasing importance has been attached to the development of a harmonious and sustainable dynamic equilibrium between the land and the sea. SD approach is adopted as a research

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method for comprehensive system theory, cybernetics, information theory and other disciplines, which has been successfully applied to analyze carbon emission (Jiang et al., 2021), climate change(Beckage et al., 2018), sustainable management (Kelly et al., 2020), urbanization (Tan et al., 2018), economy (Sušnik, 2018), water resources (Cui et al., 2019), pollution (Cordier & Uehara, 2019) and other research fields.

SSPs is used as a tool to interpret and predict the development of society (Chen et al., 2020; Huang et al., 2019; Kc & Lutz, 2017), economy (Dellink et al., 2017; Zhang et al., 2021), and the ecosystem (Li & Chen, 2020). The combination of SD and SSPs introduces a powerful toolbox to study the non-linear and time-varying phenomena of land-sea integration under scenarios with different socioeconomic variables. Resilience theory explores the persistence, perseverance and potential alternative configurations of a complex system subject to changing conditions (Li et al., 2020; McPhearson et al., 2015; Turner, 2010; Wang et al., 2021). The coastal area in China is a complex land-sea system facing a series of artificial and natural disasters, so adopting resilience thinking to address the challenges of land-sea sustainable development can have a significant impact by measuring the shock of the system and analyzing whether the internal coupling of the system can absorb external disturbances, contribute to a dynamic balance between people and ocean and the establishment of a more inclusive land-sea system.

From the perspective of land-sea integration, this paper: (1) analyze the development trajectory, marine resources exploitation and conservation, and ecological challenges facing China's coastal area; (2) identify the gaps in achieving China's coastal SDG14 and describe the complex interactions among SDG14 indexes; (3) provide recommendations for incorporating a resilience approach to China's achievement of SDG14. By predicting the impact of future economic and social development on the environment in China's coastal area, we can manage the potential risk more effectively, mitigate the effects of climate change and other coastal natural disasters, increase the resilience of the socio-economic management framework, hence achieve sustainable governance.

## 2. Material and method

### 2.1. Study Area

The study area covers mainland China's 11 coastal provinces and municipalities (Fig. 1), including Liaoning, Hebei, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi, and Hainan. The GDP of mainland China's coastal provinces and municipalities accounts for more than 60% of domestic income and is home to about 40% of the country's population in about 14% of the country's area. The rapid development of mainland China's coastal provinces and municipalities has disturbed the ecological balance of coastal area, for example, China has lost about 69% of its mangrove areas and 80% of its coral reef areas (Sajjad et al., 2018; Wang et al., 2014). Chinese government proposed the concept of "Ecological Civilization" in 2012, incorporating resource conservation and environmental protection into the guiding principles of policy-making for the first time (Hansen et al., 2018; Su et al., 2020). Marine ecological civilization construction is an important part of the ecological development construction. China's 13th Five-Year Plan (FYP) in 2016 included marine ecosystem protection as a key element of the central government's environmental agenda (Cao et al., 2017), the 14th FYP also continues to emphasize the importance of marine ecology and environmental protection (Xinhua News Agency, 2021). The Chinese government stated that the structure of marine ecological civilization should be incorporated into the overall layout of marine development and the marine natural reproduction capacity should be maintained. China's ambitious goals would aim to lead the world in Sustainable development and set an example for other coastal countries in this regard.

### 2.2 Data Sources

Most of the model's socioeconomic data and marine-related industry data are collected from bulletins, websites of provincial governments, and the China Statistical Yearbook published by the National Bureau of Statistics (https://data.stats.gov.cn/english/), which are the authoritative data released by Chinese government. China's annual carbon emission data are obtained from the CEADs database (https://www.

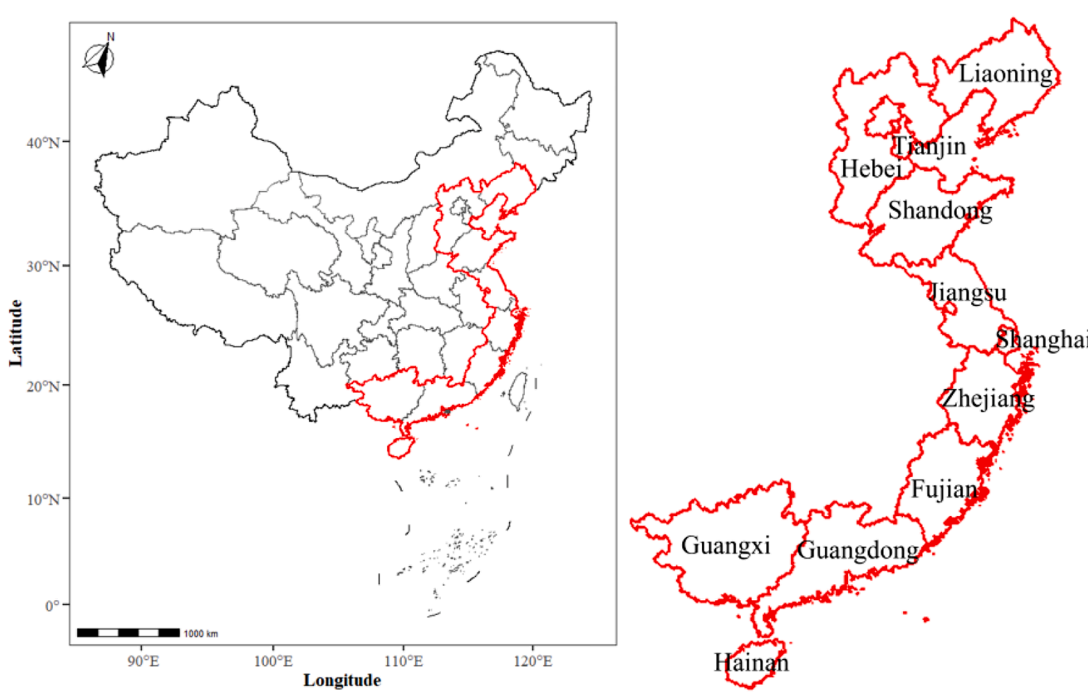


**Fig. 1.** Geographical location of mainland China's 11 coastal provinces and municipalities.

ceads.net/), which works on carbon emission accounting methods and applications in China. China provincial mariculture production data are obtained from the National Scientific Big Data Platform for Fishery from 1954-2019. The years of data required for SD model are 2005-2015, and the years of data required for shock detection are 1954-2019, however, some provinces and municipalities do not have earlier data, so these areas are analyzed from the year in which the earliest data are available. The specific selection of data years is described in sections 2.4 and 2.6.

