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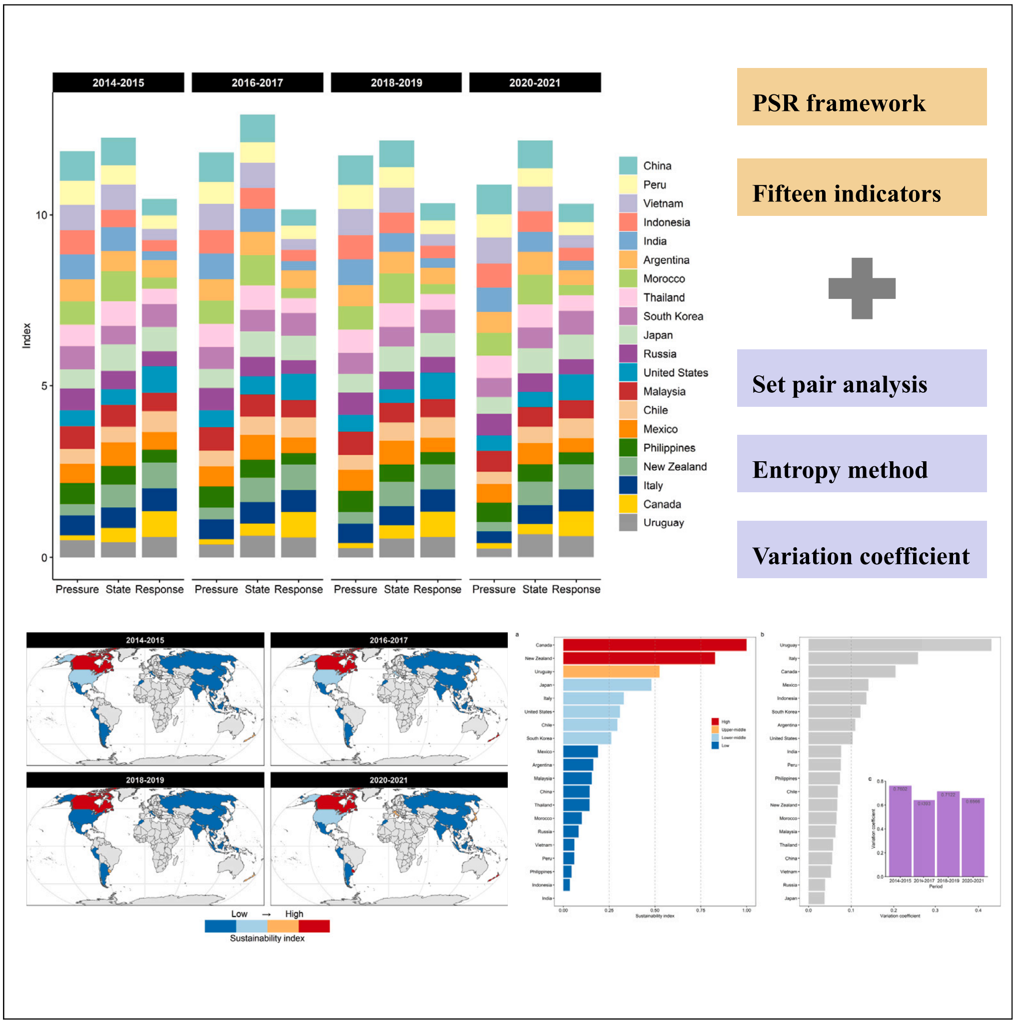
Global sustainability assessment of cephalopod fisheries based on pressure-state-response framework



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Highlights

The sustainability of fisheries in twenty major cephalopod producing countries is assessed

The CFS in developed countries is characterized by low pressure and high response

Differences in the level of CFS between the same countries are compared

The level of CFS varies greatly among countries but has narrowed slightly over time

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Global sustainability assessment of cephalopod fisheries based on pressure-state-response framework

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SUMMARY

Cephalopods are growing in commercial importance due to their unique biological characteristics; however, uncertainty about the pressure facing cephalopod fisheries poses a challenge to the health of fisheries and to policy development. Therefore, identifying and quantifying the dynamics of the sustainability of global cephalopod fisheries becomes critical. This study focuses on twenty major cephalopod producing countries around the world, using a pressure-state-response (PSR) framework together with an uncertainty assessment methodology. The results suggest that the sustainability of cephalopod fisheries varies greatly among countries; with developed countries characterized by low pressure and high response while developing countries show the opposite characteristics. Although there were large differences in the sustainability of this fishery among countries, the level of sustainability tightened slightly over time. The results emphasize that key response indicators, such as mitigating stressors on fisheries and improving the governance capacity of government departments, contribute to the sustainable use of cephalopod resources.

