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Ecological footprint and vulnerability of marine capture fisheries in China

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Abstract

China (herein referred as China's mainland, and excluding Hong Kong, Macau and Taiwan) ranks as the world's leading fishing nation, with approximately 11.1 million tons of domestic marine catch acquired in 2017. Marine fisheries resources in China are mainly exploited by its 11 coastal provinces and municipalities, and the development of fishing industry varies among them. However, few studies have examined the exploitation history of the 11 coastal provinces and municipalities. In this paper, we systematically quantified the exploitation history of marine fishery resources in China and then measured the vulnerability of the 11 coastal provinces and municipalities of China to a reduction in marine catches. Our analysis suggested that Chinese marine fisheries experienced rapid growth from the mid-1980s to the end of the 20th century, and this rapid increase in marine catches were mainly promoted by increased fishing effort. The total primary production required level amounted to approximately 80% of the average primary productivity in 2017, and Zhejiang, Fujian, Shandong, Hainan and Guangdong provinces were the main fishing provinces in China. By assessing three dimensions of vulnerability (exposure, sensitivity and adaptive capacity) to the impacts of a reduction in marine catches in the 11 coastal provinces and municipalities, we found that Hainan, Guangxi, Zhejiang and Fujian provinces had high or very high vulnerability, while the municipalities of Shanghai and Tianjin had low vulnerability. Identifying suitable adaptation policies and management plans based on the differences in vulnerability among coastal provinces is important in sustainable fisheries management.

Key words: marine capture fisheries, coastal provinces and municipalities, exploitation history, vulnerability

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1 Introduction

Fishing is likely to have the greatest anthropogenic impact on marine ecosystems (Worm et al., 2009; Watson et al., 2013, 2014). Marine capture fisheries in China (herein referred as China's mainland, and excluding Hong Kong, Macau and Taiwan) have undergone considerable development in the past few decades, the domestic marine catch totaled only 0.6 million tons in 1950 but increased dramatically to 11.1 million tons in 2017. China is now the world's largest country in terms of marine catches, accounting for approximately one-fifth of the global catch (FAO, 2016). Not surprisingly, the rapid development of China's marine fisheries has placed tremendous pressure on the country's marine ecosystems (Liu, 2013; Shen and Heino, 2014). Studying and understanding the impacts of fishery-induced changes in marine ecosystems is important for developing effective policies and management strategies (Bell et al., 2017). Marine fishery resources in China are mainly exploited by the country's 11 coastal provinces and municipalities, and the developmental history of the fishing industry varies among them. Growing efforts have been made to document the sustainability of China's marine fisheries and discuss the need for new directions in fisheries management (Yu and Yu, 2008; Pauly et al., 2014; Cao et al., 2017). However, there is a lack of quantitative information regarding the exploitation histories of these 11 coastal provinces and municipalities.

Fishing impacts on marine ecosystems, which include species across the food chain, from herbivores to top predators, cannot be fully assessed with the study of single-species catches (Swartz et al., 2010; Watson et al., 2014). The primary production required (PPR) to sustain marine catches is a measure of the primary production (PP) needed to replace the biomass of fisheries landings removed from marine ecosystems (Pauly and Christensen, 1995). The PPR can be expressed per unit of PP of the marine ecosystem, measured as the relative PPR (PPR/PP, %PPR) (Pauly and Christensen, 1995). As a commonly used metric of the ecological footprint of fishing, the %PPR allows the comparison of catches with very different species compositions from different ecosystems, and it has been increasingly used in

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the quantification of fishing pressure on marine ecosystems and the examination of historical fishing behavior of global fishing fleets (Pauly and Christensen, 1995; Swartz et al., 2010; Coll et al., 2013; Ding et al., 2017a). However, how much PP has been captured by Chinese fishing fleets over time and how the various fleets from each fishing province contribute to these changes remain unknown.

China's marine capture fisheries are currently underperforming, largely due to overfishing. The proportion of stocks assessed as overfished increased from 0% in 1950 to 52.4% in 2014 (Pauly and Zeller, 2015). To reduce the fishing pressure applied to fish stocks and achieve sustainable fishery development, the Ministry of Agriculture and Rural Affairs of the People's Republic of China (MARA) announced plans in 2017 to reduce the total marine catch to 10 million tons by 2020 (from 13 million tons in 2015). This change would require at least a 23.6% reduction in marine catches for each coastal province and municipality by the year 2020 compared to the year 2015. Marine fisheries are important as a source of food and employment in China, and understanding where a decline in marine catches may have the greatest socioeconomic impacts is therefore a necessary and important first step in informing management strategies and increasing the resilience of the coastal provinces (Cao et al., 2017).

Vulnerability is generally considered to be the degree to which a system is susceptible to and unable to cope with the adverse effects of a chronic or stochastic disturbance (Cutter, 1996; Adger, 2006), and vulnerability assessments are increasingly being used in various sectors and fields of society to develop appropriate adaptation policies and management plans for different economic sectors (Johnson and Welch, 2009; Huang et al., 2012; Ding et al., 2017b). Since Allison et al. (2009) first evaluated fisheries vulnerability to climate change, many authors have examined fisheries vulnerability in the face of various drivers (Cinner et al., 2012; 2013; Pelletier et al., 2014). The components of vulnerability—exposure, sensitivity and adaptive capacity—are expected to vary among different coastal provinces, and assessing the relative vulnerability of coastal provinces to a reduction in marine catches is an important step toward enhancing the understanding of this vulnerability and informing decision making to reduce it.