### *2.3 Setting SDG14 indicators for China's coastal area*

To facilitate a comprehensive assessment of sustainable development in the context of SDG14, each goal of SDG14 is listed in Table S1. Indicators that can help to evaluate and take specific measures are selected from the three aspects of development trajectory, marine resource exploitation and the marine ecological to analyze the implementation of SDG14 in China's coastal area and provide further information as governmental planning and decision-making support for sustainable development (Table 1).

### *2.4. Land-sea SD model with SSPs*

To illustrate the development of China land-sea system in the coastal area, the flow chart of the SD model (Fig. 2) and the land-sea SD model framework (Fig. 3) are developed, to illustrate some of the important elements needed for the model and the critical process of modeling. The SSPs provide the main simulation indicators of socio-economic development under different future scenarios, supplemented by some other drivers to generate the final SDG14 characterization indicators directly or through instrumental variables. The model considers China's coastal area's economic and social level and introduces related industries that rely on resources provided by land and the ocean ecosystem. The SD model consists of 3 subsystems, population subsystem, economy subsystem, and environment subsystem. We choose year between 2016 and 2100 to conduct experiment on an annual basis in SD model, with reference to the historical data from 2005 to 2016. This study finally generates one SD model covering the whole 11 provinces and municipalities in mainland China's coastal area.

#### *2.4.1. SSPs settings*

Five SSPs (SSP1: sustainability; SSP2: middle of the road; SSP3: regional rivalry; SSP4: inequality; and SSP5: fossil fuel development) describe the possible development scenarios based on different levels of capability for human to mitigate and adapt to future challenges (Huang et al., 2019). The various settings of SSPs are listed in Table S2, which include several elements such as population and economy (Huang et al., 2019; Kc & Lutz, 2017; Moss et al., 2010; O'Neill et al., 2017). The critical drivers of different SSPs settings listed in Table S2 are directly fed into the SD model as model variables, and the socioeconomic indicators needed to calculate SDG14 indicators (Table 1) are obtained by linking the mathematical equations summarized from the relevant studies on SSPs (Huang et al., 2019; Kc & Lutz, 2017; Moss et al., 2010; O'Neill et al., 2017), which can provide a more reliable prediction of future sustainable development in China's coastal area under different scenarios to highlight the impact of different paths on SDG14 implementation. The SSPs variables are listed in Fig. 3 (Yellow Box).

#### *2.4.2. Subsystem of the SD model*

(1) Population sub-system

For the population subsystem, the population is viewed not merely as producers to create resources but also as consumers to utilize resources, an essential part of the land-sea SD model. Therefore, the birth rate, death rate, level of education, and migration rates are chosen as principal determinants of population.

**Table 1**
SDG14 in response to challenges of land-sea integration

| Challenges | Indicators | Corresponding SDG14 | Reasons for indicator selection |
|---|---|---|---|
| Development trajectory | Total population | - | Human beings are the primary users of land-sea resources, and land-sea resources are the foundation for future development. |
| | GDP per capita | - | GDP per capita provides an economic basis for development. |
| Marine resource development | Mariculture | SDG14.A | The expansion of aquaculture has come at the cost of biodiversity loss(Lu et al., 2019; McCann et al., 2016; Szuwalski et al., 2017), which also has important implications for ocean health. |
| | | SDG14.5 | Coastal areas are limited while pressing need for development in coastal areas are competing with conservation in coastal areas, of which the expansion of the mariculture area is one of the significant causes for marine resource over-exploitation. |
| | Land-based wastewater discharged into the marine | SDG14.1 | Land-based wastewater discharged into the marine, including industrial and domestic source pollutants, directly / indirectly affect the marine environment. |
| | Marine resources | SDG14.2 | Marine resources are an essential component of marine and coastal ecosystems and carriers for healthy and productive oceans. |
| | | SDG14.7 | The development of marine transportation, marine tourism, and marine fishery depends on marine resources, but also inseparable from land resources. |
| Marine ecological environment | Carbon emissions | SDG14.3 | Approximately 1/3 of atmospheric carbon emissions are absorbed by the ocean, causing ocean acidification. Therefore, the level of ocean acidity is determined by the global carbon emission rate (Reimer et al., 2020; Rickels et al., 2016). |

(2) Economy subsystem

For the economy subsystem, the Gross Domestic Product (GDP) is the sum of the land-based economy and marine economy. The land-based economy model is established based on the Cobb-Douglas production function (Leimbach et al., 2017). The labour provided by the population subsystem is an essential input of the land-based economy, which also