INTRODUCTION

Today's global marine fisheries face multiple challenges such as climate change, marine pollution, overfishing, and habitat loss.[1–4] In the post-pandemic era, human demand for food continues to rise,[5–7] and the marine food system is a powerful contributor to meeting this demand.[8–11] In recent years, FAO has been actively promoting the Blue Transformation strategy[7,12] globally to achieve the United Nations Sustainable Development Goal 14.[13] Governments have given high priority to this strategy through a range of policies and actions such as improving fisheries management,[5,14–16] expanding aquaculture activities and promoting sustainable intensification of production,[17–20] to maximize the use of marine resources and increase the resilience of marine food systems.[7,21]

However, sustainable management of marine fishery resources is not a one-day process, and overfishing over the past decades has put some fish stocks at risk of decline.[22–25] Sustainable (long-term) increases in wild fisheries production will require rebuilding overexploited stocks, scientific assessment and management of existing fish stocks, and most importantly, effective fisheries institutional reforms to have any chance of achieving this goal in the future.[26–29] The importance of cephalopods, such as squids, cuttlefishes, and octopuses, as fishery resources are expanding worldwide due to declining finfish stocks.[30–33] This change is reflected by the steady increase in global cephalopod landings over the past decade, reaching 3–5 million metric tons (t) annually.[34] Because cephalopods are rich in many essential amino acids and proteins, their commercial importance is also sharply increasing.[35,36] Cephalopod populations can increase in response to changing environments because of their unique biological characteristics, including rapid growth, short lifespan, and robust phenotypic plasticity.[37–39]

There are numerous authors who have studied the biology, ecology, management, and market trade of cephalopods.[40–44] However, to the best of our knowledge, no assessment of the level of cephalopod fisheries sustainability (CFS) on a global scale has been found. The CFS refers to the ability to produce and sell products that meet current demand without compromising (jeopardizing) the ability of future generations to meet their needs without destroying cephalopod fishery resources.[38,44–47] This concept emphasizes the conservation of cephalopod resources to ensure that fisheries can be sustained and adverse impacts on marine ecosystems can be reduced. The goal of sustainability is to achieve the renewability of cephalopod resources and ensure the stability of marine ecosystems while providing the food and economic opportunities that people need.[1,48,49] In other words, CFS needs to be balanced between ecological, economic, and social aspects.[36,50,51]

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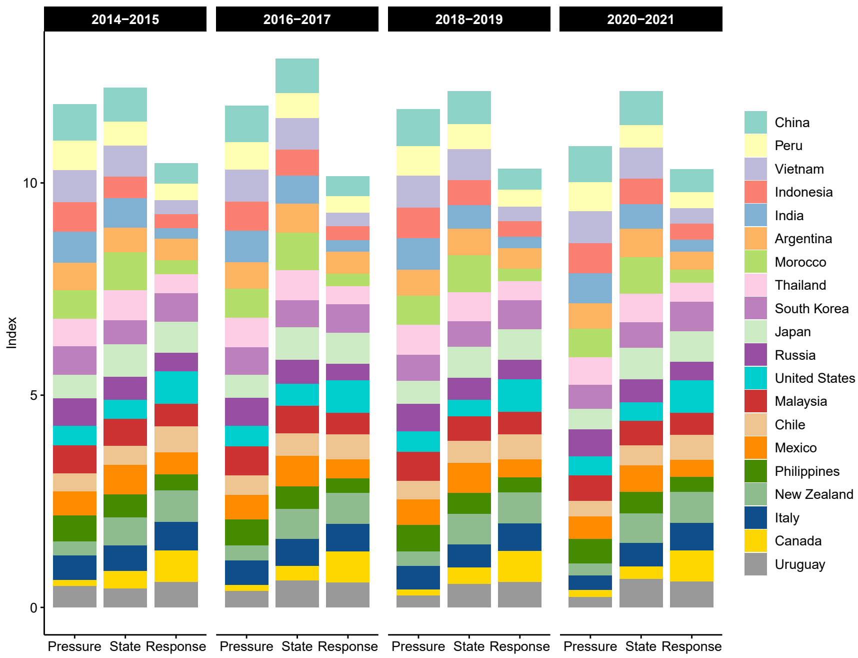

Figure 1. Trends in pressure, state, and response indexes for cephalopod fisheries during 2014–2021 in 20 countries

Based on the above considerations, and in order to fill the current gap in the literature, this article carries out an assessment of the level of CFS in major cephalopod producing, processing, and exporting countries around the world. This is essential to identify the key drivers of fisheries sustainability and to balance the socio-economic and ecological relationships. This study contributes to the understanding of the dynamics of CFS level in both the public and private sectors in each country and provides ideas for future sustainable development of cephalopod fisheries and policy formulation.