Marine capture fisheries in China have undergone rapid development over the past several decades, but how fishing fleets from various coastal provinces contribute to these changes remains an under-considered issue. The present paper examines the changes that have occurred since detailed catch statistics begin to be published annually in the mid-1980s. In this paper, we systematically evaluate the exploitation history of marine capture fisheries in China, focusing on the historical exploitation behavior of fishing fleets from the 11 coastal provinces and municipalities. Using the framework of vulnerability, we then present the most detailed comparative study to date on the vulnerability of these coastal provinces to the impacts of a reduction in marine catches. This study can assist policy makers and fisheries scientists to understand the exploitation dynamics of fishing fleets in the coastal provinces of China and provide guidance for the formulation of effective policies to reduce specific aspects of vulnerability.

2 Materials and methods

2.1 *Overview of China's fishing industry*

This study focused on domestic marine capture fisheries (excluding aquaculture, inland fisheries, and distant-water fisheries), and these fisheries data were all from China's mainland (Hong Kong, Macau and Taiwan were excluded). We used a time-series analysis of annual catch, fishing effort, and %PPR to quantify the general exploitation history of marine capture fisheries in China. Detailed catch statistics for the coastal provinces began to be published annually in the mid-1980s; thus, the time-series data for the %PPR and fishing effort started from the year 1985. The %PPR was used to quantify the fishing pressure on marine ecosystems, with a higher %PPR related to a higher level of exploitation and fishing pressure (Pauly and Christensen, 1995; Swartz et al., 2010; Watson et al., 2014). Following Pauly and Christensen (1995), the PPR can be calculated as follows:

$$\mathrm{PPR} = \sum_i \left[\frac{Y_i}{CR} \times \left(\frac{1}{TE} \right)^{TL_i - 1} \right],$$

where Y_i is the catch of species *i*, *CR* is the conversion rate of wet weight of catches to carbon, *TE* is the trophic transfer efficiency, and TL_i is the trophic level of species *i*.

Data on annual marine catch and fishing effort were obtained from the China Fisheries Statistical Yearbook (Fisheries Bureau of the Ministry of Agriculture, 1950–2018), and catch data were all corrected based on the Food and Agriculture Organization of the United Nation's (FAO) global fisheries landings statistics (www.fao.org/fishery/statistics/en). Species-specific trophic levels were obtained from FishBase (www.fishbase.org). Primary production data in the exclusive economic zone (EEZ) of China were acquired from the Sea Around Us project database (www.seaaroundus.org). Based on the United Nations Convention on the Law of the Sea, Law of the People's Republic of China on the Exclusive Economic Zone and the Continental Shelf, the total sea area under the jurisdiction of China is approximately 3 million square kilometers. Here, we applied a 9:1 ratio for *CR* and 10% for *TE* (Pauly and Christensen, 1995; Watson et al., 2014).

2.2 *Vulnerability assessment*

The MARA developed a Five-Year Plan for marine fisheries in 2017, which included at least a 23.6% reduction in marine catches for each coastal province by 2020. Using the methods of Allison et al. (2009), which were originally developed to evaluate fisheries vulnerability to climate change, we classified the vulnerability of coastal provinces to a decrease in marine catches. We used data from various sources to quantify vulnerability as a function of the following three components: a coastal province's exposure to a decrease in marine catches, its sensitivity to this change, and its adaptive capacity or potential to respond to this change (Adger, 2006) (Table 1). This paper aimed to evaluate provincial vulnerability to a reduction in marine catches to understand the causes of such vulnerability.

2.2.1 *Exposure*

The proportion of marine fisheries in total fishery production (including aquaculture, inland fisheries, and distant-water fisheries) varies significantly among the coastal provinces (Table 2); thus, different provinces may suffer from varying degrees of social-economic disturbances in the face of the same reduction in marine catches. In this paper, exposure was estimated using marine catches as a percentage of the total fishery production. All fishery production databases were obtained from the China Fishery Statistical Yearbook. For each indicator, average values for the period 2015–2017 or the most recent data available (indicator of flexibility) were used to counter interannual variability. This study assumed that a higher contribution of marine fisheries to total fishery production implied greater exposure to the reduction in marine catches.

Table 1. Summary of the variables and data sources used to calculate the exposure, sensitivity and adaptive capacity of coastal provinces to fishery vulnerability associated with a reduction in marine catches

Component	Interpretation	Variable	Data sources
Exposure	reliance on marine capture fisheries (2015–2017)	marine catches as a percentage of total fishery production	China Fishery Statistical Yearbook 2016–2018
Sensitivity	food security dependency (2015–2017)	$\frac{\text{fish protein intake/total animal protein intake}}{\text{total animal protein intake/required animal protein intake}}$	China Statistical Yearbook 2016–2018
	employment dependency (2015–2017)	marine capture fisheries employment as a percentage of the total employment	China Fishery Statistical Yearbook 2016–2018 and Statistical Yearbook of Related Provinces 2016–2018
	economic dependency (2015–2017)	economic value of marine capture fisheries as a percentage of the GDP	China Fishery Statistical Yearbook 2016–2018 and China Statistical Yearbook 2016–2018
Adaptive capacity	assets (2015–2017)	GDP per capita	China Statistical Yearbook 2016–2018
	flexibility (2010)	life expectancy at birth	China Population and Employment Statistics Yearbook 2017
	learning (2015–2017)	average years of education	China Statistical Yearbook 2016–2018
	social organization (2015–2017)	input intensity of R&D	China Statistical Yearbook on Science and Technology 2016–2018

Table 2. The percentage of fishery production of different fishery sectors in total fishery production for the 11 coastal provinces and municipalities of China, averaged over 2015–2017

Fishing provinces and municipalities	Marine capture fishery/%	Distant water fishery/%	Freshwater capture fishery /%	Aquaculture/%
Tianjin	10.5	4.1	2.2	83.2
Hebei	20.0	2.8	5.7	71.5
Liaoning	14.6	5.7	1.0	78.7
Shanghai	5.7	47.3	0.7	46.3
Jiangsu	10.6	0.5	6.1	82.8
Zhejiang	55.0	8.2	1.6	35.2
Fujian	25.7	4.7	1.0	68.6
Shandong	22.0	5.3	1.0	71.7
Guangdong	17.6	0.6	1.4	80.4
Guangxi	19.6	0.2	3.5	76.7
Hainan	65.1	0	0.9	34.0

Note: Data source: China Fishery Statistical Yearbook.

