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Reconstructing fishing capacity and landings of China's bottom trawl fisheries (1950 – 2018)

Xiong Zhang, Amanda C. J. Vincent

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Email: x.zhang@oceans.ubc.ca

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Authors: Xiong Zhang, Amanda C. J. Vincent
Institution: Project Seahorse, Institute for the Oceans and Fisheries, The University of British Columbia.
Address: 2202 Main Mall, Vancouver, BC V6M 1Z4, Canada.

Abstract

Bottom trawling (BT) has long been a global concern for its destructive impacts on marine fisheries and conservation. Revealing the evolution of BT and its impact on the marine ecosystems depends on timeseries data of the fishing capacity and landings. Such timeseries information might be well documented in developed countries but are rare in many developing nations such as China, whose bottom trawl fisheries (BTF) dwarf all other nations. Here we used timeseries models (ARIMA) and other regression models (GAM & LOESS) to reconstruct China's BTF from 1950 to 2018. We estimated the fishing capacity (vessels and engine horsepower) based on both published data from Chinese government and scientists and archived historical records from Chinese fisheries institutions. We reconstructed the catch estimates (by Sea Around US Project) with corrections in the timeseries for distant waters beyond China's coastal seas before 1985. We also extrapolated the catch timeseries up to 2018 (currently available by 2014). Our study provides vital timeseries information to understand the evolution of China's BTF and its global impacts.

Keywords: distant water fisheries, fisheries reconstruction, fishing power, overcapacity, sustainable fisheries, vessel buyback.

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1. Introduction

Scientists have long been concerned with the massive use of bottom trawlers (BTs) in marine fisheries, primarily because of their non-selective and destructive nature [1,2]. As the world's dominant commercial fishing practice, bottom trawling (BT) has consistently contributed 50% biomass of global annual catches since the late 1980s (23% of the landed catches and 60% of discards) [3]. Substantial evidence has accumulated to show that BT degrades benthic marine ecosystems, threatens non-targeted and rare marine species, and unleashes contaminants from sediments [4–6]. However, given their fishing efficiency, BTs have gradually expanded their footprints from inshore to offshore waters (including high seas) [7–9], though mitigation occurred in some regions (e.g., North America, Australia) through policy intervention (e.g., trawl bans, vessel buyback) [10,11]. A latest study based on data from the automatic identification system (AIS) and logbooks suggests that BTs only sweep ~ 14% of the studied sea bottom (24 continental shelves, multiple times) every year [12]. However, the trawling footprint and intensity varied dramatically among regions [12], and this analysis did not include data from Asia (particularly C4S), where the footprint and intensity of BT are among the highest [13–16].

Addressing BT requires a good understanding of its capacity (e.g., total number of fishing vessels participating in BT) and yields (e.g., total catch) over time. Such timeseries data could allow scientists to examine the effects of fishery management and policies [17]. To this end, developed fishing nations such as the UK have long conducted their statistics for bottom trawl fisheries (BTF) (dating back to 1889) [5]. Since 1950, FAO has made national fishery statistics available worldwide. The Sea Around Us Project (SAUP) initiative has also reconstructed the catch data based on FAO's database and other sources to include discards, artisanal fisheries, and unreported landings from 1950 through to 2014 [18,19]. Coupled such data with price information, studies have estimated the landed value of global fisheries from 1950 throughout 2014 [19–21]. Meanwhile, fisheries scientists have long developed a variety of indices to understand the health of the fisheries and marine ecosystems. These commonly used indices include catch per unit effort (CPUE) [22], mean trophic level (MTL) [23], fishing-in-balance index (FIBI) [24], and the log-relative-price index (LRPI) [25,26]. Thanks to these data and indices, we have learnt that many of the world fisheries have been depleted in a way that reduced the CPUE, MTL, and LRPI, and gradually expanded offshore with higher FIBI over time (22-26).

Although reducing fishing capacity and effort of BTs is key to the sustainability of global fisheries [1], such capacity data are often lacking especially in developing countries [17,24]. Currently, we know little about fishery capacity and efforts of BTF in many countries, especially those that had simply not monitored or not published these data [27,28]. Fishery capacity can be measured with various ways including the number and horsepower of vessels participating in the fishery, and the time spent in fishing [17,27,29]. Recently, some researchers have reconstructed fishing capacity and effort for all fishing fleets at the global scale by using FAO and EU databases [17,27]. They found that global fishing capacity and effort boosted rapidly from the late 1970s throughout 2010; notably such a trend was dominated by Asian vessels which continued to grow [17]. However, this study did not focus on BTs and used very limited data from developing countries in Asia especially the People's Republic of China (PRC, hereafter China).

