ICES Journal of Marine Science, 2022, **79**, 2741–2751
DOI: 10.1093/icesjms/fsac213
Advance access publication date: 2 December 2022
Original Article

Impact of fisheries footprint on an early warning indicator of resilience reduction in marine net primary productivity

Youzhu Zhao and Yangfan Li*

State Key Laboratory of Marine Environmental Science, Key Laboratory of Ministry of Education for Coastal and Wetland Ecosystems, Coastal and Ocean Management Institute, Xiamen University, Xiamen, China; and Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai 361102, China

**Corresponding author*. *tel: +86-592-2880256*; e-mail: yangf@xmu.edu.cn.

Human activities and climate change have profound effects on marine ecosystems, leading to changes in ecosystem functionality and even reduced resilience. Hence, a systematic assessment of the marine ecosystem resilience and the drivers of resilience is needed. This study provides an approach to help measure the resilience of reduction marine ecosystems by calculating early warning signs of marine net primary productivity, while introducing fishing activities and environmental data in the study area to evaluate the factors affecting marine ecosystem resilience. The results showed that in 36.29% of the Chinese exclusive economic zone, resilience was likely to be significantly decreased. There was a non-linear relationship between fishing activities and indicators of resilience reduction, with pixels with high-intensity fishing activities being more susceptible to resilience reduction. Fishing regulations are urgently needed in areas where marine ecosystem resilience may be reducing. Effective management and protection of marine ecosystems require assessment of the spatial overlap between marine ecosystems states and human activities. This study provides a scientific basis for sustainable management of social-ecological systems by comparing high-precision fishing data to marine environmental data, thereby analysing marine ecosystem resilience through the use of early warning indicators.

Keywords: early warning indicators, fishing footprint, marine net primary productivity, resilience.

Highlights:

(1) The early warning indicator of net primary productivity was used to measure the resilience of marine ecosystems, and the results show a significant trend of reduced resilience in 36.29% of China's exclusive economic zone (EEZ).
(2) In China's EEZ, when there is a high-intensity fishing activity, the risk of marine ecosystem resilience loss and ecosystem collapse will be higher with the increase in fishing activities.
(3) The significant decrease in marine ecosystem resilience in China's EEZ is positively correlated with sea surface temperature.

Introduction

Marine ecosystems have experienced dramatic climate change over recent decades (Johnson and Watson, 2021). In addition to climate change perturbations, human activities may potentially magnify or reduce marine ecosystems changes other than climate change. Several studies have pointed out that marine fisheries are one of the major human activities and one of the most influential anthropogenic impacts on the marine besides climate change (Sumaila and Tai, 2020). The damaging effects of overfishing on biomass loss may be much more severe than climate change (Carozza *et al.*, 2019), rendering marine ecosystems less resilient to climate change (Blanchard *et al.*, 2012). Human activities are uncertain and have had a profound influence on marine ecosystems over time (Halpern *et al.*, 2019), and the cumulative effects can induce ecosystem shifts, i.e. abrupt transformations that occur when a system hits a threshold of a specific state. Ecosystem resilience is a key measure of a system's emergent response to stressors, and resilience is an emergent property of systems (Wu *et al.*, 2017). Emerging theories and new multidisciplinary approaches indicate the importance of assessing and actively managing resilience, i.e. the extent to which ecosystems can absorb recurrent natural and human perturbations and continue to regenerate without slowly degrading or unexpectedly flipping into alternate states (Hughes *et al.*, 2005). However, there are limited studies on the effects of human activities on marine ecosystem resilience.

The coupling between human and environmental systems can induce non-linear shifts, and regime shift occur in non-linear dynamic systems when the system shifts from one stable equilibrium to another. The bifurcation point where this transition occurs is the tipping point, while a system is resilient when far from an undesired tipping point (Bauch *et al.*, 2016). As the system approaches a tipping point, the system resilience decreases, i.e. it takes longer to recover to a stable equilibrium state when the system is subject to perturbations. This property means that regime shifts generally indicate characteristic early warning signals (Scheffer *et al.*, 2009). The phenomenon of "critical slowing down" prior to a tipping point can provide a generic early warning signal (Van Putten *et al.*, 2019) that a system is slowing down to recover from short-term fluctuations prior to an abrupt shift. Measuring ecosystem resilience is difficult, but this early warning signal of slowing down is often referred to in ecology as "loss of resilience". Decreased resilience before a regime shift can be manifested by effects such as critical slowing down, i.e. with increases in autocorrela-

Received: June 13, 2022. **Revised:** November 3, 2022. **Accepted:** November 4, 2022

tion, variance, and other statistics (Bauch *et al.*, 2016; Su *et al.*, 2020), providing a way to assess the resilience of ecosystems.

Early warning signals have been widely used to measure ecosystem resilience (Bauch *et al.*, 2016; Ma *et al.*, 2021), e.g. terrestrial normalized difference vegetation index resilience (Feng *et al.*, 2021), but rarely have been applied to marine ecosystems. Hakspiel-Segura *et al.*, (2022) used marine chlorophyll data to demonstrate that early warning indicators (EWIs) are effective for monitoring the resilience of marine ecosystems. The net organic carbon formation rate of marine phytoplankton, i.e. the net primary production (NPP) of marine phytoplankton (Laufkotter *et al.*, 2015), is an important indicator of marine primary productivity and therefore be useful for measuring the resilience of marine ecosystems. NPP by marine phytoplankton is responsible for ∼50% of global biogenic carbon fixation and is a key determinant of atmospheric CO_2 concentrations (Kwiatkowski *et al.*, 2017). Marine NPP provides the foundation for the marine food web through the production of organic matter (Laufkotter *et al.*, 2015), providing energy for marine ecosystems (Carozza *et al.*, 2019; Krumhardt *et al.*, 2020). NPP is, in turn, associated with adequate nutrient, light, and appropriate temperature availability (Lam *et al.*, 2020), which regulate the specific rate of NPP. The resulting magnitude of phytoplankton stocks is also governed by losses due to grazing and mortality (Tagliabue *et al.*, 2020), constraining NPP in a top-down sense (Laufkotter *et al.*, 2015). NPP is also an important component of the marine carbon cycle and a critical factor in determining the surface ocean organic carbon export (Laufkotter *et al.*, 2015). Fishing activity affects phytoplankton through top-down control (Lynam *et al.*, 2017), consuming marine production and fish carbon sink through fishing (Kwiatkowski *et al.*, 2017). Hence NPP is an important indicator for representing marine function, providing a potentially useful approach for measuring the resilience of marine ecosystems with early warning signal indicators.

China is the largest producer and consumer of marine resources globally (Cao *et al.*, 2017), and its exclusive economic zone (EEZ) covers the Bohai, Yellow, East, and South China Seas, which are affected by climate change and overexploitation of fish resources. China's ocean warming rate is among the top 10% globally (Kang *et al.*, 2021), while intensive fishing pressure has led to a shift in catch composition from large, high-trophic-level species to smaller, lower trophic-level species (Cao *et al.*, 2017). The Chinese EEZ is in a state of rapid degradation under severe stress (Kang *et al.*, 2021), thus providing an important reference for investigating the response of marine NPP resilience to human activities. However, there are limited studies on the analysis of spatial and temporal patterns of marine fishery intensity in China's EEZ, and there is an urgent need to comprehensively assess fishing activities in China's EEZ as having a potentially important influence on changes in marine ecosystem resilience.