2.2.2 *Sensitivity*

Sensitivity was defined as the degree to which a coastal province was dependent on marine fisheries for its economy and food security, and it was calculated using three indices: employment dependency, economic dependency, and food security dependency (Barange et al., 2014). Employment dependency was represented using marine capture fisheries employment as a percentage of total employment. Economic dependency was estimated using the economic value of marine capture fisheries as a percentage of GDP. Food security dependency was calculated by adopting a previously developed methodology (Table 1). Data on fish protein intake, total animal protein intake, and GDP were sourced from the China Statistical Yearbook. Marine capture fisheries employment and its fishery economic value were derived from the China Fishery Statistical Yearbook. Total employment data for each province were obtained from the statistical yearbook of corresponding provinces. In accordance with earlier studies, we used a minimum requirement of 36 g animal protein per capita day for an average adult (Akpan et al., 2013). Sensitivity was determined by taking the average of the three indices, and we assumed that higher dependency on marine capture fisheries reflected greater sensitivity.

2.2.3 *Adaptive capacity*

Adaptive capacity was defined as the ability of coastal provinces to handle changes in marine catches. Based on an earlier work in which adaptive capacity was disaggregated into four categories—assets, flexibility, learning, and social organization (Cinner et al., 2009), this study calculated adaptive capacity using four key indicators in the above categories: GDP per capita, life expectancy at birth, average years of education, and input intensity of research and development (R&D). Data on GDP per capita and average years of education were obtained from the China Statistical Yearbook, while the data on the life expectancy at birth and input intensity of R&D were provided by the China Population and Employment Statistics Yearbook and China Statistical Yearbook on Science and Technology, respectively. Adaptive capacity was calculated as an average of the above four indicators, with higher values reflecting greater adaptive capacity.

2.3 *Analysis*

Vulnerability, as a broad concept, has the characteristics of uncertainty and relativity. Therefore, the criteria used to evaluate vulnerability are also uncertain and can be selected according to the actual situation (Monnereau et al., 2015). In this paper, the method of set pair analysis (SPA) was used to estimate the vulnerability of coastal provinces to a reduction in marine catches (Zhao, 2000).

The core concept behind SPA is to analyze the certainty and uncertainty factors in a set pair. Set E and set U have certain connections between each other, and these two sets are regarded as set pair H. We obtain N features by analyzing set pair H in the context of specific condition Q. Of the N features, the number of common features in sets E and U is represented by S and the number of different features in sets E and U is represented by P. The number of remaining uncertainty features is represented by F (F=N–S–P). Thus, the connection degree (u) of the two sets is

$$u = \frac{S}{N} + \frac{F}{N}i + \frac{P}{N}j = a + bi + cj,$$

where a, b and c are the identical degree, difference degree, and opposite degree, respectively. i is the tag of difference degree, and j is the coefficient of opposite degree. The value of i is between –1 and 1, and j is set at –1. a, b and c describe the connections between the above two sets from different aspects. We analyzed the connection degree of set pairs based on the size relationship of a, b and c.

We assessed the exposure, sensitivity, and adaptive capacity of coastal provinces to a reduction in marine catches based on SPA. Variables were standardized to a 0–1 scale using the following conversion: $(X–X_{\min})/(X_{\max}–X_{\min})$. The indicators were regarded as set E, and the corresponding evaluation criteria were treated as set U. The exposure, sensitivity and adaptive capacity indices were calculated as averages of the standardized variables. We identified the exposure, sensitivity, and adaptive capacity as

$$Q = \{E, G, W, D\},$$

where E is the set of evaluation objects (E=$\{e_1, e_2, ..., e_m\}$, and m is the number of coastal provinces assessed); G is the set of indicators (G=$\{g_1, g_2, ..., g_n\}$, and n is the number of indicators); and W is the set of indicator weights (W=$\{w_1, w_2, ..., w_n\}$). Evaluation matrix D for question Q is as follows, where d_{kp} is the indicator value for an assessed coastal province (k=1, 2, ..., m; p=1, 2, ..., n):

$$D = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ d_{m1} & d_{m1} & \cdots & d_{mn} \end{bmatrix}.$$

By comparing the indicators among different evaluation objects, we can obtain the maximum indicator set U=$\{u_1, u_2, ..., u_n\}$ and the minimum indicator set V=$\{v_1, v_2, ..., v_n\}$. Identical degree a_{kp} and opposite degree c_{kp} for d_{kp} in evaluation matrix D are calculated as follows:
when there is a positive effect on the results:

$$\begin{cases} a_{kp} = \dfrac{d_{kp}}{u_p + v_p}, \\ c_{kp} = \dfrac{u_p v_p}{d_{kp}\left(u_p + v_p\right)}, \end{cases}$$

when there is a negative effect on the results:

$$\begin{cases} a_{kp} = \dfrac{u_p v_p}{d_{kp}\left(u_p + v_p\right)}, \\ c_{kp} = \dfrac{d_{kp}}{u_p + v_p}, \end{cases}$$

the connection degree (u) of set pair $\{E_k, U\}$ in the interval $[V, U]$ is

$$\begin{cases} u_{(E_k,U)} = a_k + b_k i + c_k j, \\ a_k = \sum w_p a_{kp}, \\ c_k = \sum w_p c_{kp}, \end{cases}$$

the close degree (r_k) between E_k and the maximum case is defined as

$$r_k = \frac{a_k}{a_k + c_k},$$

where r_k reflects the correlation between case E_k and the maximum case, and a higher value of r_k indicates that case E_k is closer to the maximum value. Accordingly, the exposure (r_e), sensitivity (r_s), and adaptive capacity (r_a) of coastal provinces in China can be calculated, with greater values of r_e, r_s, and r_a indicating higher levels of exposure, sensitivity, and adaptive capacity, respectively.