RESULTS

Pressure index

The cephalopod fisheries in twenty countries are under high pressure, with a pressure index exceeding 0.60 in 2014–2021 for China, Peru, Vietnam, Indonesia, India, Argentina, Morocco, Thailand, Russia, and Malaysia (Figure 1). High cephalopod production drives the pressure index, which is reflected by the pressure weights (Figure 2); with the industry concentration ratio (ICR) exceeding 0.48 in 2014–2021. Also contributing to the pressure index are food provision-fisheries (FPF) and species condition (SC), both of which have a weight of more than 0.13 in all four periods. In terms of the trend of the pressure index for cephalopod fisheries, many countries showed a decreasing trend. Uruguay's pressure index declined from 0.5028 in 2014–2015 to 0.2441 in 2020–2021, a decrease of approximately 51% (Figure 1). In the same period, Italy, South Korea, and Chile decreased by 41%, 17%, and 15%, respectively. The pressure index increased in just four countries, namely Canada (16%), Vietnam (2%), Thailand (1%) and Indonesia (1%).

State index

In terms of state index for cephalopod fisheries, China, Vietnam, Morocco, Thailand, Japan, Mexico, and New Zealand have high state index, which exceeded 0.60 in 2014–2021 (Figure 1). This means that these countries exhibit strong cephalopod processing capability and trade competitiveness. The key factors driving the state index include a proportion of processed (PP), export mean price (EMP), and revealed comparative advantage index (RCAI), which all have a weight of more than 0.17 in all four periods (Figure 2). From the trend of the state index, many countries showed a downward trend. Canada's index declined from 0.4127 in 2014–2015 to 0.2965 in 2020–2021, a decrease of approximately 28% (Figure 1). This change is related to the weakening competitiveness of the Canadian cephalopod trade. During the same period, India, Mexico, and Malaysia declined by 17%, 9%, and 8%, respectively. There were only seven countries with an increase in the state index, i.e., Uruguay (49%), Indonesia (20%), Argentina (14%), South Korea (8%), Chile (4%), New Zealand (4%) and Russia (1%).

Response index

In terms of response indexes for cephalopod fisheries, a variety of inputs and measures contributed to high response indexes in South Korea, Japan, the United States, New Zealand, Italy, and Canada, which exceeded 0.60 in 2014–2021 (Figure 1). The main factors driving the response index are GDP per capita (GDPPC), government effectiveness (GE), and life expectancy at birth (LEB), which have weights of more than 0.34,

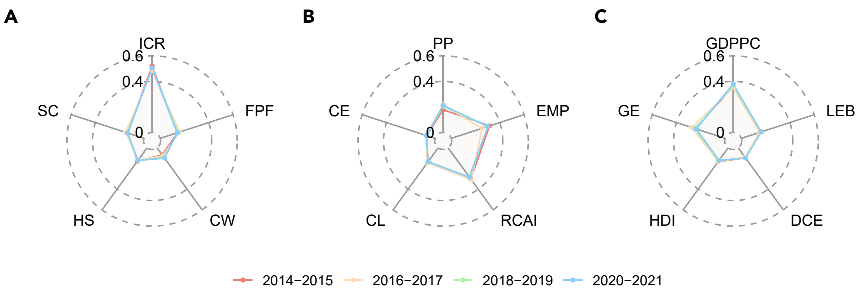

Figure 2. Indicator weights for cephalopod fisheries, with abbreviations in the figure corresponding to method details

(A) Pressure.

(B) State.

(C) Response.

0.23, and 0.15, respectively, in 2014–2021 (Figure 2). From the trend of the response index, there are eight countries whose response indexes are in an increasing trend in 2020–2021 compared to 2014–2015, namely Indonesia (16%), India (12%), China (11%), Vietnam (11%), South Korea (4%), Uruguay (2%), Russia (0.20%) and United States (0.03%) (Figure 1). The countries with larger declines were Mexico (20%), Argentina (17%), Philippines (7%), Morocco (6%) and Chile (6%).

Sustainability index

From the spatial distribution of CFS level (Figure 3), most countries are at low sustainability levels. The only country that consistently maintains a high sustainability level is Canada; followed by New Zealand, which is at an upper-middle sustainability level in 2014–2015 and in 2018–2019, and at a high sustainability level in the remaining two periods (2016–2017 and 2020–2021). Uruguay's sustainability level is characterized by a stepwise pattern, steadily increasing from a low sustainability level in 2014–2015 to a lower-middle level in 2016–2017, an upper-middle level in 2018–2019, and a high level in 2020–2021. Japan and Italy both have upper-middle levels in 2020–2021. South Korea and Chile had low levels in 2014–2015 and lower-middle levels in 2016–2021.