The impacts of human activities and climate change on marine ecosystems are still highly uncertain, so gaining an understanding of their relationship with NPP resilience, as a critical component of the ocean carbon cycle and the basis of the food web, can further support ecosystem-based ocean management. Remote sensing provides the data foundation for this study, and both NPP and fishing activities data used in this study are derived from remote sensing inversions. This study first examined the spatial and temporal dynamics of marine fishing and measured changes in marine NPP resilience based on EWIs. It then assessed the interaction between fishing activities and marine NPP resilience while overlaying the effects of climate change to investigate how driving factors such as fishing activities and climate change may affect the resilience of marine NPP.

Material and methods

Study area

China's EEZ covers the Bohai, Yellow, East, and South China Seas, adjacent to the edge of mainland China, interconnected and spanning the temperate, subtropical, and tropical zones (Figure 1), with abundant fishery resources and critical ecological functions. The Bohai Sea, as a semi-enclosed shallow sea, is the only inland sea in China and is vulnerable to human activities. The Yellow Sea is a northern marginal sea in the North Pacific Ocean, connected to the Yellow Sea through the Bohai Strait, and with high productivity. The East China Sea is a large marginal sea in the western North Pacific Ocean and is China's most crucial fishing ground (Sun *et al.*, 2021), with highly exploited fishery resources. The South China Sea, located between the Pacific and Indian Oceans, is a tropical fishery with high temperatures and benefits plankton blooms and is a substantial tropical fishery. The marine ecosystems in China's EEZ is complicated and high potential for exploitation, but due to global warming and high fisheries exploitation, China's marine biodiversity and environmental status have severely declined (Kang *et al.*, 2021). China introduced the concept of "Ecological Civilization" in 2012 and implemented policies for resource conservation and environmental protection (Su *et al.*, 2020), establishing an extended network of marine protected areas to protect marine species diversity, and China has established Aquatic germplasm reserves (AGRs) to protect rare and endangered fish species of great commercial importance. This study assesses the resilience of ecosystems in China's EEZ under exploitation and protection and their interactions with marine fisheries activities.

Data source

NPP and sea surface temperature data

This study uses NPP data provided by Oregon State University (http://sites.science.oregonstate.edu/ocean.productivity/eppley.model.php). The database estimates NPP according to remote sensing data from MODIS aqua satellite for 2002–2020 using the Vertically Generalized Production Model (VGPM) algorithm (Behrenfeld and Falkowski, 1997). Siswanto *et al.*, (2006) validated the VGPM algorithm using a long-term empirical dataset from the East China Sea, showing that the VGPM algorithm can produce accurate and reliable results, and that the dataset is widely used with high spatial and temporal resolution and is suitable for regional studies. Therefore, this study uses the monthly NPP dataset (units of mg C/m^2/day) from July 2002–July 2020 provided by the site with a spatial resolution of 1/6°. The Bio-ORACLE database (https://www.bio-oracle.org/downloads-to-email.php) (Assis *et al.*, 2018) provides mean sea surface temperature (SST) data for the period 2000–2014, with SST data assigned to 1/6° grid cells to match the resolution of the NPP data.

Fisheries footprint

Automatic identification system (AIS) is a vessel safety and collision avoidance system with global coverage, which pro-

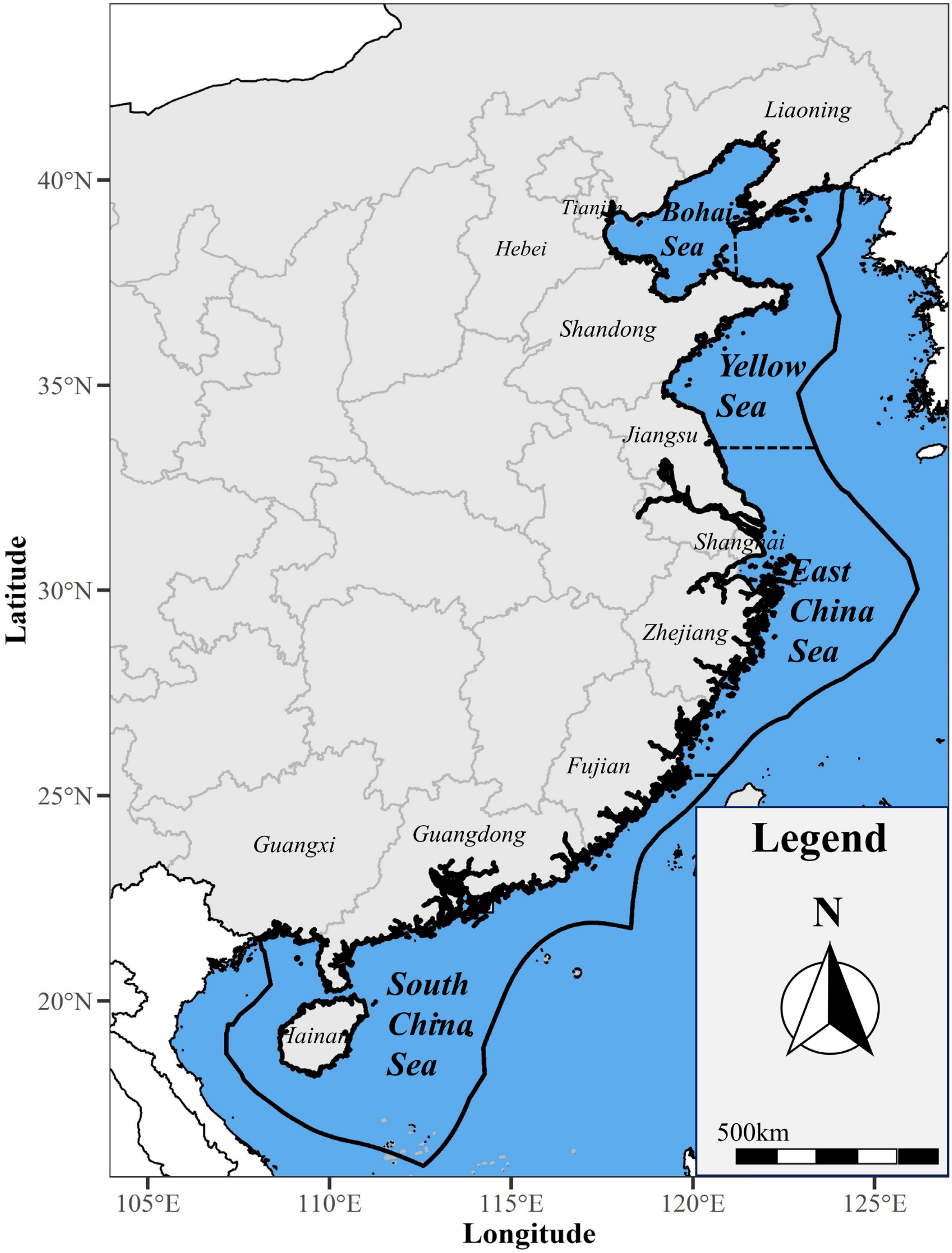

Figure 1. Map of mainland China's EEZ. The region studied in this work is marked by a thick black box, the provinces located in the China coastal region are also depicted on the map (Liaoning, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi and Hainan). The scope of China EEZ is from the Marineregions website (https://www.marineregions.org/)

vides a remote sensing basis for tracking marine fishing operations by locating vessels globally. Kroodsma *et al.*, (2018) assembled high-resolution vessel monitoring data provided by AIS collected since 2012 to create the Global Fishing Watch database (https://globalfishingwatch.org/map-and-data/) to track the fishing footprint of each fishing vessel. Global Fishing Watch contains the most active fishing vessels >24 m and statistics on fishing worldwide at high temporal and spatial resolution, i.e. the number of fishing hours per day on a unit grid, and categories of different types of fishing gear based on two neural network algorithms. Estimating fishing effort through inversion of remote sensing data is an emerging field and results remain uncertain as research on specific spatial analyses is debated. However, Global Fishing Watch (GFW) data has improved vessel (gear) type classification algorithms and continues to refine the dataset to correct for regional errors (Harry *et al.*, 2021). Also the study area of this study, China, has AIS installed for ships in accordance with the International Maritime Organization regulations and for ships not included in the regulations (Liu *et al.*, 2021), the installation of AIS equipment in China is widespread and provides reliable data input for the neural network algorithm to reduce uncertainty in the regional scale. Therefore, despite the limitations of GFW data, it is still the best available high spatial and temporal resolution data for the China's EEZ.