Using exposure, sensitivity and adaptive capacity as the basic indices, vulnerability (r_v) was calculated as the unweighted mean of the standardized values of these indices. Greater values of r_v indicate higher vulnerability among the coastal provinces. Therefore, the values of r_v were highest for the most vulnerable provinces and lowest for the least vulnerable provinces. For the purpose of presentation, the final indicator scores for exposure, sensitivity, adaptive capacity, and vulnerability were categorized into “low (0, AVG-STD)”, “moderate (AVG-STD, AVG)”, “high (AVG, AVG+STD)”, and “very high (AVG+STD, 1)” groups based on the mean and standard deviation of the corresponding index (Wu and Yang, 2012).

3 Results

3.1 *Exploitation history of marine fisheries in China*

To examine the exploitation history of marine fisheries in China, we analyzed the changes in total marine catch in China since the early 1950s. The results showed that China’s marine capture fisheries underwent an accelerated development beginning in the mid-1980s (Fig. 1). The annual marine catch, which was only 0.6 million tons in 1950, slowly increased to approximately 4 million tons in 1985. In 1985, the Chinese government introduced the No. 5 Central Document, a policy directive that aimed to accelerate marine fisheries development within Chinese waters, which resulted in a considerable increase in marine catch, reaching a peak of 12.0 million tons in 1999. In 1999, MARA proposed the “Zero Growth” policy, which led to a decline in marine catch beginning in 2000 and reached about 11.1 million tons in 2004. Marine catch were relatively stable since then (Fig. 1).

Detailed marine catch statistics began to be published annually in the mid-1980s, and this study analyzed the temporal patterns of fishing effort and %PPR during 1985–2017 in China. The results showed that the substantial increase in marine catches was mainly promoted by increasing fishing effort (Fig. 2). The total fishing effort grew substantially from 3.4 million kilowatts in 1985 to 10.8 million kilowatts in 1999. Subsequently, it increased with fluctuations and reached a peak of 12.3 million kilowatts in 2011, but slightly decreased in recent years with 11.2 million kilowatts in 2017. Figure 3 also clearly illustrates the rapid develop-

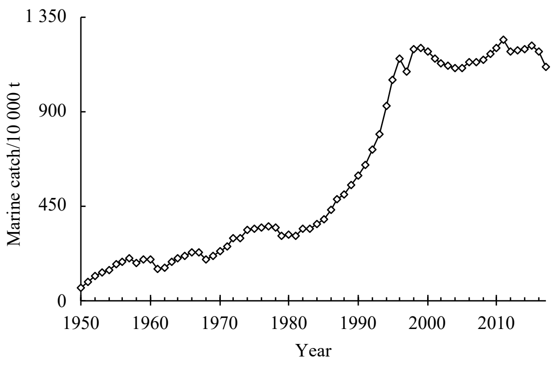

Fig. 1. Domestic marine catch in China during 1950–2017.

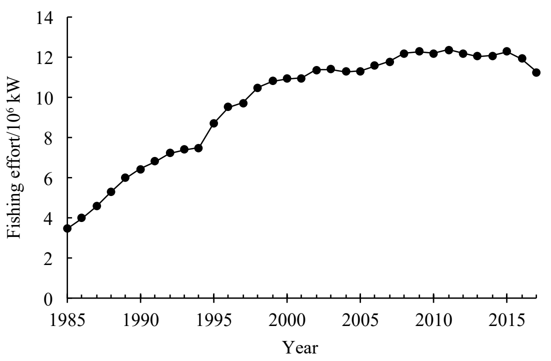

Fig. 2. Total fishing effort in China during 1985–2017.

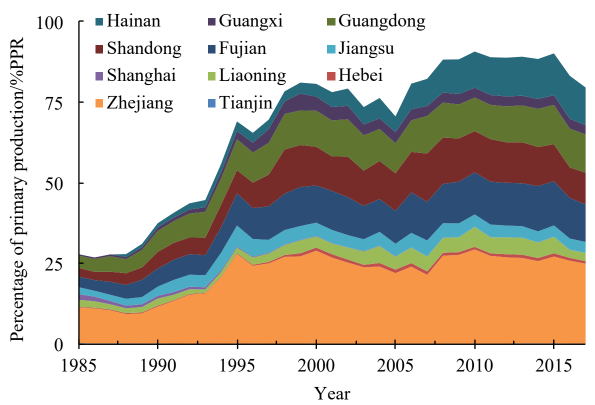

Fig. 3. Primary production required to sustain marine catches during 1985–2017 (expressed as a percentage of primary production, %PPR).

ment of marine capture fisheries since the 1980s. Specifically, the %PPR increased from 28% in 1985 to 80% in 2017. The most prominent feature of the %PPR was the period of rapid growth from the late 1980s to the end of the 20th century. Total %PPR increased throughout the time series and more than tripled from the 1980s to the 2010s but with great variability among coastal provinces (Fig. 3). Most of the growth in %PPR was driven by fleets from Zhejiang, Fujian, Shandong, Hainan, and Guangdong provinces.