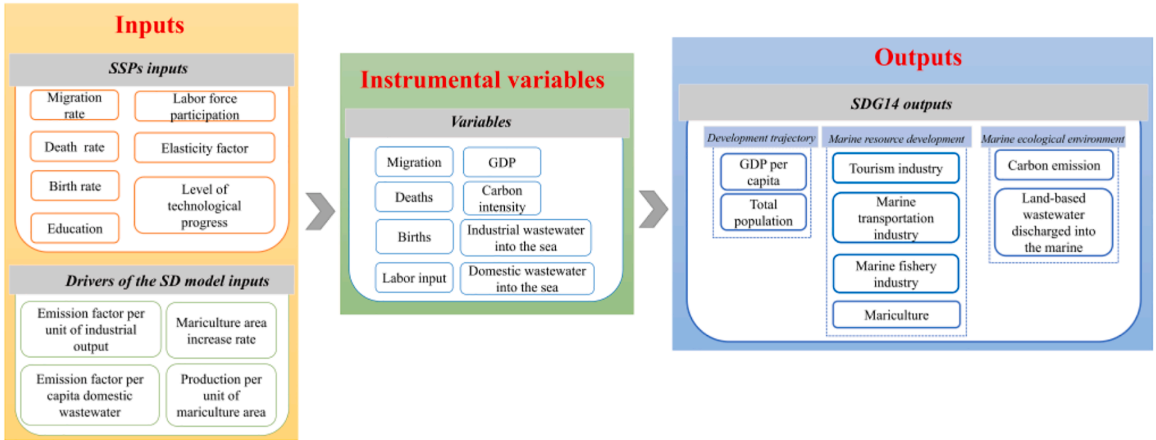


**Fig. 2.** Flow chart of main steps in developing the land-sea integration SD model

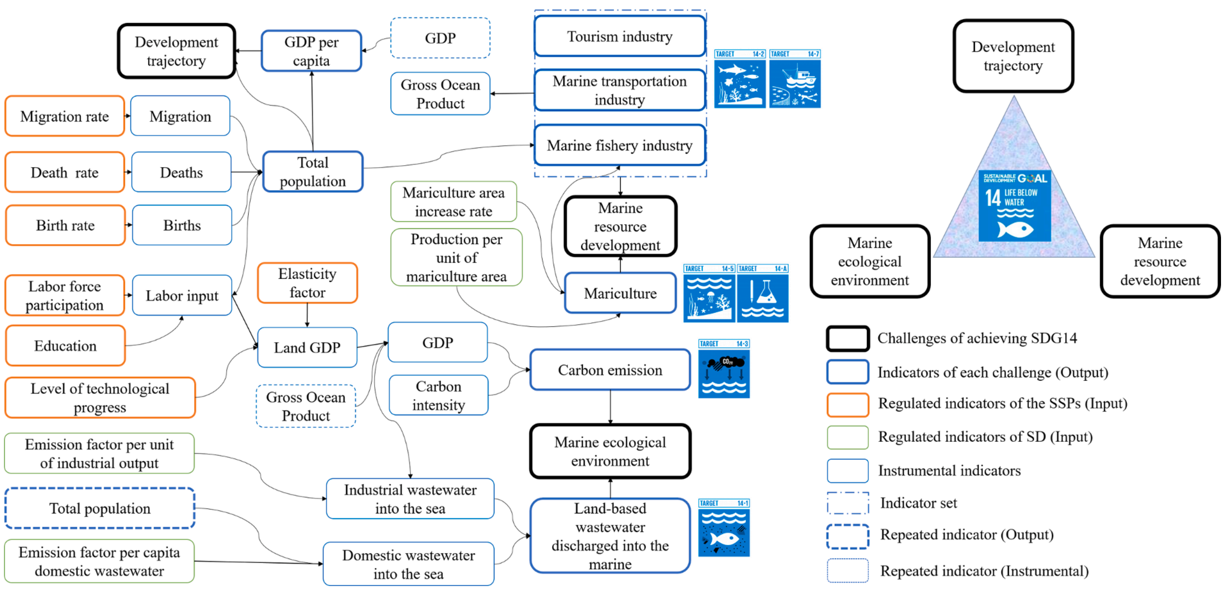


**Fig. 3.** Framework of the land-sea integration SD model.

dramatically influences marine-related industries.

(3) Environment subsystem

The development of population and economy leads to environmental degradation and also accelerates the depletion of resources. The environment subsystem simulates the critical processes of pollutant emission, emission reduction, and resource consumption. Besides, changes in the environment further affect social and economic development. The socioeconomic variables are the primary drivers of the SD model, which affects the environmental subsystem. SSPs has proposed a set of future development paths, and some scholars have set the parameters of future development path according to the development orientation proposed by SSPs, which is worth learning (Huang et al., 2019; Moss et al., 2010; O'Neill et al., 2017). Therefore, different settings of SSPs can be assigned into the SD model to dynamically simulate the overall development trend of the system and the degree of influence of the economy subsystem on the land-sea integrated system.

### *2.4.3. Model validation*

The future trend cannot be predicted with 100% accuracy, but by using SD we simulate the general trend of the world based on historical data, to avoid large deviation from the real data. To ensure the simulation results of land-sea integration in China's coastal area are objective and accurate, the effectiveness of the SD model is verified by a historical value test (Joshi et al., 2021). The historical value test uses the relative error method to compare the simulated values of the model simulation from 2005 to 2015 with the actual data, and the simulation results show that the relative error between the simulation values and historical values of each variable is less than 7%, most frequent error is between 2%-5% (Table S3), which are more accurate compared with other research findings (Cui et al., 2019; Tan et al., 2018), so the model is of reasonable accuracy. Further details on the SD model can be found in SI Text S1, Fig. S1 and Table S3.

## *2.5. Decoupling index*

To analyze whether the industries using marine resources can achieve coordinated development while maintaining the system's resilience, the decoupling indexes among traditional marine industries including tourism, fishery, and marine transportation are introduced. We define $\Delta A_t = (A_t - A_{t-1}) / A_t$ (A: Added value of the tourism industry) and $\Delta B_t = (B_t - B_{t-1}) / B_t$ (B: Added value of marine fishery industry), and the decoupling index (DI) in year t: $DI = \Delta A_t / \Delta B_t$. When DI $\geq 1$, it means tourism industry keeps pace with or is higher than marine fishery industry; when $0 < DI < 1$, it implies tourism industry is short of that of marine fishery industry; when DI=0, it means marine fishery industry is growing, while tourism industry remains constant; when DI<0, it implies tourism industry decrease while marine fishery industry keeps growing.