This study used the fishing effort grid data from the Global Fishing Watch database for 2012–2020 to extract the fishing hours in the Chinese EEZ and collate the operations of different fishing gears. Fishing hours were counted and summed within each 1/6° grid cell, and assigned all spatial data to 1/6° grid cells to match the resolution of the NPP data.

Statistical analyses

Resilience analysis

Resilience is defined as the ability of a system to return to its initial state after a disturbance (Buxton *et al.*, 2022). A reduction in resilience indicates that an ecosystem is moving towards a critical slowing down point, which can trigger an abrupt shift to another stable state, so the degree of reduction in resilience can be quantified by early warning signals. Following the algorithm proposed by Feng *et al.*, (2021), EWIs for marine NPP are potentially useful for measuring the resilience of marine ecosystems. The EWI of the NPP was first calculated for each pixel in the study area based on a monthly NPP sliding window of temporal detrending: autocorrelation at first lag (ACF1), autoregressive coefficient of a first-order model (AR1), standard deviation (*SD*), skewness (SK), kurtosis (KURT), return rate (RR), and density ratio (DR) with a sliding window set to an integer multiple of 12 for 36 months. The indicators are calculated as follows:

$$\mathrm{ACF1} = \frac{\sum_{t=1}^{n} (z_t - \mu)(z_{t+1} - \mu)}{\sigma_z^2}$$

$$\mathrm{AR1} = \frac{z_{t+1} - \varepsilon_t}{z_t}$$

$$SD = \frac{1}{n+1} \sum_{t=1}^{n} (z_t - \mu)^2$$

$$\mathrm{SK} = \frac{\frac{1}{n} \sum_{t=1}^{n} (z_t - \mu)^3}{\sqrt{\frac{1}{n} \sum_{t=1}^{n} (z_t - \mu)^2}}$$

$$\mathrm{KURT} = \frac{\frac{1}{n} \sum_{t=1}^{n} (z_t - \mu)^4}{\left(\sqrt{\frac{1}{n} \sum_{t=1}^{n} (z_t - \mu)^2}\right)^2}$$

$$\mathrm{RR} = \frac{1}{\mathrm{AR1}}$$

$$\mathrm{DR} = \frac{\mathrm{SP}\ (0.05)}{\mathrm{SP}\ (0.5)},$$

where z_t is the subset of the marine NPP detrended time series within the current sliding window; μ and σ_z^2 are the mean and variance of z_t, respectively. n is the window size (36 months); z_{t+1} is the first-order lag series; ε_t is the residual obtained by ordinary least squares; and $SP(*)$ is the spectral density function in power spectrum analysis.

The combined EWIs (Composite EWI, CEWI) can enhance the overall predictive ability by combining multiple EWIs (Su *et al.*, 2020), so this study indicates the resilience based on CEWI. To avoid covariance among multiple EWIs, the highly correlated EWI indicators are removed using the variance inflation factor (VIF) algorithm, and when the VIFs of the remaining EWIs are <10, the remaining indicators are *z*-score transformed to improve the comparability of the indicators and summed with equal weights to calculate the CEWI.

$$\mathrm{CEWI}_t = \sum_{i=1}^{N} z\text{-score}\left(\mathrm{EWI}_{t,i}\right),$$

where CEWI_t is the CEWI at time t; z-score$(\mathrm{EWI}_{t,i})$ is the ith EWI of the z-score transformed at time t; and N is the number of EWI indicators.

Lastly, following Feng *et al.*, (2021), the rank correlation coefficient (Kendall's τ) between CEWI and time was calculated to assess the trend of CEWI. A larger positive Kendall's τ indicates an increasing trend of CEWI, i.e. a faster decreasing trend of resilience. In this study, the Kendall's τ index of CEWI of NPP for each pixel was calculated to generate a spatial distribution of marine ecosystem resilience in the study area, and mainly showed a significantly positive ($p < 0.05$) spatial distribution of Kendall's τ for CEWI.

Correlation analysis

Nutrients and organic matter from freshwater discharge, terrestrial environment, and shallow sediments in coastal areas enhance primary and secondary production in the nearshore environment (Wang *et al.*, 2019). With increasing distance from population centres, dispersion and dilution of terrestrial inputs (Holbrook *et al.*, 2022) causes a pronounced spatial gradient in environmental disturbance that may affect marine NPP CEWI. This study introduces Theil–Sen regressions to investigate this spatial covariance pattern between the level of NPP resilience reduction and distance from shore. The level of NPP resilience reduction was indicated using Kendall's τ of the CEWI of NPP. Kendall's τ values that indicated significant reductions in resilience were then used as the dependent variable in regressions to further explore the spatial characteristics of reduced NPP resilience. Theil–Sen regressions are a robust method for determining the slope of a regression line by the median of the slope. This study used the mblm package in R (Komsta, 2019) for Theil–Sen regressions analysis, and the sf package (Pebesma, 2018) to calculate the distance from the shore for each pixel.

To investigate the influence of other anthropogenic stressors on marine NPP resilience, the annual average fishing days per pixel in the Chinese EEZ from 2012 to 2020 were categorized by gear type. The correlation between stressors (fishing activity and SST) and the occurrence of decreased resilience of marine NPP was calculated by fitting logistic regression with a generalized linear model (GLM). The study area was divided into two categories: significant decreasing resilience and non-significant decreasing resilience. When a positive Kendall's τ for CEWI was detected within a pixel with a significant trend