Classification, ranking, and differences in sustainability index

By the average of the four periods of the sustainability index (reported in quartiles) (Figure 4A), there are two countries with high sustainability levels (Canada and New Zealand), Uruguay with upper-middle level, five countries with lower-middle levels (Japan, Italy, United States, Chile, and South Korea), and twelve countries with low levels (Mexico, Argentina, Malaysia, China, Thailand, Morocco, Russia, Vietnam, Peru, Philippines, Indonesia and India). Ranked by the variation coefficient of the sustainability index (Figure 4B), the highest is Uruguay (0.4301), followed by Italy (0.2568) and Canada (0.2040). Other countries with variation coefficient above 0.1 were Mexico (0.1405), Indonesia (0.1358), Korea (0.1217), Argentina (0.1098), and the United States (0.1037). This indicates that the level of CFS in the above eight countries varied greatly in 2014–2021. Whereas, the countries with a variation coefficient below 0.1 were India, Peru, Philippines, Chile, New Zealand, Morocco, Malaysia, Thailand, China, Vietnam, Russia, and Japan. This indicates that the level of CFS in these twelve countries varied relatively little from 2014 to 2021. The variation coefficient of sustainability level among the twenty countries showed a decreasing trend over time, with the variation coefficient in the range of 0.6393–0.7602 (Figure 4C). The variation coefficient decreased from 0.7602 in 2014–2015 to 0.6566 in 2020–2021.

DISCUSSION

The present study shows that the sustainability of cephalopod fisheries in developed countries is determined by low pressure and high response, while developing countries are characterized by high pressure and low response. Potential distribution and resource shifts of cephalopod are influenced by a combination of climate change and marine environmental conditions, and countries closer to cephalopod-rich fishing grounds may benefit.[52–55] However, the expansion of cephalopod production has put fisheries sustainability under higher pressure, which is more evident in developing countries.[40,41,56,57] Cephalopod populations are monitored, assessed, and regulated more in developed countries than in developing countries.[31,58] More importantly, economic globalization has promoted and facilitated the trade and circulation of seafood between countries,[9,59–61] which has allowed developed countries to import large quantities of seafood from developing countries, greatly reducing the pressure on them to overfishing.[51,62–64]

It is worth mentioning that there is a clear downward trend in the cephalopod fisheries pressure index in most countries, which is inextricably linked to the Blue Transformation strategy. Specifically, countries (especially developing countries) have further strengthened the management and regulation of fishery resources in recent years, and have successively carried out and promoted many effective management measures and actions, including 1) establishment and improvement of financial support policies to support basic fisheries monitoring and improved data statistics.[32,65–68] 2) control of domestic fishing activities and expansion of high seas activities,[69] but recent conferences have called on countries to strengthen and support high seas biodiversity conservation[70,71]; considering the large global population and

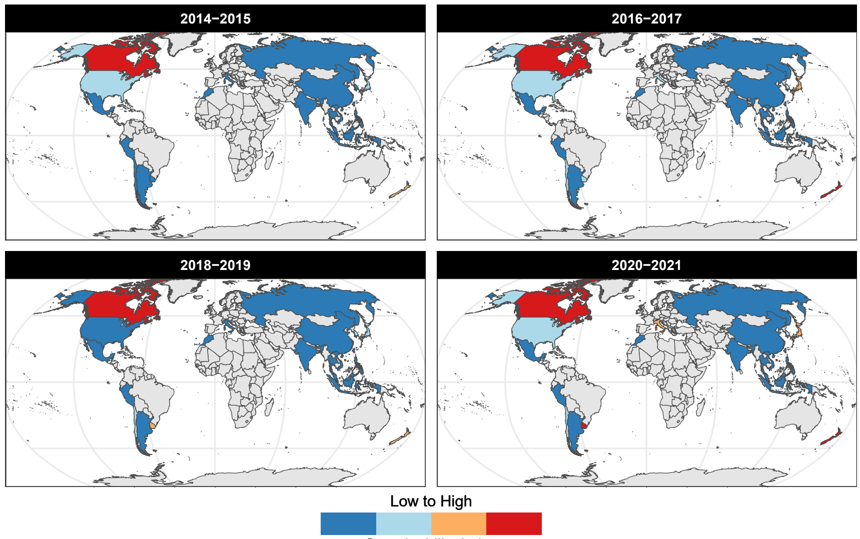

Figure 3. Spatial distribution of sustainability levels of cephalopod fisheries during 2014–2021 in 20 countries

growing demand for seafood, weighing the socio-economic and ecological relationships is necessary. 3) pilot implementation of the Total Allowable Catch (TAC)[72,73] and exploring the adoption of an ecosystem approach to management.[74–76] 4) carry out seasonal closure (fishing moratorium) in exclusive economic zones (EEZs) and the high seas.[36,77,78]

The state index of cephalopod fisheries was high in all countries. This is not difficult to explain as the twenty countries selected for the study are important cephalopod producers, processors, and exporters in the world. Although cephalopod production in developed countries (South Korea, Japan, United States, and Italy) has been decreasing over recent years, the total imports of the four countries in 2021 were more than 700,000 t (Table S4), while the processed production of the largest global producer (China) was only about 580,000 t (Table S2). Production in New Zealand and Canada has continued to expand in recent years, even though neither of them are producing much. Uruguay's rapid development of the cephalopod processing trade compensates for its low production, giving it a high ranking. The increase in processing capacity in developing countries is not only for the purpose of expanding exports (to developed countries),[35,62] but also due to the transition in the direction of domestic consumer consumption, with high value-added products (e.g., healthcare products and casual foods) being favored by consumers.[43,44,79–81]

The results of the variation coefficient suggest that cephalopod fisheries in developed countries have a higher level of sustainability compared to developing countries in the long run. This is consistent with similar findings and is mainly due to the small scale of this fishery in developed countries and their dependence on import trade (which promotes exports from developing countries).[82,83] In addition, the levels of CFS themselves have not changed much over time across countries. However, differences in the level of sustainability across countries are large and show a slight trend of narrowing over time. The results of this trend further confirm the efforts of these countries to alleviate the pressure on cephalopod fisheries.