To systematically quantify the historical fishing behavior of fishing fleets from different coastal provinces, we created maps of %PPR by coastal province and decade (Fig. 4). Most coastal provinces underwent the largest increase in %PPR during the 1990s. After the gradual increase in %PPR starting in the 1980s, the %PPR in Jiangsu and Guangxi provinces slightly declined and then stabilized since the end of 20th century. Furthermore, the %PPR in Liaoning, Hebei, Shandong, Zhejiang, Fujian and Guangdong provinces continued to increase and became relatively stable throughout the 2010s whereas the %PPR in Hainan Province continued to show increasing trends. In contrast, the %PPR in the municipalities of Shanghai and Tianjin had been declining since the 1980s, but Tianjin showed a sharp increase in %PPR over the last five years.

Fishing effort in China mainly came from Zhejiang, Guangdong, Fujian, Hainan and Shandong provinces. Specifically, fishing effort in the above five provinces accounted for 78% of the total in 2017. Of the 11 coastal provinces and municipalities in China, fishing effort in Shanghai showed a declining trend since the 1990s, while that in Tianjin did not show a clear trend over the past several decades. However, fishing effort in the other coastal provinces generally increased initially and then stabilized in recent years (Fig. 5).

3.2 *Vulnerability of coastal provinces to a reduction in marine catches*

In light of the considerable variability in the proportion of marine fisheries in total fishery production and the socioeconomic status of coastal provinces, this study provided an indicator-based analysis of the relative vulnerabilities of all 11 coastal provinces and municipalities to the impacts of a reduction in marine catches. The vulnerability scores varied from a low of 0.11 in the municipality of Shanghai to a high of 0.90 in Hainan Province. We categorized the final exposure, sensitivity, adaptive capacity, and vulnerability scores into "low", "moderate", "high" and "very high" levels based on the mean and standard deviation of the corresponding indices (Fig. 6).

Both Hainan and Guangxi provinces exhibited very high vulnerability. Hainan Province had the highest vulnerability score due to a combination of very high exposure to a reduction in marine catches, very high sensitivity and low adaptive capacity. Marine capture fisheries contributed 62% of the total production in 2017 in this province, and it showed the highest economic and nutritional dependence on fish but fewer available resources to invest in adaptation. Additionally, the low adaptive capacity score together with the high level of exposure and moderate level of sensitivity in Guangxi Province also resulted in very high vulnerability.

Both Zhejiang Province and Fujian Province had similarly high vulnerability scores, but the drivers of their high levels of vulnerability were different. Zhejiang Province had a very high exposure level; specifically, marine catches accounted for 52% of the total fishery production in this province in 2017. However, it had high levels of sensitivity and adaptive capacity. In contrast, Fujian Province was identified as having high vulnerability due to a combination of high exposure and very high sensitivity but moderate adaptive capacity.

Other coastal provinces had below-average vulnerability scores, of which, Liaoning, Hebei, Shandong, Jiangsu and Guangdong provinces had moderate vulnerability levels. Jiangsu and Guangdong provinces were generally characterized as having low or moderate levels of exposure and sensitivity and high or very high adaptive capacity. However, Hebei and Shandong provinces were the exceptions; the high level of exposure in Hebei Province was countervailed by its low sensitivity to a decrease in marine catches, while Shandong Province had high exposure, which was offset by the relatively moderate dependence on fisheries and high adaptive capacity. Therefore, these two