### 2.6. Shock detection

China mariculture production is growing annually and has already surpassed that of marine capture. According to the National Bureau of Statistics, mariculture production accounted for about 60% of seafood production in 2015. Considering the vital contribution of mariculture to China's SDGs, the shock detection approach of Gephart (2017) is used to identify and compare the shock occurrence in China's coastal provinces and municipalities. This approach modifies existing methods commonly used in exploratory spatial statistics to identify outliers to detect shocks based on autocorrelation deviations. For the shock detection analysis of mariculture production in each province, the time series were selected with all-time series available at the National Scientific Big Data Platform for Fishery, with 1954-2019 for Liaoning, Zhejiang, Fujian and Shandong, 1955-2019 for Hebei and Guangdong, Jiangsu for 1958-2019, Tianjin for 1960-2019, Guangxi for 1965-2019, Shanghai for 1979-2019, and Hainan for 1988-2019.

For all China's coastal provinces and municipalities, shocks are identified as outlier deviations or points with high Cook's D values (>0.35), of which Cook's D is used in regression analysis to find influential outliers in a set of predictor variables (Gephart et al., 2017), in a regression of the residuals and lag-1 residuals from a Locally Weighted Scatterplot Smoothing (LOWESS) fit of the time series with a smoother span of 2/3 (Gephart et al., 2017).

## 3. Results

### 3.1. Development trajectory of socioeconomic indicators in achieving SDG14 under SSPs

Sustainable population and economic development are prerequisites for the successful development of SDGs, therefore it is essential to discuss the development trajectory of SDG14. In terms of China's coastal area population size, the trajectories resulting from five SSPs will remain similar until about 2030 (Fig. 4a). By the middle of the 21st century (2050), the differences of each trajectory are visible, with the largest population of about 629.25 million in the SSP2 and the smallest population of 595.41 million under SSP3. All SSPs predict that the total population will continue to decrease in the future, similar trends existed in Kc and Lutz's (2017) simulations. There are many challenges to the sustainable development in China's coastal area due to growing population demands and limited resources (Liu et al., 2018); however, the decrease of the population under five SSPs in the future can further reduce the use of resources, which contributes to the conservation and sustainable use of resources.

As can be seen from the simulation of GDP per capita in Fig. 4b, all five SSPs illustrate significant growth trends with different growth levels, from which the future economy would show considerable development, similar trends existed in Zhang et al. (2021) and Leimbach et al. (2017) simulations. Due to the momentum of China's coastal area population growth by the middle of this century, the growth rate of GDP per capita under five SSPs in the early period is slightly lower than that in the later period. Higher GDP per capita simulated by the SD model means more convenience in accessing capital for development, and an increase in GDP per capita also means more assets for sustainable development and further adaptation to changes in socioeconomic development. However, as simulated by SD, unregulated over-exploitation accompanied by rapid socioeconomic development, might eventually undermine the prospects of long-term environmental conservation and sustainable development (Cinner & Barnes, 2019), thus there is still room for research on balancing economic growth and sustainable development.

### 3.2. Achievement of SDG14 for marine resource-dependent industries under SSPs

Important marine industries, including mariculture, transportation, tourism and fishery, all depend on the exploitation of marine resources. The development of these industries poses a threat to the sustainable development of coastal area, which may further hinder the achievement of SDG14 (Table 1)

#### 3.2.1. Development trajectory of SDG14 indicators related to mariculture resource

Mariculture plays a vital role and covers many aspects of SDG14 (Table 1), while the mariculture area, as an essential carrier of mariculture, is a physical resource that can support sustainable development, so the expansion of mariculture area is included in the analysis of SDG14.

The SD model simulates the change of mariculture area in China (Fig. 5), to analyze whether there is an overabundance of mariculture production, the expansion of the mariculture area can also explore the SDG14.5 for protected areas (Table 1), and the level of implementation to the achievement of SDG14.A could be expressed in terms of the impact from aquaculture on species diversity and marine health (Table 1). Taking the per capita mariculture production in 2005 as a reference indicator, the increase in per capita mariculture production after 2005 is regarded as a redundant increase, for the expansion of mariculture area $EM_t$ is calculated as

$$EM_t = \frac{TP_t \times PM_{2005}}{PMA_t} - MA$$

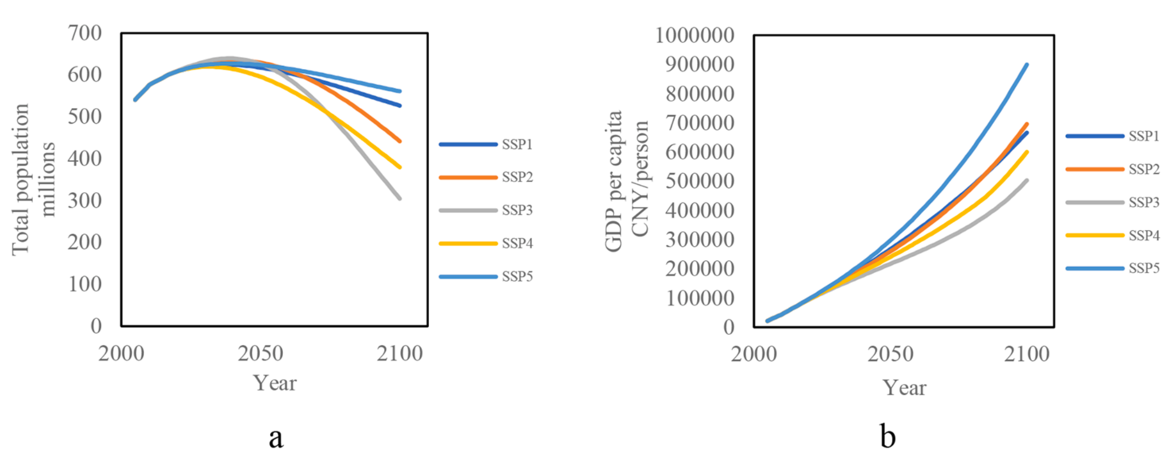


**Fig. 4.** Development trajectory of China's coastal area. a, Total population of China's coastal area under five SSPs. b, GDP per capita of China's coastal area under five SSPs

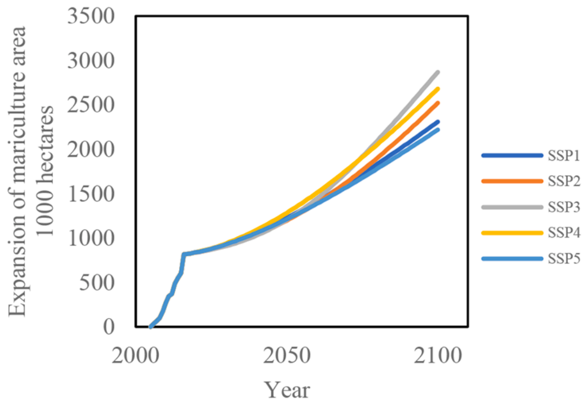


**Fig. 5.** Expansion of mariculture area in China's coastal area under five SSPs

Where $TP_t$ is the total population of China's coastal area in year t, $PM_{2005}$ is the per capita mariculture production in 2005, $PMA_t$ is the production per unit of mariculture area, $MA$ is the mariculture area of China's coastal area in year t.