The results of our analysis inform policymakers, managers, and the industry, that they should not only focus on the sources of pressure on cephalopod fisheries, but also promote sustained and healthy economic development, and enhance the governance capacity of the public sector, which can help to achieve the sustainable use of cephalopod resources. Regulation of fishing activities should focus not only on domestic coastal waters but also on distant waters.[84,85] For example, China has proposed and formulated relevant policies and action programs in its national-level planning.[86] Particularly with regard to pelagic fisheries, proposed measures include combating illegal fishing activities, strengthening conservation and sustainable utilization of fishery resources, and developing fishery exchanges and cooperation between countries and regions.[87]

Limitations of the study

The findings and insights of this study are only a beginning. The research limitations include 1) it is challenging to fully capture the required intermediate factor data in existing relevant databases. The broader applicability of the research framework and indicators needs to be further refined (e.g., the distinction between industrial and artisanal fisheries, and the degree of spatial agglomeration in cephalopod fisheries). 2) the research process may have overlooked differences in synergistic processes and dynamic mechanisms between subsystems. We also acknowledge that promoting sustainable development of cephalopod fisheries does not rely on a single model of fisheries management, and published studies agree on the need to integrate social, economic, and ecological factors, and to tailor, categorize, and promote policies according to local conditions.[27,29,46,88,89] Examples include ecosystem-based fisheries management (EBFM) promoted by ecologists[90] and rights-based fisheries management (RBFM) proposed by economists.[91] In addition, despite the rapid development of cephalopod aquaculture, the

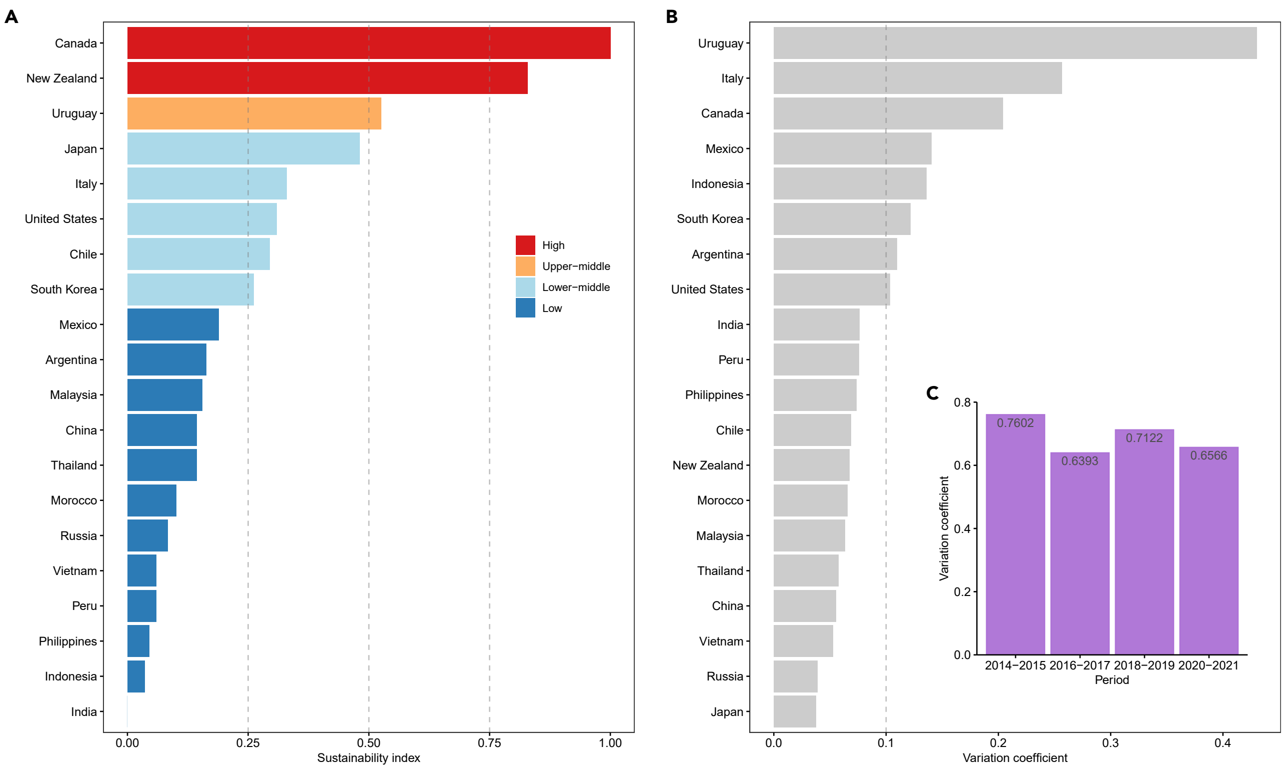

Figure 4. Ranking results by mean and variation coefficient of sustainability levels in 20 countries
(A) Sustainability level ranking.
(B) Variation coefficient ranking.
(C) Trends of variation coefficient in 2014–2021.