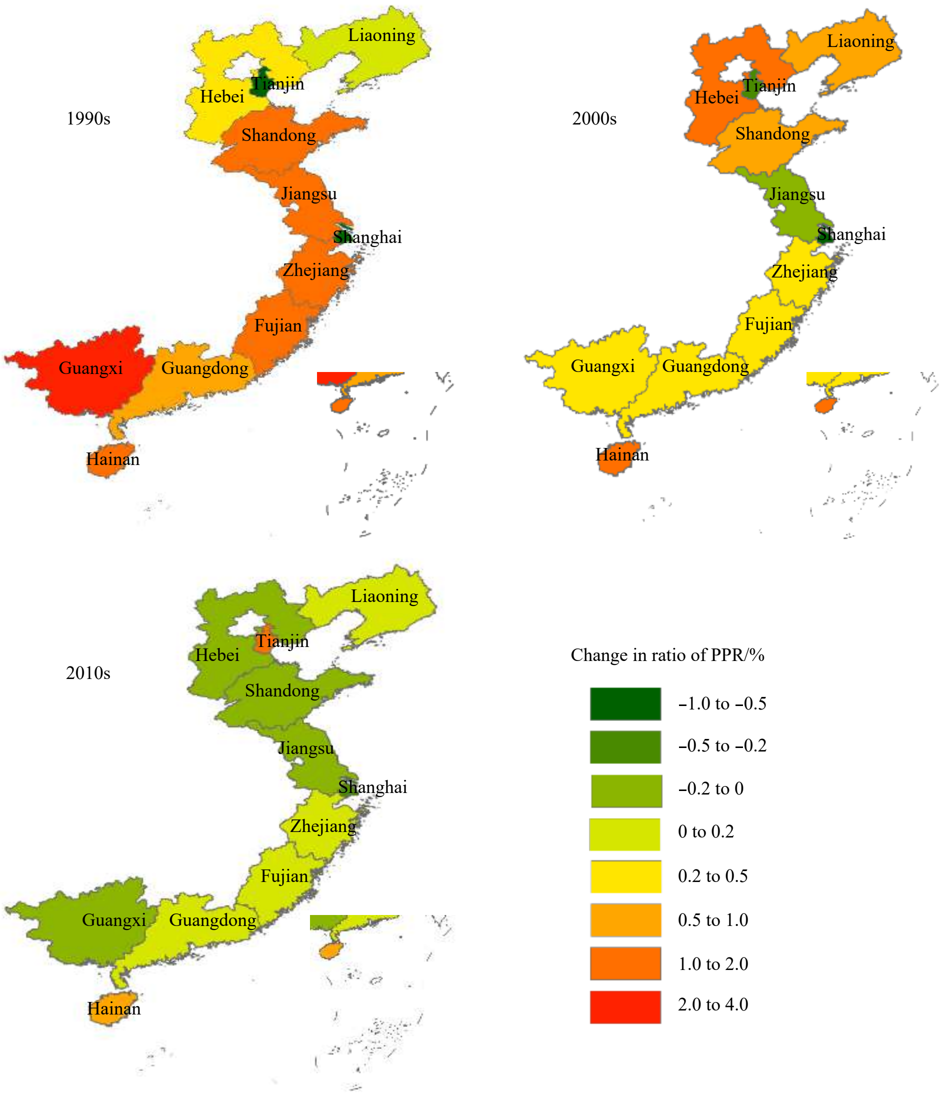

Fig. 4. Maps of the interdecadal changes in the percentage of primary production (%PPR) for the 11 coastal provinces in China.

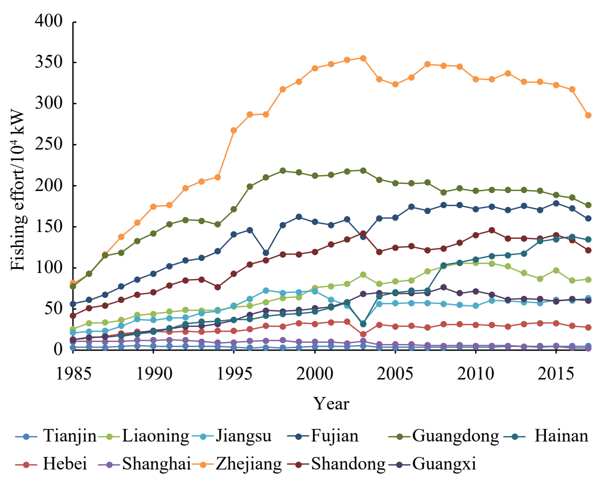

Fig. 5. Fishing effort for the 11 coastal provinces in China during 1985–2017.

provinces were also categorized as having moderate vulnerability levels. Furthermore, the high level of sensitivity in Liaoning Province was offset by its moderate levels of sensitivity exposure and adaptive capacity, which also resulted in a below-average vulnerability score.

The municipalities of Shanghai and Tianjin were ranked as having low vulnerability. Shanghai had the lowest exposure score. Specifically, marine catch only contributed 6% of the total production in 2017. In addition, this municipality exhibited low sensitivity and very high adaptive capacity. Tianjin was also identified as having low vulnerability due to its relatively low level of exposure to a reduction in marine catches, low sensitivity and very high adaptive capacity.

The component scores for each coastal province indicated that no single driver of vulnerability or single underlying mechanism made a province particularly vulnerable to declines in marine catches. Instead, coastal provinces suffered high vulnerability as the result of unique combinations of exposure, sensitivity and adaptive capacity. Our analysis revealed three different types of vulnerability: first, provinces with relatively high adaptive capacity and high levels of exposure and sensitivity, such as