Mariculture area can only measure the status of resource exploitation, while the expansion of mariculture area can further measure the level of overexploitation and relative exploitation intensity of the resource, and quantify how much of the growth in human demand is in relative surplus, and the expansion of mariculture area can also measure the decoupling of supply and demand with more extreme values.

As Fig. 5 indicates, under five SSPs, the expansion of the mariculture area are different, but all have shown an increasing trend. According to the status quo, the development is carried out referring to Table 1, the goals of SDG14.A will be challenging to achieve, which will draw a pessimistic picture of the conservation and sustainable development of resources. According to simulation results, the area of mariculture in 2015 was $2.32 \times 10^6$ hectares (actual data from the national bureau of statistics of China), and SSP3 will have the lowest expansion of mariculture area in 2020 at around $8 \times 10^5$ hectares according to simulation results, which is about 35% of 2015. Considering the coastal area demand from other human activities, the coastal area would be over-compressed and will not meet the SDG14.5 of conserving at least 10 percent of coastal and marine areas.

However, the Chinese government has proposed legislation to restrict the expansion of reclamation. As the primary source of mariculture land, future expansion of mariculture may not be as much as the simulation. Therefore, this simulation is only a reference reflecting the current level of mariculture.

#### *3.2.2. Development trajectory of SDG14 indicators related to other major marine industries*

SD model dynamically simulates the development trend of the marine transportation industry, tourism industry and fishery industry, which all depend on land-sea resources, without considering the impact of SSPs, therefore, the marine-related industries added value varies little in different SSPs, so the assumption only takes SSP1 as an example for simulation (Fig. 6). Fig. 6 indicates that in 2030, the marine transportation industry will be about CNY 1200 billion, coastal tourism industry will grow to about CNY 3500 billion, and marine fishery industry will be about CNY 640 billion, and relevant land-sea industries can continue to increase in revenue by 2030 and meet SDG14.7.

The revenue input in the marine and coastal tourism industry will continue to grow along the decade with it being the most significant and fastest-growing sector in China, but the focus on the development of the tourism industry can be fixed in a particular way of thinking, which will make the system less resilience due to the barrier to understanding the changes and adapting to choices (Cinner et al., 2018). Furthermore, it may lead to the region's increasing dependence on the tourism industry,

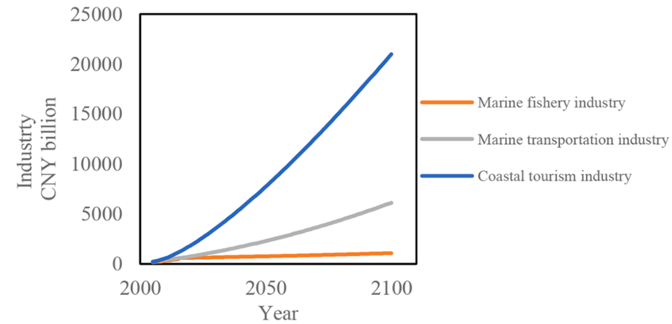


**Fig. 6.** Development trajectory of major marine industries

which eventually results in the over-exploitation of essential habitats, further hinder the conservation and sustainable use of resources, and fail to achieve the goal of SDG14.2, which describes the ability of a system to respond to shocks.

### *3.3. Projection of human impact on the marine ecosystem in achieving SDG14 under SSPs*

#### *3.3.1. Land-based wastewater discharged into the marine environment*

Achieving SDG14 requires functional ecosystems, and the corollary of maintaining ecosystem functioning includes the provision of services derived from healthy marine ecosystems, including the reduction of land-based wastewater discharge. Fig. 7 shows the simulation of land-based wastewater discharged into the marine environment to analyze the discharge of terrestrial pollutants into the marine environment under five SSPs.

According to the simulation results in Fig. 7, the land-based wastewater discharged into the marine is at a medium level under the middle of the road of SSP2 at the start, and the land-based wastewater discharged into the marine in 2025 is about 11.19 billion tons, then begin to decline, and the future decline of SSP2 is the fastest among all SSPs. Hence sustainable development of the SDG14.1 associated with marine pollution according to Table 1 is most likely to be achieved under the development of the middle of the road.

#### *3.3.2. Carbon emissions under different SSPs*

By analyzing the carbon emissions of different SSPs (Fig. 8), it is found that the SSP5 fossil fuel development path shows the highest carbon emissions scenario, while SSP1 is second to SSP5. Although SSP1 characterizes a world of rapid technological advancement, low carbon energy, and high productivity, the rapid development of the economy cannot prevent the increase of carbon emissions under the current situation. However, considering the technical constraints and the uncertainty of future technology, the SD model didn't simulate the scenario of rapid decline in carbon intensity but assumed that the simulation of carbon intensity trend will maintain the current technological standards. According to the SD model, carbon emissions will continue to rise until 2030, but at a much slower rate, with SSP1, SSP2, SSP4 and SSP5 emitting about 5700 Mt in 2030 and SSP3 emitting about 5600 Mt in 2030, and carbon emissions under five SSPs all start to show decline trends in the middle of the century. Under the current conditions, the carbon emissions in China's coastal area would offer a more encouraging trend, while ocean acidification is linked to carbon emissions (the lower the carbon emissions associated with lower ocean acidification) (Algunaibet et al., 2019), hence the goal of SDG14.3 associated with ocean acidification is likely to be achieved in the long term.