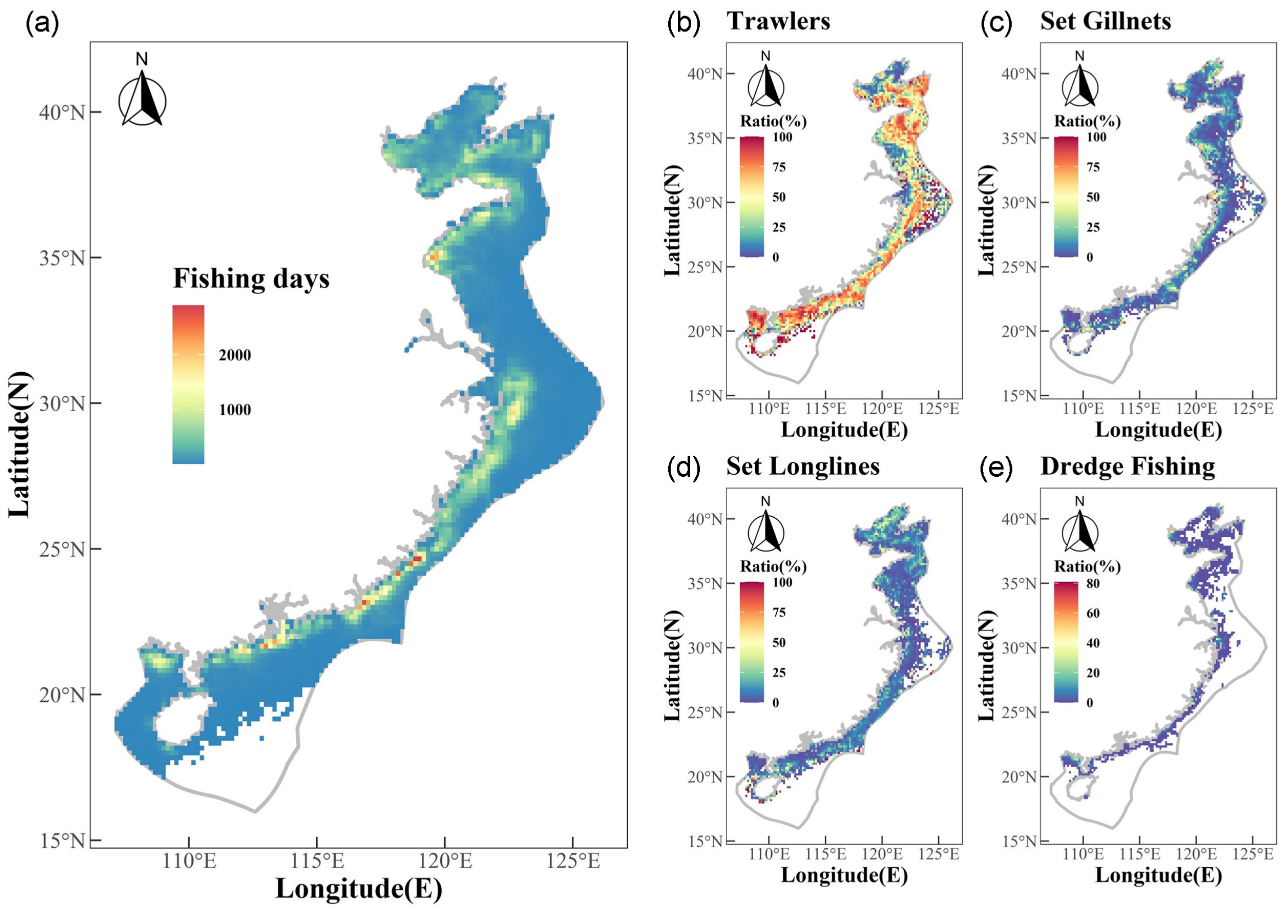

Figure 2. Spatial Distribution of fishing activities in China's EEZ. (a) Spatial distribution of the average annual fishing days, and spatial distribution of the proportion of fishing activities for (b) trawlers, (c) set gillnets, (d) set longlines, and (e) dredge fishing.

($p < 0.05$), the pixel was assigned a value of 1; otherwise, the pixel was assigned a value of 0. The pixel was generated into binary data of 1 or 0 to be the dependent variable of the logistic regression, and standardized SST and fishing effort (average annual fishing days from 2012 to 2020) included as independent variables. To take into account non-linear effects, the squares of standardized SST and fishing effort were also included as independent variables. The GLM fitted logistic regression was analysed using the glm function of R statistical software, version 4.0.5 (R Core Team, 2021).

Results

Spatial and temporal patterns of marine fishing

This study examined the spatial distribution of fishing activities and the proportion of fishing activities by fishing gears in the Chinese EEZ based on the Global fishing watch database (Figure 2) to explore the behavioural features and spatial preferences of fishing activities. The four most frequent fishing gear types in the Chinese EEZ are: trawlers, set gillnets, set longlines, and dredge fishing (Figure 2, Supplementary Appendix Text S1). According to the Global fishing watch database, the Supplementary Appendix Figure S2 presents the proportion of spatial fishing activities of the remaining fishing gears in the Chinese EEZ. Figure 2 indicates that fishing activities in China are clustered in the offshore areas, with more intensive fishing activities in the Bohai Sea region. Fishing activities in the Yellow Sea region at the junction of Jiangsu and Shandong are intensive. Most of the intense fishing activities are clustered in the offshore waters of Shandong, while fishing intensity in the non-junctional offshore waters of Jiangsu is limited. There are some fishing activities in Zhejiang offshore, and intense fishing activities in offshore waters of Fujian and Guangdong provinces. Overall, fishing activity is relatively intense in offshore of Shandong, Fujian, and Guangdong provinces, as Shandong, Guangdong, and Fujian are all major fisheries provinces in China (Szuwalski *et al.*, 2020).

According to the analysis of the temporal trend of total fishing hours in the study area from 2013 to 2020 (Figure 3), fishing activities in China's EEZ present a seasonal fluctuation with an annual cycle, with a significant tendency to rest fishing activities during the fishing moratorium from June to September in summer and the Spring Festival holiday in winter each year, and a relatively significant extension of the moratorium since 2017. The fishing activities intensity will rapidly rise to a peak point after the end of the fishing moratorium each year and then slowly declines. Fishing activities show a relatively rapid increasing trend after the end of the Chinese New Year holiday in winter each year, but the rising trend is weaker than the fishing activities after the moratorium.

Notably, the fishing intensity is lower in the early period mainly due to the fewer vessels equipped with positioning system AIS beforehand, but as the awareness of safety at sea is raised, the installation of AIS equipment on vessels became

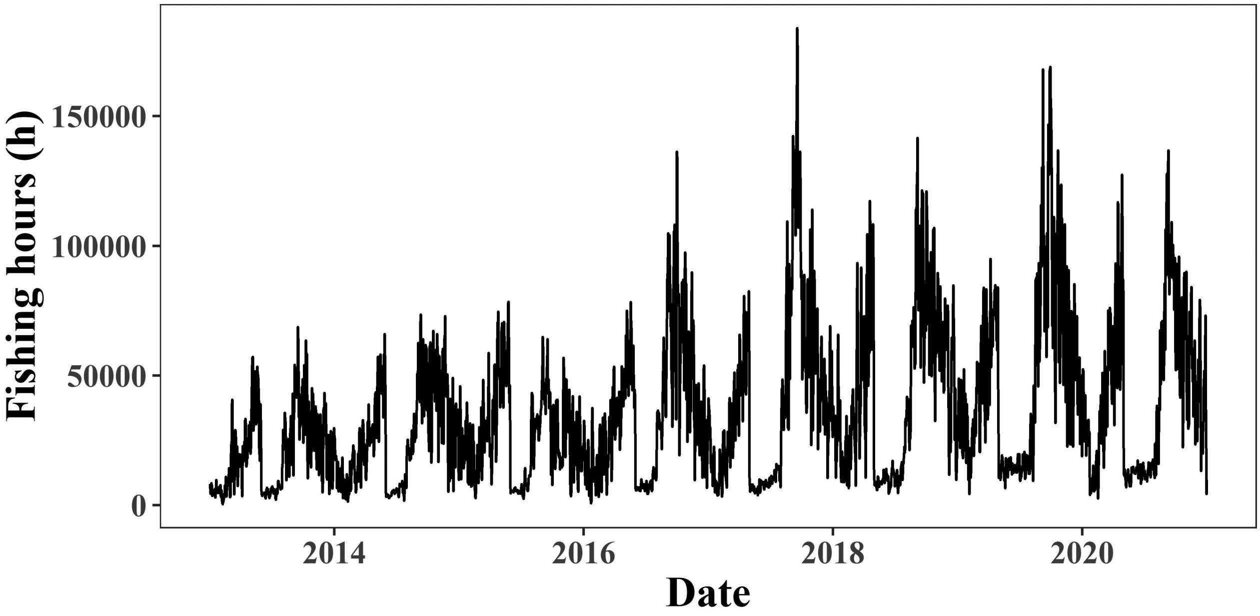

Figure 3. Time series of total fishing in China's EEZ. Fishing hours per day in China's EEZ is introduced as a proxy for fishing efforts.

popular, so the data in the early period of Global fishing watch covers a lower degree than the later period, but the present data provide an estimate of the lower limit of the actual fishing situation.