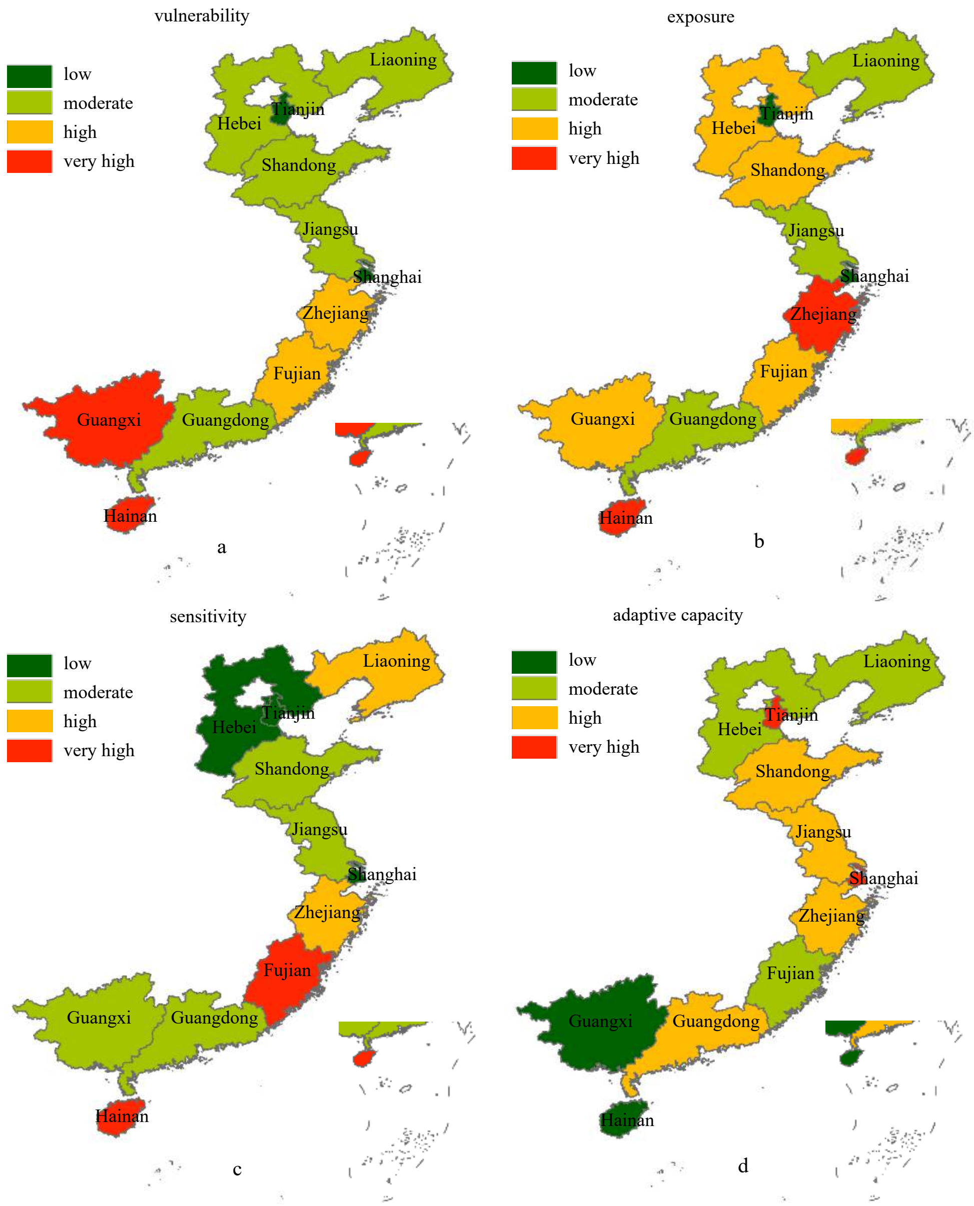

Fig. 6. Overall vulnerability (a), exposure (b), sensitivity (c), and adaptive capacity (d) of the 11 coastal provinces in China to a reduction in marine catches.

Zhejiang; second, provinces with low adaptive capacity and moderate level of sensitivity but high level of exposure, such as Guangxi; third, provinces with low or moderate adaptive capacity and high levels of exposure and sensitivity, such as Fujian and Hainan (Fig. 6).

4 Discussion

Maintaining the sustainability of marine fisheries in China is of both ecological and socioeconomic importance (Blomeyer et al., 2012; Cao et al., 2017). According to the China Fishery Statistical Yearbook, the domestic marine capture fisheries contributed RMB 198.7 billion to the national economy in 2017. In this paper, we examined the exploitation history of marine capture fisheries in China and further evaluated vulnerability to a reduction in marine fisheries at provincial level to understand the causes of such vulnerability. Our analysis suggested that the development of the Chinese marine fishing industry experienced rapid growth from the mid-1980s to the end of the 20th century and stabilized over the last few years of the time series. However, the rapid increase in marine catches was mainly promoted by increasing fishing effort. The total PPR level currently amounts to approximately 80% of the average primary productivity. Zhejiang, Fujian, Shandong, Hainan and Guangdong provinces were the main fishing provinces in China, accounting for 78% of the total marine catch in 2017. Among the 11 coastal provinces and municipalities in China, Hainan, Guangxi, Zhejiang and Fujian provinces had high or very high vulnerability to the impacts of a reduction in marine catches, while Shanghai and Tianjin were ranked as having low vulnerability.

In this study, we used the %PPR to quantify the effects of fishing on marine ecosystems. Total %PPR in China underwent the largest increase during the 1990s, and most of this growth was driven by fleets from Shandong, Zhejiang, Fujian, Guangdong and Hainan provinces. For the sustainable exploitation of wild fish resources, the MARA introduced a "zero-growth" strategy in 1999 and a "negative-growth" strategy in 2000 for total marine catch (Shen and Heino, 2014), which resulted in a slight decline in total %PPR between 2000 and 2005. However, total %PPR continued to show a slowly increasing trend and stabilized beginning in the 2010s, and marine fishery resources still suffer from intense fishing pressure. Most of the growth in %PPR after the year 2005 was driven by fleets from Hainan, Zhejiang, Fujian and Guangdong provinces.

In response to overfishing and the steady degradation of coastal ecosystems, the Chinese government has formulated and organized a series of conservation and management regimes and measures (Yu and Yu, 2008; Shen and Heino, 2014). However, fisheries management in China mainly relies on input control measures (such as licensing systems, and the "Double Control" system) and technical measures (such as spatial and temporal closures and gear restrictions), and there is no direct control of marine catch. The poor enforcement of management measures designed to sustain fish stocks has resulted in the transfer of catch species from large, high-valued traditional fish stocks to lower-valued, small, pelagic fishes in the coastal seas of China. Although specific attention has been paid to fisheries volume control in Chinese fisheries management recently, marine fishery resource depletion is still a serious problem.

Although the total %PPR in China has significantly increased over the last three decades, the %PPR in the municipalities of Shanghai and Tianjin have shown a decreasing trend since the 1980s. This gradually declining trend of %PPR may be attributed to the following two factors. First, fishing effort in Shanghai and Tianjin has not shown a clear upward trend associated with the depletion of coastal marine fishery resources. In fact, fishing effort in Shanghai has shown a decreasing trend since the 1980s. Previous studies found that greater harvesting outside EEZs can alleviate ecosystem degradation to some extent (Clausen and York, 2008). China began to develop distant-water fisheries in the year 1985, and the distant-water fisheries have become a fast-growing seafood-producing sector (Shen and Heino, 2014). The landings from distant-water fisheries in Shanghai amounted to 129.9 thousand tons in 2017, which is over 8 times greater than the coastal marine catches for this municipality (Fisheries Bureau of the Ministry of Agriculture, 1950–2018), and the movement of fishing effort from coastal seas to more distant productive waters can relieve fishing pressure in the EEZ areas (Clausen and York, 2008). Second, aquaculture and increased fish imports can help the municipality meet its intensifying demand for fish to a certain extent. Aquaculture production accounted for approximately 86% of the total fish supply for Tianjin in 2017. In addition, as a net fish importer, the net import of seafood in Shanghai was 28 times greater than its domestic marine catch in 2017. The sharp increase in %PPR for Tianjin in the last five years is due to the increased catch of anchovy (*Engraulis japonicus*), which may relate to climate change (Niu and Wang, 2017).