### *3.4. Gaps in achieving China's coastal SDG14*

As the results shown above, the rising trajectory of the mariculture and marine fishery industry fail to achieve SDG14.2, SDG14.5, and

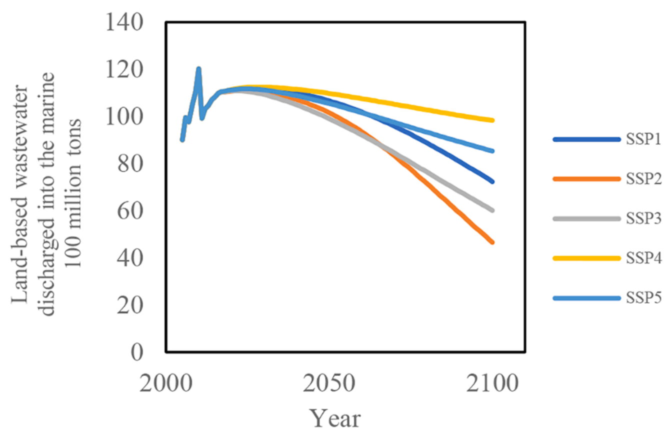


**Fig. 7.** Discharge of terrestrial pollutants into marine environment

SDG14.A, Xu et al. (2020) also pointed that the implementation of SDG14 is less satisfying than the implementation of other SDGs. Furthermore, marine fishery is the slowest to develop among the various industries (Fig. 6), and the future focus will be on the development of marine fishery to reduce imbalance development of the industry and increase system resilience. However, it should be noted that the expansion of mariculture area needs to be slowed down as far as possible in the development of marine fishery, and the focus should be on technological development, including increasing mariculture production per unit area and increasing the output value of the marine catches industry within the limits of ecological permission.

### 3.4.1. SDG14 gaps based on the decoupling between marine-related industries

Considering that the implementation of SDG14.2 may be hindered due to the imbalanced development of the marine-related industries, an inter-industry decoupling index is introduced to analyze the coordinated development of industries using land and marine resources. The simulation results are shown in Fig. 9.

Based on the analysis of the decoupling index (Fig. 9), the related industries of land-sea integration in China are in a coupling stage (decoupling index > 0), but the related industries would show a tendency of synergy as Fig. 9 shows that the decoupling index is declining in the future, from the perspective of resilience, this process is the stage of recovery and adaptation, during which the stability of the system tends to increase. The industry of marine transportation industry could keep pace with tourism industries (decoupling index = 1); however, the

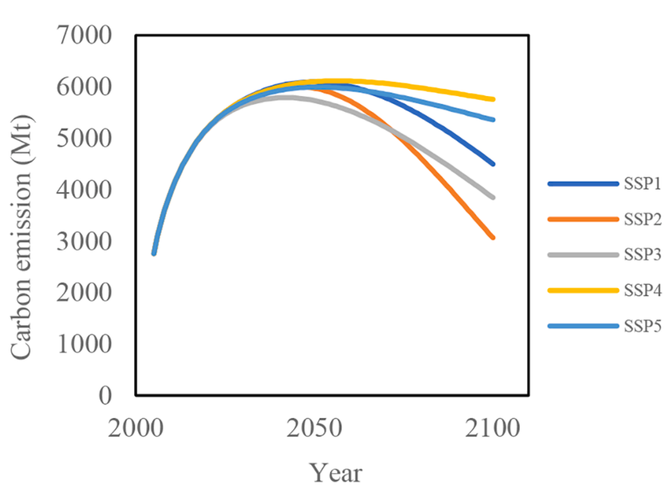


**Fig. 8.** Carbon emissions in China's coastal area under five SSPs

development of the marine fishery industry couldn't keep pace with other industries. Thus China marine fisheries largely determine whether the stability of the land-sea system can increase and SDG14.2 can be achieved in the future; however, China mariculture production accounts for most of the increased seafood productions in recent decades (Su et al., 2020), and accounted for about 60% of seafood production in 2015 (National Bureau of Statistics). Considering the "strengthening resilience" proposed in SDG14.2 (Table S1) and the importance of mariculture in marine fishery and SDG14, the development of mariculture in China should be discussed based on resilience.

### 3.4.2. SDG14 gaps based on mariculture production shock detection

Resilience is the characteristic of a system a respond to a shock. Mariculture production may be affected by shocks, i.e. sudden and unexpected changes, including natural disasters, economic crises, policy changes, etc. (Gephart et al., 2017). Shocks may pose challenges for SDGs (Cottrell et al., 2019), for example, decreases in fishermen incomes would affect SDG1 (No Poverty) and SDG8 (Decent Work and Economic Growth), food shortages could affect SDG2 (Zero Hunger) and SDG3 (Good Health and Wellbeing), and nutrient deficiencies could affect SDG10 (Reduced Inequalities), imbalances in seafood supply may affect SDG12 (Sustainable Consumption and Production) and SDG17 (Partnerships for the goals), so describing the frequency and forms of shocks on mariculture can help to achieve SDGs.

We analyze the shocks in mariculture production time series for each province in China, and shock detection results are shown in Fig. 10. As shown in Fig. 10, Fujian, Shandong, Guangdong and Guangxi received a shock in 1996, Shanghai in 1991 and 1992, Hainan in 2006 and Liaoning in 2007. It should be noted that the shocks in Hebei and Tianjin occurred in the last two years of the time series respectively, and needed to be determined with more extended time series, so they are excluded.

Relevant literature, reports and news are reviewed to explain the possible causes of these shocks. It is to be noted that the possible causes are not intended to be specific about the factors that could trigger the shock, instead, they rather represent only possible potential factors or significant disturbances occurring (Cottrell et al., 2019; Gephart et al., 2017).