industrialization and scale of cephalopods has been hampered by factors such as artificial breeding, culture technologies, and consumer preferences,[92] and with this, animal welfare has received attention from both the public sector and the scientific community.[93,94]

Conclusions

This article is based on the PSR framework and integrates relevant socioeconomic and ecological data to conduct a global assessment of the CFS level. Integrating the pressure, state, and response dimensions, the CFS level varies among countries, with developed countries tending to have low pressure and high response, while developing countries, on the contrary, have high pressure and low response. Overall, cephalopod fisheries were more sustainable in developed countries compared to developing countries, owing to the small scale of the industry in developed countries and their dependence on imports. Although there were large differences in CFS levels between countries, the levels have contracted slightly over time. In addition, the study highlights which key response indicators can be used to enhance the sustainability of cephalopod fisheries. Our study suggests promoting the sustainability of global cephalopod fisheries is a long-term task that is both easy to understand and difficult to implement, and one that requires and deserves the sustained efforts of governments, industry, scientists, fishers, and stakeholders.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact: Yugui Zhu (zhuyugui@ouc.edu.cn).

Materials availability

This study did not generate new materials.

Data and code availability

- All data are publicly available and sources are listed in the key resources table.
- This article does not report original code.
- Any additional information required to reanalyze the data reported in this article is available from the lead contact upon request.

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AUTHOR CONTRIBUTIONS

Conceptualization: D.P., Y.Z., and J.C.
Methodology: D.P.
Formal analysis: D.P. and Y.Z.
Investigation: D.P., H.L., W.Z., L.X., and R.J.
Resources: D.P., H.L., W.Z., L.X., and R.J.
Data curation: D.P., H.L., W.Z., L.X., and R.J.
Writing - original draft: D.P.
Writing - review and editing: D.P., H.L., W.Z., L.X., R.J., Y.Z., I.G.L., J.C., U.R.S.
Supervision: Y.Z. and J.C.
Project administration: Y.Z. and J.C.
Funding acquisition: Y.Z. and J.C.

DECLARATION OF INTERESTS

The authors declare no competing interests.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- METHOD DETAILS
  - Data sources and treatment
  - Fisheries sustainability assessment framework
  - Methodology

SUPPLEMENTAL INFORMATION

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Production, processing and trade	FishStat	https://www.fao.org/fishery/en/fishstat/collections
Economic development, life and education	World Bank	https://data.worldbank.org
Ocean Health Index	Ocean Health Index	https://oceanhealthindex.org/; https://raw.githack.com/OHI-Science/ohi-global/draft/documents/methods/Supplement.html
Human Development Index	UNDP-HDI	https://hdr.undp.org/
Government effectiveness	Worldwide Governance Indicators	https://www.worldbank.org/en/publication/worldwide-governance-indicators
Software and algorithms		
R v 4.3.1	R: A Language and Environment for Statistical Computing	https://www.r-project.org/

METHOD DETAILS

Data sources and treatment

All data were collected from the FishStat,[34] World Bank,[95] Ocean Health Index,[48,96] Human Development Index,[97] and Worldwide Governance Indicators.[98] In this study, twenty major cephalopod producing, processing and exporting countries in the world were selected for analysis, which accounted for 87%, 81% and 74% of the global total production, total processed production and total export share, respectively, and all of them produced more than they exported (supplemental information). Other countries and regions accounted for only a negligible proportion of global cephalopod production, processed production and export share and were therefore not included in the assessment of CFS. Cephalopods, which include squids, cuttlefishes, and octopuses, were the focus of research during 2014–2021.[99] Considering the fluctuating nature of cephalopod production and to reduce the impact of inter-annual variation on the results, the time series was divided into four periods (consecutive two-year intervals) for assessment. Spatial visualization mapping was performed through the ggplot2 package in R v 4.3.1.[100,101]