Spatial distribution of marine NPP resilience

The spatial distribution of reduction in marine ecosystem resilience in China's EEZ is shown in Figure 4. Only the pixels with significantly positive Kendall's τ ($p < 0.05$) are displayed, representing a reduction in resilience. It is estimated that 36.29% of the pixels in the study area show a trend of significant resilience reduction. In addition, 48.40% of the pixels in the study area show a reduction in resilience. Theil–Sen regressions (Figure 4) showed a highly significant ($p < 0.001$) negative correlation between distance from shore and resilience trends in regions with significantly reduced resilience. That is, the rapid reduction of resilience occurs primarily in areas closer to the shore in China's EEZ.

Significantly reduced resilience in the Bohai Bay is sparsely distributed. Nearshore areas at the junction of Shandong and Jiangsu in the Yellow Sea show a significant reduction in resilience and a rapid reduction trend. In contrast, the Yellow Sea area in China's EEZ has more clusters and patchy regions of reduced resilience. The southern part of Jiangsu Province, near Zhejiang Province, shows fewer pixels with significantly reduced resilience, which are only sporadically distributed offshore. The East China Sea of China's EEZ has fewer pixels with reduced resilience, and most of the pixels are sparsely distributed in the waters far from the mainland of China's EEZ. The South China Sea of China's EEZ has more pixels with reduced resilience in a patchy distribution, but Kendall's τ values are less than those in the Yellow Sea nearshore regions, indicating lesser reductions in resilience. In addition, fewer pixels with significantly reduced resilience are located in the nearshore waters of Guangdong, rather mainly in the waters slightly farther from shore. Generally speaking, the sea near Shandong, Fujian, and Guangdong, where fishing activities are more intense, has a higher percentage of significantly reduced resilience pixels. Areas with rarer fishing activities, including the waters of Jiangsu near Shandong and Jiangsu near Zhejiang show fewer pixels and less extreme reductions in resilience. The spatial distribution of pixels with significantly negative Kendall's τ for CEWI of NPP is shown in the Supplementary Appendix Figure S3, showing that 35.34% of the pixels in the study area have a significant trend of reduced CEWI.

Factors associated with reduction in marine NPP resilience

The GLM results for the factors associated with reduction in marine NPP resilience (Figure 5) revealed that for all waters with fishing activities (Model of Fishing), SST was significantly positively correlated with the marine NPP resilience reduction. Fishing activities were significantly negatively correlated with the marine NPP resilience reduction, but the square of fishing activities was significantly positively correlated with marine NPP resilience reduction. Accordingly, there is a non-linear relationship between fishing activities and marine NPP resilience reduction. When the fishing activities are less, the negative relationship is dominant, but when the fishing activities meet the threshold, the positive relationship begins to appear, which will increase the risk of marine NPP resilience reduction. This effect is universal in different gear types (Model of Trawler, Set gillnets, Set longlines of Figure 5). Heat maps of the spatial overlap between marine NPP resilience and fishing activities are plotted in the Supplementary Appendix Text S2 and Figure S4 to analyse the effect between fishing activities, SST, and resilience.

Discussion

Potential drivers of reduction in marine NPP resilience

Marine ecosystems are complex, exposed to natural and anthropogenic stresses, and tend to undergo abrupt reorganization to adapt to changing external pressures when resilience is

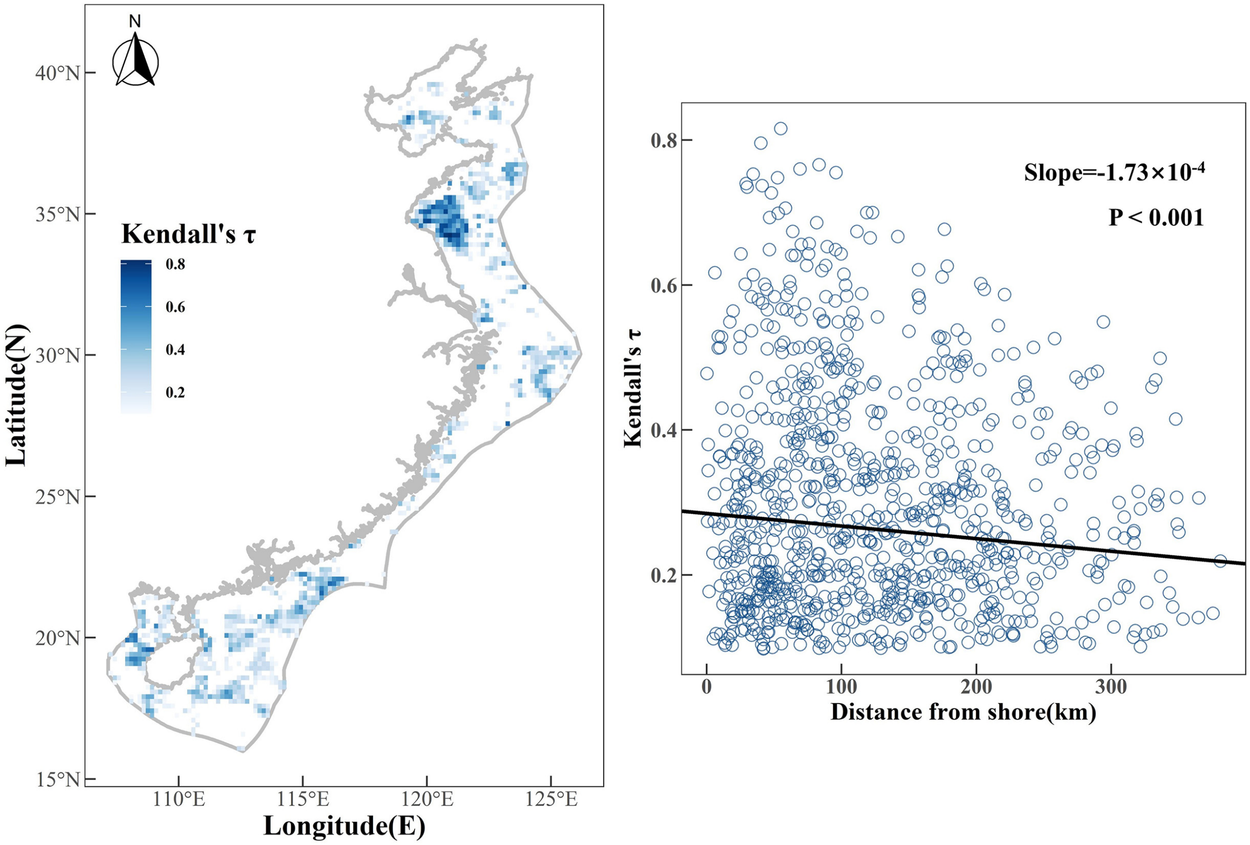

Figure 4. Spatial pattern of resilience (Kendall's τ for marine NPP CEWI) in China's EEZ. Only the regions with significantly positive Kendall's τ are presented, where the ecological resilience is reduced. The right panel is the Theil–Sen regression of Kendall's τ for marine NPP CEWI and distance from shore.

reduced (Feng *et al.*, 2021). Understanding causes of resilience reduction is a critical challenge for the future, for which analysing EWIs may provide a potentially useful methodological basis.

This study identifies areas of significantly reduced marine ecosystem resilience in China's EEZ based on EWIs. The results indicate a non-linear relationship between the risk of significant reduction in marine ecosystem resilience and fishing activities in China's EEZ. The risk of significant reduction in marine ecosystem resilience increase with increasing fishing activity when fishing activities exceed a certain threshold. Holbrook *et al.*, (2022) also point out that overfishing reduces the resilience of marine ecosystems to climate change. Ramírez *et al.*, (2018) found that the combination of ocean warming and fishing pressure synergistically affects fish stocks. Kovac *et al.*, (2020) also indicated that high zooplankton exploitation may decrease the resilience of the pelagic system.