Shocks in China's coastal area have not become more frequent over time except Shanghai, where other provinces and municipalities have experienced one shock at most. Most of these provinces and municipalities had a shock on mariculture in 1996, while China launched the China Ocean Agenda 21 in 1996, which called for sustainable fisheries management, and these provinces and municipalities have not experienced shocks ever since, among which Fujian, Shandong and Guangdong are all major mariculture provinces, Guangxi also ranks high in mariculture production among China. The Five-Year Plan for National Fisheries Development of the People's Republic of China was implemented in 2006 to promote sustainable fisheries development (Su et al., 2020), Hainan experienced a shock that year and has not experienced another shock since then, and mariculture production has shown a continuously increasing trend after a decline in the following year. On the contrary, Liaoning had a heavy snowstorm in 2007, and there was also a shock that year. Shanghai had two shocks in 1991 and 1992, and there was a flood in Shanghai in 1991 and a heavy snowstorm in 1991-1992.

These shocks were mainly caused by changes in fisheries policies and natural disasters, and some provinces and municipalities have started sustainable development of fishery after experiencing a short-term shock following the adjustment of changes in sustainable fisheries policies. Therefore, China should continue to implement and improve the 1996 China ocean agenda 21 and 2006 FYP while avoiding the expansion of mariculture area as much as possible. It is noteworthy that China launched its 13th FYP in 2016 (Su et al., 2020) and has just adopted the 14th FYP (2021–2025) in 2021. The 14th FYP proposed to optimize the distribution of green aquaculture in coastal areas, build marine pastures, and develop sustainable pelagic fisheries (Xinhua News Agency, 2021). Therefore, China should take this opportunity to re-evaluate the management design of sustainable marine fisheries development in the FYP,

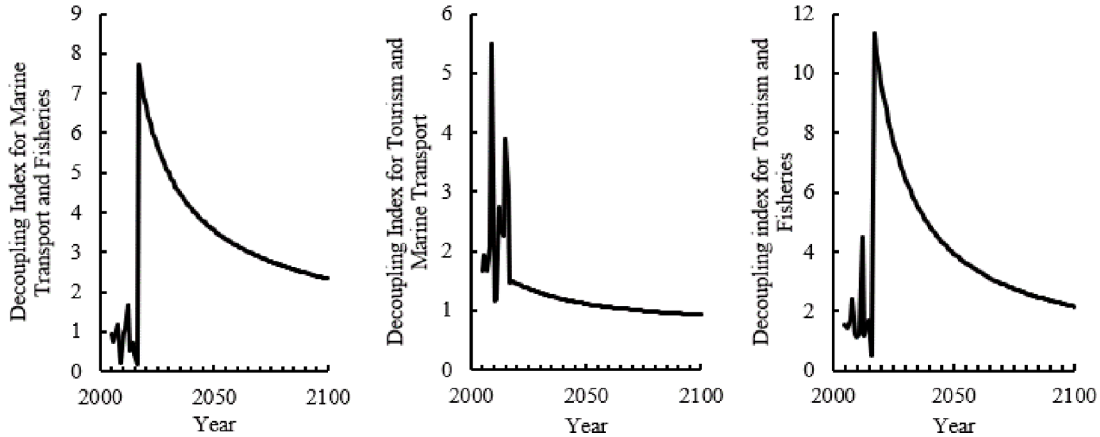


**Fig. 9.** Decoupling Index of the marine industry in China's coastal area

especially the initiatives since 2006, and to help the sustainable development of mariculture in coastal provinces and municipalities, enhance the resilience of land-sea systems anticipate or prevent shocks.

## 4. Discussion

Effective ocean governance promotes coastal resilience and enhances its ability to mitigate future disturbances. In 2018, China introduced a "cross-ministry reform" which reorganized institutions with similar functions and operations into a larger government department, e.g.: Ministry of Natural Resources, Ministry of Ecology and Environment. The Ministry of Land and Resources took China's coastal area as a whole and integrated land and sea-related affairs to meet future challenges. The cross-ministry reform is a uniquely Chinese administrative tool to achieve land-sea integration by merging the land and marine resource management departments into one large natural resource management department, while the China cross-ministry reform is sustainable administration with prominent top-down characteristics and lacks a bottom-up sustainable governance framework. It is recommended to combine the international sustainable governance theories and practices to increase the bottom-up management tools such as public participation, public data sharing, stakeholder involvement.

China's coastal areas have almost all moved into the new phase of sustained growth after disturbances caused by shifting fisheries policies