Fisheries sustainability assessment framework

For the assessment of CFS, it is necessary to consider both the sustainable utilization of cephalopod resources and the trade-off between socio-economic and ecological relationships. The indicator system should be constructed according to the principles of importance, scientificity, and representativeness of the indicators, and cover the attributes and characteristics of all aspects of CFS. From the perspective of managers and policymakers, they are more concerned with the operationalization of the overall methodology and indicator system.[102,103] Therefore, indicators are selected to avoid or reduce some indicator interpretation ambiguities, and indicators that are difficult to quantify or collect can be eliminated or replaced with easily quantifiable or similar indicators.[104] As the pressure-state-response (PSR) framework can better reflect the interaction relationship between indicators and ensure the coordination and integrity of the indicator system.[105,106] Therefore, the PSR framework (or the enhanced framework, i.e., driver-pressure-state-impact-response) has been widely used in the study of sustainable development and environmental issues, and has been adopted by many researchers in the field of fisheries.[107,108] For example, Mangi et al. (2007) evaluated the current status of coral reef fisheries management based on this framework.[102] Ou and Liu (2010) designed a system of indicators to identify changes in regional fisheries system pressure, state and response.[109] Zhao and He (2023) conducted a risk assessment of the pelagic fisheries industry.[103]

In summary, this study constructs an assessment system based on the PSR framework and establishes a corresponding indicator system according to the three dimensions of pressure, status and response to clearly demonstrate the status and trend of the level of CFS in the main producing countries. In addition, compared with other frameworks, the study adopts the PSR framework to better match the collected data indicators. Eventually, fifteen indicators were selected in this study to establish an indicator system for the CFS (Table). Pressure refers to the loads on marine and coastal ecosystems caused by cephalopod fisheries fishing activities and human socioeconomic activities, and the pressure indicators include resource pressures (cephalopod industry concentration ratio, food supply capacity) and ecological pressures (clean waters, critical habitats, and native marine species). Some countries conduct cephalopod fishing activities not only in coastal waters but also in distant waters, making it difficult to compare the degree of spatial agglomeration of cephalopod production between countries. Therefore, the study used the ratio of production (industry concentration ratio) to reflect the characteristics of industrial agglomeration.[110] State refers to the current status of the cephalopod fisheries (industry) at a given stage, using cephalopod processing capacity, trade competitiveness, and the status of livelihoods and economic gains from the marine sector as state indicators. It should be noted that this study focuses on the sustainable utilization of cephalopod resources. Such sustainable development requires a trade-off between socio-economic and ecological relationships, and cephalopod processing capacity and trade competitiveness are prerequisites for sustainable industrial development. Various inputs and measures such as economic development, educational potential for blue growth, and social governance are used as response indicators to represent the adaptive capacity and resilience of the cephalopod fisheries.

Indicator system and data sources for assessing the sustainability of cephalopod fisheries

Subsystem	Factor	Indicator	Description	Data sources
Pressure	Resource pressure	Industry concentration ratio (ICR)	Reflects the degree of spatial agglomeration of cephalopod fisheries. Industry concentration ratio = Cephalopod production in a country/Global cephalopod production	FishStat
		Food provision-fisheries (FPF)	Reflects the ability to sustainably harvest wild seafood.	Ocean Health Index
	Eco-environmental pressure	Clean waters (CW)	Reflects the extent to which marine areas are protected from pollutants.	Ocean Health Index
		Habitat status (HS)	Reflects the status of critical habitat.	Ocean Health Index
		Species condition (SC)	Reflect species conservation status.	Ocean Health Index
State	Processing capability	Proportion of processed (PP)	Reflects the development level of cephalopod processing trade. Proportion of processed = Cephalopod processed production/(Cephalopod production + Cephalopod import quantity)	FishStat
	Trade competitiveness	Export mean price (EMP)	Reflects the export benefits of cephalopods. Export mean price = Cephalopod export value/Cephalopod export quantity	FishStat
		Revealed comparative advantage index (RCAI)	Reflects the degree of comparative advantage of cephalopods in the international market. Revealed comparative advantage index = (Cephalopod export value in a country/Aquatic products export value in a country)/(Global cephalopod export value/Global aquatic products export value) Aquatic products include aquatic plants, crustaceans, fishes, and molluscs.	FishStat
	Coastal livelihoods and economies	Coastal livelihoods (CL)	Reflecting the livelihoods generated by the marine sector.	Ocean Health Index
		Coastal economies (CE)	Reflects the economic revenues generated by the marine sector.	Ocean Health Index
Response	Economic development	GDP per capita (GDPPC)	Reflects the level of affluence and economic development of a country.	World Bank
	Educational potential	Life expectancy at birth (LEB)	Reflects the educational potential of blue growth.	World Bank
		Duration of compulsory education (DCE)	Reflects the educational potential of blue growth.	World Bank
		Human Development Index (HDI)	Reflects the educational potential of blue growth.	UNDP-HDI
	Social governance	Government effectiveness (GE)	Reflects social governance capacity.	Worldwide Governance Indicators

Methodology

Set pair analysis (SPA) is a theory for the analysis of certainty and uncertainty problems, which is widely used in the fields of carrying capacity prediction, ecological footprint, evaluation and management.[111–113] Fisheries systems are inherently characterized by uncertainty and fisheries sustainability is a broad concept.[114] Therefore, this paper uses SPA to assess the level of CFS across countries.