In addition, chronic anthropogenic nutrient loads caused by high-intensity human activities such as sewage discharge or agricultural runoff form a clear spatial trend with distance from shore as they become gradually diluted. This trend covaried with resilience reduction negatively. Nearshore marine ecosystems may therefore be at a high risk of experiencing a shift in the composition of phytoplankton, which can cause abrupt changes in marine ecosystems (Cael *et al.*, 2021), further leading to a decrease in resilience.

A positive relationship was similarly found with SST. Ma *et al.*, (2021) suggest that dramatic increases in SST and small fluctuations in the corresponding thresholds can trigger critical transitions, further leading to resilience decrease in marine ecosystems. In addition to chronic slow ocean warming, short-term extreme warming events in the ocean, such as ocean heat waves, are becoming more widespread and frequent. Hakspiel-Segura *et al.*, (2022) also revealed that anomalous changes in marine temperature can induce decreasing resilience of marine ecosystems.

Fisheries may affect marine ecosystem resilience

Marine fisheries reduce the resilience of marine ecosystems through greenhouse gas emissions, lost gear and marine litter, and changes in food web structure that disrupt marine ecosystems. For instance, overfishing of cod in the 1990s caused changes in marine ecosystems that weakened the biological pump in the North Atlantic (Hammerschlag *et al.*, 2019), further reducing ocean carbon sink functions; fishing activities on Caribbean reefs have led to a reduction in fish-mediated trophic capacity, further leading to a reduction in primary productivity (Allgeier *et al.*, 2016); and overfishing herbivorous fish in Jamaica combined with climate change has led to a shift from highly productive coral-dominated habitats to lower productive algae-dominated habitats in some areas (Levin and Möllmann, 2015).

Most previous studies have used SST as a stressor to assess impacts on marine ecosystems, but this study also focuses on the non-linear effects of fishing activities. Harvesting marine fish at the beginning will potentially induce an increase in phytoplankton growth and further increase carbon sequestra-

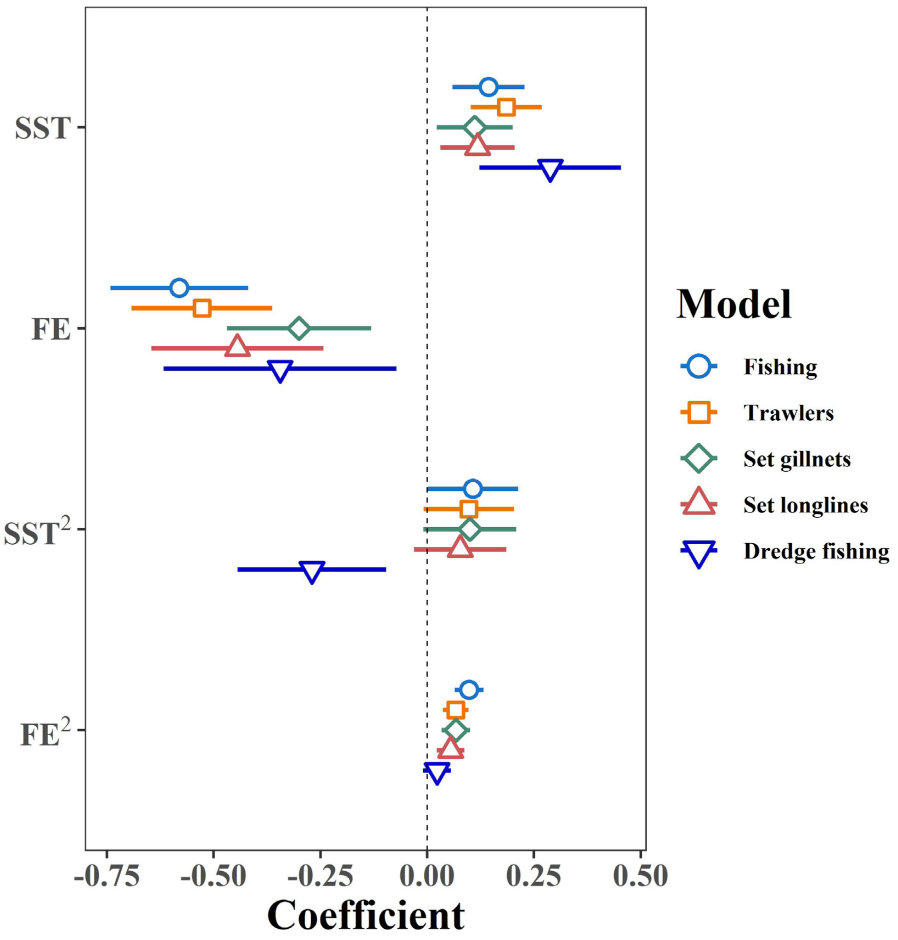

Figure 5. Coefficients from the GLM linking with resilience reduction. SST = sea surface temperature; FE = fishing effort (fishing days); SST^2 = square of SST; FE^2 = square of fishing days. Dots represent mean model coefficients; and whiskers show the 95% credible intervals.

tion. However, as fishing activities and phytoplankton growth meet a certain threshold, complex trophic cascade effects, as well as eutrophication and competition interactions come into play (Van Denderen *et al.*, 2018). Weakening of the biological pump through fishing (Hammerschlag *et al.*, 2019) can reduce growth rates and even show a decreasing trend in marine NPP. A study in the Bohai Sea of China noted that the trophic cascade effect caused by fishing led to a shift in the Bohai Sea ecosystem, with the loss of large fish causing an increase in fish and jellyfish. This further reduced the biomass of herbivorous zooplankton, which was followed by an increase in zooplankton biomass as small fish were also depleted by fishing. As a result, phytoplankton were suppressed and primary production declined (Liang and Pauly, 2020).

In the case of China, overfishing has led to a reduction in the productivity of marine ecosystems and a decrease in marine biomass. For example, economic fish species have declined in the Bohai Sea and big T. albacores resources have collapsed in the East China Sea (Fu *et al.*, 2018). This study points out that Trawlers are the dominant marine fishing gear type and widely distributed in China's EEZ. While extensive trawler fishing pressure threatens the sustainability of offshore ecosystem, bottom trawling can induce the release of substantial carbon stored in deep-sea sediments and affect the carbon storage capacity (Paradis *et al.*, 2021). Bottom trawling also further affects carbon biogeochemical cycling by transferring dissolved and particulate nutrients from benthic systems to pelagic systems (Lomartire *et al.*, 2021). The impacts of trawlers on marine ecosystems are persistent; especially the destructive exploitation of sediment organic matter from deep-sea trawlers takes a long time to recover (Paradis *et al.*, 2021).

China ecosystem-based sustainable fisheries management

The United Nations Sustainable Development Goal 14 "Life under water" calls on the international community to "Conserve and sustainably use the oceans, seas and marine resources for sustainable development. For sustainable development." (Ovando *et al.*, 2021), but the limited data available constrains the assessment of the exploitation of marine resources and marine ecosystems, especially marine fisheries. With increasing remote sensing data, the inversion method of human fisheries activity data based on the satellite data may become more established. This would enable the observation and detection of real-world fishing activities based on remote sensing data, further tracking the marine fisheries footprint and providing a realistic data basis for ecosystem-based fisheries management.