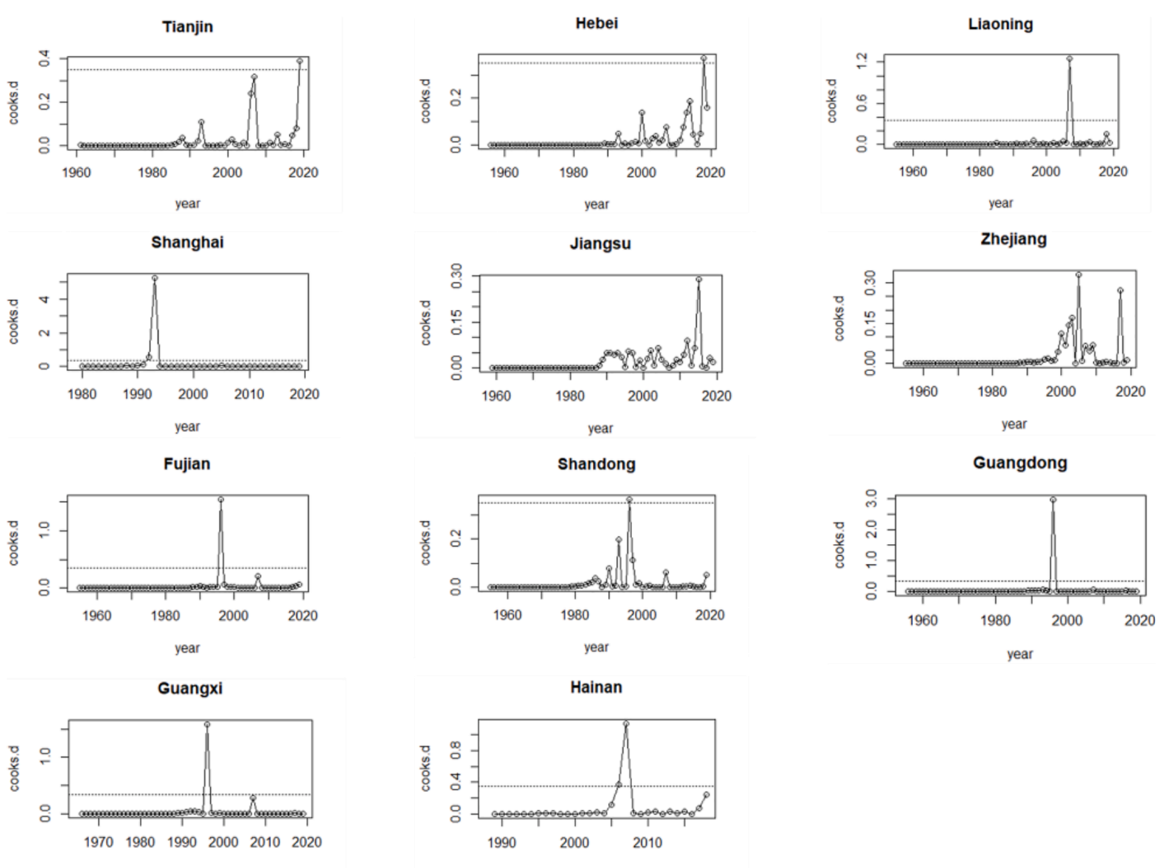


**Fig. 10.** Shock of mariculture production in coastal provinces and municipalities of China. Points with Cook's D greater than 0.35 are identified as shocks (the dotted line is Cook's D of 0.35).

and natural disasters, coastal regions in China have become more resilient and are more capable of mitigating future disturbances, while policy implementation from the regional government ensure the sustainable development and the dynamic equilibrium between human and ocean in those coastal areas could be achieved.

Special economic zones, including Shenzhen Zhuhai and Shantou in Guangdong province, Xiamen in Fujian province, were established in 1979, and Qingdao in Shandong province was selected as a pilot for economic reform in 1984 (Lu et al., 2019). Shandong, Fujian and Guangdong provinces all have received national financial and policy support, and all have urban agglomerations (Table 2) as critical geographical nodes of land and sea transport (Cui et al., 2019; Hui et al., 2020; Wang et al., 2018), which are considered to be prioritized in achieving sustainable development of ocean based on the results of shock detection (Table 2).

**Table 2**
China's coastal provinces with regional advantages for SDG 14

| Province | Related factors of SDG14 | Regional Advantages to lead SDG14 |
|---|---|---|
| Shandong | Urban Agglomeration | Shandong Peninsula |
| | Area | 73 000 $km^2$ |
| | GDP share of China economy | 3.3% |
| | Regional advantages | The first Chinese urban agglomeration to formulate a regional development strategy based on marine economy and a traditional heavy industry province. |
| | Shock detection | 1991-1992, the shock was caused by natural disasters (snowstorms and flooding). |
| | Advantages in coastal sustainable development | Strengthen the ability to resist natural disasters and build a resilient coastal city to further promote China's coastal sustainable development. |
| Fujian | Urban Agglomeration | The southern region of Fujian Province (Xiamen, Quanzhou and Zhangzhou cities) |
| | Area | 26 000 $km^2$ |
| | GDP share of China economy | 2.1% |
| | Regional advantages | Geographical advantage adjacent to Taiwan province attracts stable investments and an essential node of the maritime silk road. |
| | Shock detection | 1996, when China launched the China Ocean Agenda 21. Changes in policies caused the shock. |
| | Advantages in coastal sustainable development | Attracting foreign investment to improve China's coastal sustainable development based on national policy reform. |
| Guangdong | Urban Agglomeration | Guangdong-Hong Kong-Macao Greater Bay Area (GBA) |
| | Area | 56 000 $km^2$ |
| | GDP share of China economy | 8.8%[1] |
| | Regional advantages | GBA is considered an important support for constructing the "Belt and Road", which would be built into a world-class urban agglomeration and an international scientific and technological innovation centre. |
| | Shock detection | 1996, when China launched the China Ocean Agenda 21. Changes in policies caused the shock. |
| | Advantages in coastal sustainable development | Promoting the sustainable development of science and technology-based on national policy reform. |

[1] GDP of the GBA is calculated only for cities located in Guangdong Province in this study.

Reformation of the land-sea integration established the principle of managing coastal system as a whole and coordinates conflicts between land and ocean, which contributed to the achievement of land-ocean economic, social and ecologically sustainable development, which can better detect the impact of policy changes on the management system through the land-sea SD model with SSPs and the shock detection method.

## 5. Conclusions

The attainments of SDG14 will significantly depend on whether it can coordinate the relationship between land-sea resources and human activities and whether it can balance the trade-off between land and sea resources. This study used the SD method combined with the prediction of SSPs to identify the gaps in achieving China's coastal SDG14. The results show that although SDG14.1, 14.3 and SDG14.7 can be achieved, the implementation of SDG14.2, SDG14.5 and SDG14. A fail to achieve before 2100 in China, from this SDG14 would only be achieved partially. The resilience analysis points out that mariculture is the primary determinant for China to achieve SDG14. The mariculture industry meets the growing human demand for fishery resources in China, but the increasing mariculture encroaches on the spatial resources of coastal areas and leads to the decline of marine and coastal biodiversity. Besides, the unbalanced development of marine fisheries relative to other marine-related industries also hinders the sustainable development of China's coastal areas.

The application of resilience thinking is vital in promoting sustainable development, so shock detection of relevant variables and decoupling analysis can provide a resilience-based management framework for China to achieve SDG14

## CRediT authorship contribution statement

**Youzhu Zhao:** Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft. **Yangfan Li:** Conceptualization, Validation, Resources, Writing – review & editing, Supervision. **Xinwei Wang:** Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Supplementary materials

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