The multi-attribute evaluation problem is denoted as $P = \{F,E,W,X\}$; where, the scheme set $F = \{f_1,f_2,...,f_m\}$, indicator set $E = \{e_1,e_2,...,e_n\}$, weight set $W = \{w_1,w_2,...,w_n\}$, and initial matrix $X = (x_{kr})_{m\times n}$. The study uses a two-year period and the average of the two-year indicators as the attribute value of a country for a certain indicator in that period. The steps for analyzing the pressure, state, and response indexes for the three dimensions are as follows.

Step 1. Construction of initial matrix

$$X = (x_{kr})_{m\times n} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad \text{(Equation 1)}$$

The above formula indicates that evaluation is performed on n indicators of m countries, and the r-th indicator of the k-th country is expressed as x_{kr}.

Step 2. Determination of the best and worst solutions

Compare and determine the best and worst indicators in each evaluation scheme in the same space:

$$U = (u_1, u_2, ..., u_n), V = (v_1, v_2, ..., v_n) \quad \text{(Equation 2)}$$

Where, U and V represent the best and worst solutions, respectively; and u_r and v_r are the best (maximum) and worst (minimum) values of the r-th indicator of all countries in a certain period, respectively. Note $[v_r,u_r]$ constitutes the comparison interval of the indicator e_r, and $[V,U]$ constitutes the comparison space of the scheme f_k.

Step 3. Calculation of connectivity

(i) In the comparison interval of $[v_r,u_r]$, the connection degree of $[x_{kr},u_r]$ is

$$\mu_{kr} = a_{kr} + b_{kr}i + c_{kr}j \quad \text{(Equation 3)}$$

Where, μ_{kr} represents the connectivity of x_{kr} to the best (worst) solution; there are two types of indicators, i.e., benefit and cost indicators.

Benefit indicator:

$$\begin{cases} a_{kr} = \dfrac{x_{kr}}{u_r+v_r} \\ c_{kr} = \dfrac{u_r v_r}{(u_r+v_r)x_{kr}} \\ b_{kr} = 1 - a_{kr} - c_{kr} = \dfrac{(u_r - x_{kr})(x_{kr} - v_r)}{(u_r+v_r)x_{kr}} \end{cases} \quad \text{(Equation 4)}$$

where, the uncertain degree b_{kr} is calculated according to $a+b+c = 1$.

Connectivity is

$$\mu\{x_{kr}, u_r\} = \frac{x_{kr}}{u_r+v_r} + \frac{(u_r - x_{kr})(x_{kr} - v_r)}{(u_r+v_r)x_{kr}}i + \frac{u_r v_r}{(u_r+v_r)x_{kr}}j \quad \text{(Equation 5)}$$

Cost indicator:

$$\begin{cases} a_{kr} = \dfrac{u_r v_r}{(u_r+v_r)x_{kr}} \\ c_{kr} = \dfrac{x_{kr}}{u_r+v_r} \\ b_{kr} = 1 - a_{kr} - c_{kr} = \dfrac{(u_r - x_{kr})(x_{kr} - v_r)}{(u_r+v_r)x_{kr}} \end{cases} \quad \text{(Equation 6)}$$

Connectivity is

$$\mu\{x_{kr}, v_r\} = \frac{u_r v_r}{(u_r+v_r)x_{kr}} + \frac{(u_r - x_{kr})(x_{kr} - v_r)}{(u_r+v_r)x_{kr}}i + \frac{x_{kr}}{u_r+v_r}j \quad \text{(Equation 7)}$$

(ii) In the comparison space of $[V,U]$, the connection degree of $[f_k,U]$ is

$$\mu_k = a_k + b_k i + c_k j \quad \text{(Equation 8)}$$

$$a_k = \sum_{r=1}^{n} w_r a_{kr},\ b_k = \sum_{r=1}^{n} w_r b_{kr},\ c_k = \sum_{r=1}^{n} w_r c_{kr} \quad \text{(Equation 9)}$$

In Equations 8 and 9, μ_k represents the comprehensive connection degree of the best (worst) solution of a country; w_r is the weight calculated by the entropy method and the initial matrix data needs to be normalized (min-max method).[115,116]

Step 4. Calculation of closeness

The closeness of a country to the optimal solution U is:

$$S_k = a_k / (a_k + c_k) \quad \text{(Equation 10)}$$

The larger the value of S_k, the stronger the pressure, state, or response index.

Step 5. Calculation of the level of sustainability

In order to better reflect the synergy between the three-dimensional indexes,[117–119] this study used a multiplicative model to calculate sustainability. Larger values represent higher levels of sustainability. The formula is as follows.

$$\text{Sustainability level} = (\text{State} \times \text{Response}) / \text{Pressure} \quad \text{(Equation 11)}$$

The pressure, state, and response indexes for each period are presented using the calculated raw values, while the level of sustainability for each period and the average of its four periods are presented in quartiles (high, upper-middle, lower-middle, and low).

Step 6. Variation coefficient

To compare the differences in the level of CFS between countries, the variation coefficient of closeness is therefore calculated.[120]