China's marine fisheries management has begun to focus on restoring coastal and fishery resources in the last decade to achieve sustainable development of marine fisheries. China's Fisheries Law of the People's Republic of China, revised after 2000, provides a quota fishing policy for China fisheries, and the Total Allowable Catch is the basic policy for marine fisheries management in many international countries, aiming to protect marine resources and maintain sustainable exploitation of fisheries. China announced the “Marine Ecological Civilization Building Policy” in 2015 (Crona *et al.*, 2020), which focuses on marine ecology and sustainable development of marine ecosystem, and promulgated “total resources management” and “quota fishing management” in 2017 (Su *et al.*, 2021), aiming to implement the most severe fishing moratorium in history. Fishing moratoriums prohibit certain types of gear fishing activities at given times and locations each year, thereby mitigating the impacts of fishing activities on marine fishery resources and marine ecosystems. China, also with a tradition of marine conservation, has established marine nature reserves that prohibit fishing; special marine protected areas that allow only sustainable fishing while establishing no-take core areas; and AGRs, also known as fishery conservation zones, which aim to protect commercially valuable, rare, or endangered fish species (Bohorquez *et al.*, 2021) (Supplementary Appendix Text S3). As the world’s largest consumer of fisheries production, China is suffering from the combined pressures of climate change and overfishing, yet the Chinese government is increasingly focusing on environmental protection and ecological civilization (Cao *et al.*, 2017). However, there is still a trend of significant reduction in the resilience of about 1/3 of China’s EEZ, and low resilience areas are often under severe fishing activity. Therefore, China should continue to search for new solutions for fisheries reform.

Conclusion

This study provides an assessment of the relationship between fishing activities and marine ecosystem resilience indicators in China’s EEZ. It is found that 36.29% of China’s EEZ showed a trend of significant reduction in a resilience indicator, and areas with a rapid reduction tended to also suffer from high-intensity fishing activities. The interaction between human activities and marine ecosystems warrants research, but currently more research appears focused on the interaction between climate change and the marine ecosystem. Human activities are less often analysed perhaps due to a lack of spatial data on human activities. Remote sensing has the potential to reduce data limitations, as this study was founded on chlorophyll and SST data tracked from space as well as fishing activity data tracked from AIS. Although the response of marine ecosystems to human activities is complex, this study takes a first step towards understanding resilience changes in marine ecosystems under human influence.

Acknowledgements

We would thank all the reviewers and editors for the insightful comments and suggestions, which substantially improved the manuscript.

Supplementary data

Supplementary material is available at the *ICESJMS* online.

Conflict of interest

There are no conflicts of interest with the publication of this article.

Funding

This work was supported by the National Natural Science Foundation of China grants (No. 41976208), the Innovation Group Project of Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai) (No. 311021004), and the Internal Program of State Key Laboratory of Marine Environmental Science (No. MELRI2205).

Author contributions

YZ: conceptualization, methodology, software, formal analysis, data curation, and writing—original draft.
YL: conceptualization, validation, resources, writing—review and editing, and supervision.

Data availability

The fisheries footprint data are available in Global Fishing Watch database at https://globalfishingwatch.org/map-and-data/. The net primary productivity data are available in Oregon State University at http://sites.science.oregonstate.edu/ocean.productivity/eppley.model.php. The SST data are available in Bio-ORACLE database at https://www.bio-oracle.org/downloads-to-email.php.

Reference

Allgeier, J. E., Valdivia, A., Cox, C., and Layman, C. A. 2016. Fishing down nutrients on coral reefs. Nature Communications, 7: 1–5.

Assis, J., Tyberghein, L., Bosch, S., Verbruggen, H., Serrão, E. A., and Clerck, O. De. 2018. Bio-ORACLE v2.0: extending marine data layers for bioclimatic modelling. Global Ecology and Biogeography, 27: 277–284.

Bauch, C. T., Sigdel, R., Pharaon, J., and Anand, M. 2016. Early warning signals of regime shifts in coupled human-environment systems. Proceedings of the National Academy of Sciences, 113: 14560–14567.

Behrenfeld, M. J., and Falkowski, P. G. 1997. Photosynthetic rates derived from satellite-based chlorophyll concentration. Limnology and Oceanography, 42: 1–20.

Blanchard, J. L., Jennings, S., Holmes, R., Harle, J., Merino, G., Allen, J. I., Holt, J. *et al.* 2012. Potential consequences of climate change for primary production and fish production in large marine ecosystems. Philosophical Transactions of the Royal Society B: Biological Sciences, 367: 2979.

Bohorquez, J. J., Xue, G., Frankstone, T., Grima, M. M., Kleinhaus, K., Zhao, Y., and Pikitch, E. K. 2021. China’s little-known efforts to protect its marine ecosystems safeguard some habitats but omit others. Science Advances, 7: 1569.

Buxton, J. E., Abrams, J. F., Boulton, C. A., Barlow, N., Rangel Smith, C., Van Stroud, S., Lees, K. J. *et al.* 2022. Quantitatively monitoring the resilience of patterned vegetation in the Sahel. Global Change Biology, 28: 571–587.

Cael, B. B., Dutkiewicz, S., and Henson, S. 2021. Abrupt shifts in 21st-century plankton communities. Science Advances, 7: 8593–8622.

Cao, L., Chen, Y., Dong, S., Hanson, A., Huang, B. O., Leadbitter, D., Little, D. C. *et al.* 2017. Opportunity for marine fisheries reform in China. Proceedings of the National Academy of Sciences, 114: 435–442.

Carozza, D. A., Bianchi, D., and Galbraith, E. D. 2019. Metabolic impacts of climate change on marine ecosystems: implications for fish communities and fisheries. Global Ecology and Biogeography, 28: 158–169.

Crona, B., Wassénius, E., Troell, M., Barclay, K., Mallory, T., Fabinyi, M., Zhang, W. *et al.* 2020. China at a crossroads: an analysis of

China's changing seafood production and consumption. One Earth, 3: 32–44.

Feng, Y., Su, H., Tang, Z., Wang, S., Zhao, X., Zhang, H., Ji, C. *et al.* 2021. Reduced resilience of terrestrial ecosystems locally is not reflected on a global scale. Communications Earth & Environment, 2: 88.

Fu, X. M., Zhang, M. Q., Liu, Y., Shao, C. L., Hu, Y., Wang, X. Y., Su, L. R. *et al.* 2018. Protective exploitation of marine bioresources in China. Ocean & Coastal Management, 163: 192–204.

Hakspiel-Segura, C., Martínez-López, A., Antonio Delgado-Contreras, J., Robinson, C. J., and Gómez-Gutiérrez, J. 2022. Temporal variability of satellite chlorophyll-a as an ecological resilience indicator in the central region of the Gulf of California. Progress in Oceanography, 205: 102825.

Halpern, B. S., Frazier, M., Afflerbach, J., Lowndes, J. S., Micheli, F., O'Hara, C., Scarborough, C. *et al.* 2019. Recent pace of change in human impact on the world's ocean. Scientific Reports, 9: 1–8.

Hammerschlag, N., Schmitz, O. J., Flecker, A. S., Lafferty, K. D., Sih, A., Atwood, T. B., Gallagher, A. J. *et al.* 2019. Ecosystem function and services of aquatic predators in the Anthropocene. Trends in Ecology & Evolution, 34: 369–383.

Harry, A. V, Braccini, M., Queiroz, N., and Shelf, N. W. 2021. Reply to: caution over the use of ecological big data for conservation. Nature, 595: E17–E19.

Holbrook, S. J., Wencélius, J., Dubel, A. K., Adam, T. C., Cook, D. C., Hunter, C. E., Lauer, M. *et al.* 2022. Spatial covariation in nutrient enrichment and fishing of herbivores in an oceanic coral reef ecosystem. Ecological Applications, 32: e2515.