With the excessive appropriation of PP, a reduction in PPR is necessary for Chinese marine fisheries to be put on a path toward sustainability. The MARA developed a Five-Year Plan for fisheries in 2017, which included at least a 23.6% reduction in marine catches for each fishing province by the year 2020 compared to the year 2015 (Cao et al., 2017). The impacts of a decrease in marine catches will vary across provinces as a result of their exposure, sensitivity and level of adaptive capacity. This study first introduced the SPA method in vulnerability assessments and evaluated the comparative magnitude and distribution of the potential impacts of a decline in marine catches for coastal provinces. Although Hainan, Guangxi, Zhejiang and Fujian provinces all exhibited high or very high vulnerability, the underlying causes of vulnerability differed among the provinces.

Vulnerability assessments have received increasing attention from policy makers and academics. Understanding these distinctions is important because specific policy tools may be required to address different dimensions of vulnerability (Allison et al., 2009; Hughes et al., 2012; Mamauag et al., 2013). In this study, three common vulnerability characterizations were recognized. Zhejiang Province belonged to the first type, Guangxi Province belonged to the second type, and Fujian and Hainan provinces belonged to the third type, respectively. For the first type, policy interventions should focus on reducing exposure and sensitivity. Nevertheless, developing context-specific measures to build adaptive capacity and further reduce exposure are likely to play a more important role in reducing the vulnerability of Guangxi Province. To reduce the vulnerability of Hainan and Fujian provinces, both decreasing exposure and sensitivity and increasing adaptive capacity are needed. This paper describes key policy actions that can help reduce vulnerability to the impacts caused by a reduction in marine catches.

Reducing fishery dependence on marine capture fisheries can help decrease exposure and sensitivity, thereby lowering the vulnerability of coastal provinces to declines in marine catches. This effect can be achieved by further strengthening the development of aquaculture and promoting the regulated and orderly development of distant-water fisheries (Cao et al., 2017). Aquaculture is expected to be a key component of a diversified fisheries production system. Aquaculture expansion can make a significant contribution to food security, and developing aquaculture can also be an efficient way to reduce fishing pressure on wild fishery resources (FAO, 2016). In fact, aquaculture accounts for approximately three-quarters of current fish supply in China. Similarly, distant-water fisheries in China have rapidly developed since 1985, with catches from distant-water fisheries accounting for approximately 18% of the total domestic marine catches in 2017. We should continue to promote sustainable aquaculture development that does not damage marine ecosystems and further enhance the competitiveness of Chinese distant-water fisheries, helping the country meet its increasing domestic demand for fish. In addition, China not only ranks as the world's leading fishing nation but also has the greatest number of people employed in the fishing sector (Cao et al., 2017). Supplemental livelihood activities and alternative livelihoods can reduce sensitivity by starting to link fishing households with new occupational sectors, and investment in new job opportunities for fishing communities is also necessary (Cinner et al., 2012).

Vulnerability can also be reduced through interventions that build adaptive capacity. Fishing provinces with high adaptive capacity are less likely to suffer from the impacts of a reduction in marine catches and are therefore better able to take advantage of the opportunities to enhance their socioeconomic resilience (McClanahan et al., 2015). The ability of fishing provinces to adapt depends on their economic strength, flexibility, education level, and social development (Hughes et al., 2012). Possible actions include developing alternative economic activities, increasing the availability of alternative income and protein sources, increasing the education and environmental literacy of fishers, reducing the economic dependence on fishing, and so on.

As a commonly used metric for the ecological footprint of fishing, the %PPR allows the quantification of fishing pressure on marine ecosystems (Swartz et al., 2010). We examined how the %PPR levels increased in China and further explored how various fishing fleets contributed to these changes. Previous studies found that the majority of LME areas have a coefficient of interannual variation in PP of <5%; thus, average PP levels are representative and it is unlikely that these levels greatly deviated from the average (Watson et al., 2014). In addition, Pauly and Christensen (1995) found a range of efficiency values (3% to 18%) but suggested that these were extreme and that a rate of 10% was the most representative. Therefore, our analysis assumed a constant PP over the study period and used a fixed transfer efficiency of 10% between trophic levels in the food chain.

Studies addressing fishery vulnerability mainly focus on climate change-related impacts, while the influence of socioeconomic change is less considered. This study examined the exploitation history of Chinese marine capture fisheries since the mid-1980s and provides the first vulnerability analysis framework focused on the socioeconomic implications of a reduction in marine catches at provincial level. We found that the total %PPR in China increased from 28% in 1985 to 80% in 2017, and now, Zhejiang, Fujian, Shandong, Hainan and Guangdong provinces are the main fishing provinces. Of the 11 coastal provinces and municipalities in China, Hainan and Guangxi provinces showed very high vulnerability to a reduction in marine catches, while Zhejiang and Fujian provinces showed high vulnerability. To reduce such vulnerability to declines in marine catches, context-specific policies and actions should be developed for different economic sectors. As demand for fish continues to grow, we suggest that linked socio-ecological assessments such as the one in this study are essential tools for guiding sustainable fisheries management.

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