Hughes, T. P., Bellwood, D. R., Folke, C., Steneck, R. S., and Wilson, J. 2005. New paradigms for supporting the resilience of marine ecosystems. Trends in Ecology & Evolution, 20: 380–386.

Johnson, S. M., and Watson, J. R. 2021. Novel environmental conditions due to climate change in the world's largest marine protected areas. One Earth, 4: 1625–1634.

Kang, B., Pecl, G. T., Lin, L., Sun, P., Zhang, P., Li, Y., Zhao, L. *et al.* 2021. Climate change impacts on China's marine ecosystems. Reviews in Fish Biology and Fisheries, 31: 599–629.

Komsta, L. 2019. mblm: median-based linear models. R Package Version 0.12.1. https://cran.r-project.org/web/packages/mblm/index.html (last accessed May 2022)

Kovac, Z., Platt, T., and Sathyendranath, S. 2020. Stability and resilience in a nutrient-phytoplankton marine ecosystem model. ICES Journal of Marine Science, 77: 1556–1572.

Kroodsma, D. A., Mayorga, J., Hochberg, T., Miller, N. A., Boerder, K., Ferretti, F., Wilson, A. *et al.* 2018. Tracking the global footprint of fisheries. Science, 359: 904–908.

Krumhardt, K. M., Lovenduski, N. S., Long, M. C., Luo, J. Y., Lindsay, K., Yeager, S., and Harrison, C. 2020. Potential predictability of net primary production in the ocean. Global Biogeochemical Cycles, 34. https://doi.org/10.1029/2020GB006531

Kwiatkowski, L., Bopp, L., Aumont, O., Ciais, P., Cox, P. M., Laufkötter, C., Li, Y. *et al.* 2017. Emergent constraints on projections of declining primary production in the tropical oceans. Nature Climate Change, 7: 355–358.

Lam, V. W. Y., Allison, E. H., Bell, J. D., Blythe, J., Cheung, W. W. L., Frölicher, T. L., Gasalla, M. A. *et al.* 2020. Climate change, tropical fisheries and prospects for sustainable development. Nature Reviews Earth & Environment, 1: 440–454.

Laufkotter, C., Vogt, M., Gruber, N., Aita-Noguchi, M., Aumont, O., Bopp, L., Buitenhuis, E. *et al.* 2015. Drivers and uncertainties of future global marine primary production in marine ecosystem models. Biogeosciences, 12: 6955–6984.

Levin, P. S., and Möllmann, C. 2015. Marine ecosystem regime shifts: challenges and opportunities for ecosystem-based management. Philosophical Transactions of the Royal Society B: Biological Sciences, 370: 1–8.

Liang, C., and Pauly, D. 2020. Masking and unmasking fishing down effects: the Bohai Sea (China) as a case study. Ocean & Coastal Management, 184: 105033.

Liu, B., Wu, X., Liu, X., and Gong, M. 2021. Assessment of ecological stress caused by maritime vessels based on a comprehensive model using AIS data: case study of the Bohai Sea, China. Ecological Indicators, 126: 107592.

Lomartire, S., Marques, J. C., and Gonçalves, A. M. M. 2021. The key role of zooplankton in ecosystem services: a perspective of interaction between zooplankton and fish recruitment. Ecological Indicators, 129: 107867.

Lynam, C. P., Llope, M., Möllmann, C., Helaouët, P., Bayliss-Brown, G. A., and Stenseth, N. C. 2017. Interaction between top-down and bottom-up control in marine food webs. Proceedings of the National Academy of Sciences, 114: 1952–1957.

Ma, S., Liu, D., Tian, Y., Fu, C., Li, J., Ju, P., Sun, P. *et al.* 2021. Critical transitions and ecological resilience of large marine ecosystems in the Northwestern Pacific in response to global warming. Global Change Biology, 27: 5310–5328.

Ovando, D., Hilborn, R., Monnahan, C., Rudd, M., Sharma, R., Thorson, J. T., Rousseau, Y. *et al.* 2021. Improving estimates of the state of global fisheries depends on better data. Fish and Fisheries, 22: 1377–1391.

Paradis, S., Goñi, M., Masqué, P., Durán, R., Arjona-Camas, M., Palanques, A., and Puig, P. 2021. Persistence of biogeochemical alterations of deep-sea sediments by bottom trawling. Geophysical Research Letters, 48: e2020GL091279.

Pebesma, E. 2018. Simple features for R: standardized support for spatial vector data. The R Journal, 10: 439–446.

R Core Team. 2021. R: a language and environment for statistical computing (4.0.5). R Foundation for Statistical Computing. https://www.r-project.org/ (last accessed May 2022)

Ramírez, F., Coll, M., Navarro, J., Bustamante, J., and Green, A. J. 2018. Spatial congruence between multiple stressors in the Mediterranean Sea may reduce its resilience to climate impacts. Scientific Reports, 8: 1–8.

Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., Held, H. *et al.* 2009. Early-warning signals for critical transitions. Nature, 461: 53–59.

Siswanto, E., Ishizaka, J., and Yokouchi, K. 2006. Optimal primary production model and parameterization in the eastern East China Sea. Journal of Oceanography, 62: 361–372.

Su, H., Wang, R., Feng, Y., Li, Y., Li, Y., Chen, J., Xu, C. *et al.* 2020. Long-term empirical evidence, early warning signals and multiple drivers of regime shifts in a lake ecosystem. Journal of Ecology, 109: 3182–3194.

Su, M., Wang, L., Xiang, J., and Ma, Y. 2021. Adjustment trend of China's marine fishery policy since 2011. Marine Policy, 124: 104322.

Sumaila, U. R., and Tai, T. C. 2020. End overfishing and increase the resilience of the ocean to climate change. Frontiers in Marine Science, 7. https://doi.org/10.3389/FMARS.2020.00523

Sun, D., Chen, Y., Feng, Y., Liu, Z., Peng, X., Cai, Y., Yu, P. *et al.* 2021. Seasonal variation in size diversity: explaining the spatial mismatch between phytoplankton and mesozooplankton in fishing grounds of the East China Sea. Ecological Indicators, 131: 108201.

Szuwalski, C., Jin, X., Shan, X., and Clavelle, T. 2020. Marine seafood production via intense exploitation and cultivation in China: costs, benefits, and risks. PLoS One, 15: e0227106.

Tagliabue, A., Barrier, N., Du Pontavice, H., Kwiatkowski, L., Aumont, O., Bopp, L., Cheung, W. W. L. *et al.* 2020. An iron cycle cascade governs the response of equatorial Pacific ecosystems to climate change. Global Change Biology, 26: 6168–6179.

Van Denderen, P. D., Lindegren, M., MacKenzie, B. R., Watson, R. A., and Andersen, K. H. 2018. Global patterns in marine predatory fish. Nature Ecology and Evolution, 2: 65–70.

Van Putten, I., Boschetti, F., Ling, S., Richards, S. A., and Link, J. 2019. Perceptions of system-identity and regime shift for marine ecosystems. ICES Journal of Marine Science, 76: 1736–1747.

Wang, Z., Juarez, D. L., Pan, J. F., Blinebry, S. K., Gronniger, J., Clark, J. S., Johnson, Z. I. *et al.* 2019. Microbial communities across nearshore to offshore coastal transects are primarily shaped by distance and temperature. Environmental Microbiology, 21: 3862–3872.

Wu, P. P. Y., Mengersen, K., McMahon, K., Kendrick, G. A., Chartrand, K., York, P. H., Rasheed, M. A. *et al.* 2017. Timing anthropogenic stressors to mitigate their impact on marine ecosystem resilience. Nature Communications, 8: 1–11.

Handling Editor: Pamela Woods