China is one of the countries with a poor track record of reporting fisheries (capacity?) data [30], despite that China plays a pivotal role in reducing BT and its impacts on global marine fisheries [31–33]. China is the world largest fishing nation; its annual total landings amount to about 20% of global marine landings [34]. China has only started fisheries statistics since 1950 (after the founding of the People's Republic of China in late 1949) and published the data in the China Fishery Statistical Yearbooks (CFSY) since 1979. According to the latest CFSY, ~ half (by biomass) of China's marine landings comes from trawlers in 2018 (4.9 million tons) [35]. However, capacity and yields of its BTs have not been specifically mentioned in the Yearbooks, although most Chinese trawlers are known to be BTs [36]. The reconstructed data from SAU also indicated that BTs has consistently accounted for ~ 90% of the catch of China's trawl fisheries since 1950 (Fig. S1.1) [37]. Meanwhile, China is also home to perhaps the largest number of trawlers, with 28,364 trawlers registered in 2018 [35]. Although most Chinese boats fish only in its domestic waters, ~ 2,700 fishing vessels (including many BTs) are operated in foreign EEZ and high seas with significant global effects on marine fisheries [33,35]. Notably, China's BTF contribute a large portion of the 'trash fish' (low-

valued bycatch including juveniles of commercial stocks) used directly or indirectly in animal farms especially its aquaculture [31,36], which is the major supply of food fish in China and worldwide [38].

China has issued over a hundred policy documents, including capacity and yield controls, to guide the development of its BTF since 1950 [39]. However, the effectiveness of many of these policies are unknown because of the paucity of long-term timeseries data of the capacity, yields, and fishery health indicators for China's BTF. A major data gap in CFSYs is fishing capacity (e.g., total number and horsepower) of China's BTs in domestic and distant waters, although they published data about trawlers since 2003 [40,41]. To fill this gap, there is a need to collate information from local Chinese fishery governments and institutions who might have some records of BTs in their administrative regions over time. Meanwhile, fishery studies on China's BTF are not rare, although they have been primarily published on Chinese literature and rarely been seen in English-language or international journals. Tapping into these local resources is therefore beneficial to help us reconstruct the capacity trajectory of China's BTs and then promote understanding of its fishery policies.

We here present the methods to reconstruct the timeseries of fishing capacity (vessels and their engine horsepower) for China's BTF (both within and beyond Chinese 4 seas) to the greatest extent possible. We collected both published data from Chinese government documents (CFSY) and peer-reviewed literature (in Chinese). We were able to get access to two regional compilations of fishing fleet information (including bottom trawlers) from Chinese fisheries institutions. We then used various models, including generalized additive models (GAM), locally estimated scatterplot smoothing (LOESS), and auto regressive integrated moving average (ARIMA) to fill the gaps. To validate our estimation, we compared the results with independent data. Our study provides the essential baseline knowledge to understand the evolution of China's BTF and their global impacts.

2. Study areas

Our study focused on four waters (or two pairs) that we could find available data to understand China's BTF.

China's claimed EEZ vs. distant waters. Here, it referred to five EEZs claimed by the People's Republic of China (PRC, a.k.a., mainland China): (i) EEZ under the administration of PRC, (ii) EEZ under the administration of Taiwan (province of China), (iii) EEZ disputed among PRC, Taiwan (province of China), and Japan, (iv) EEZ surrounded the Paracel Islands, and (v) EEZ surrounded the Spratly Islands (Fig.1). These are the EEZ regions for China used by the Sea Around Us (SAUP) as a spatial unit to reconstruct yield statistics (e.g., catch and landed value) [42], and we adopted it as our yield data were reconstructed based on the SAUP database. Correspondingly, the distant waters refer to waters beyond the claimed EEZ as described above. We were interested in understanding the expansion of China's BTF to distant waters in terms of catch and landed values.

China's 4 seas (C4S) vs. distant waters beyond C4S. The former water body refers to the four seas, i.e., Bohai Sea, Yellow Sea, East China Sea, and South China Sea, which surround China's continent and covers China's claimed EEZ. The total area of the four seas amounts to 4.8 million km^2; and 32% of the area is the continental shelf within the 200-m isobath, where most fishery resources are concentrated [43,44]. The C4S also represents a most heavily trawled area around the world (Fig. 2) [14,15]. We used a collection of EEZ subregions (defined by SAUP) within C4S to represent C4S when reconstructing catch by China's BTF from C4S [45], given that the boundaries of these waters are vague. Notably, China considers fisheries in the four seas as 'domestic fisheries' and those beyond as 'distant-water fisheries', as used in the yearbooks (i.e., CFSYs) [33,46]. Before the establishment of EEZ by China (in 1996), there were no clear national boundaries between China and other neighboring countries on the four seas. Even after the establishment of the EEZ regime, there were disputed EEZs with Japan, South Korea, and some nations in the South (e.g., Vietnam). After 1996, China's fishery scientists and governments continued to consider fisheries within the four seas as 'domestic fisheries' (Dr. Z. CHEN & Dr. X. SHAN, Chinese Academy of Fisheries Science; Nov. 2019, personal communications). We therefore interpreted the capacity data for 'domestic fisheries' and 'distant-water' fisheries from China as statistics for C4S and waters beyond C4S, respectively.

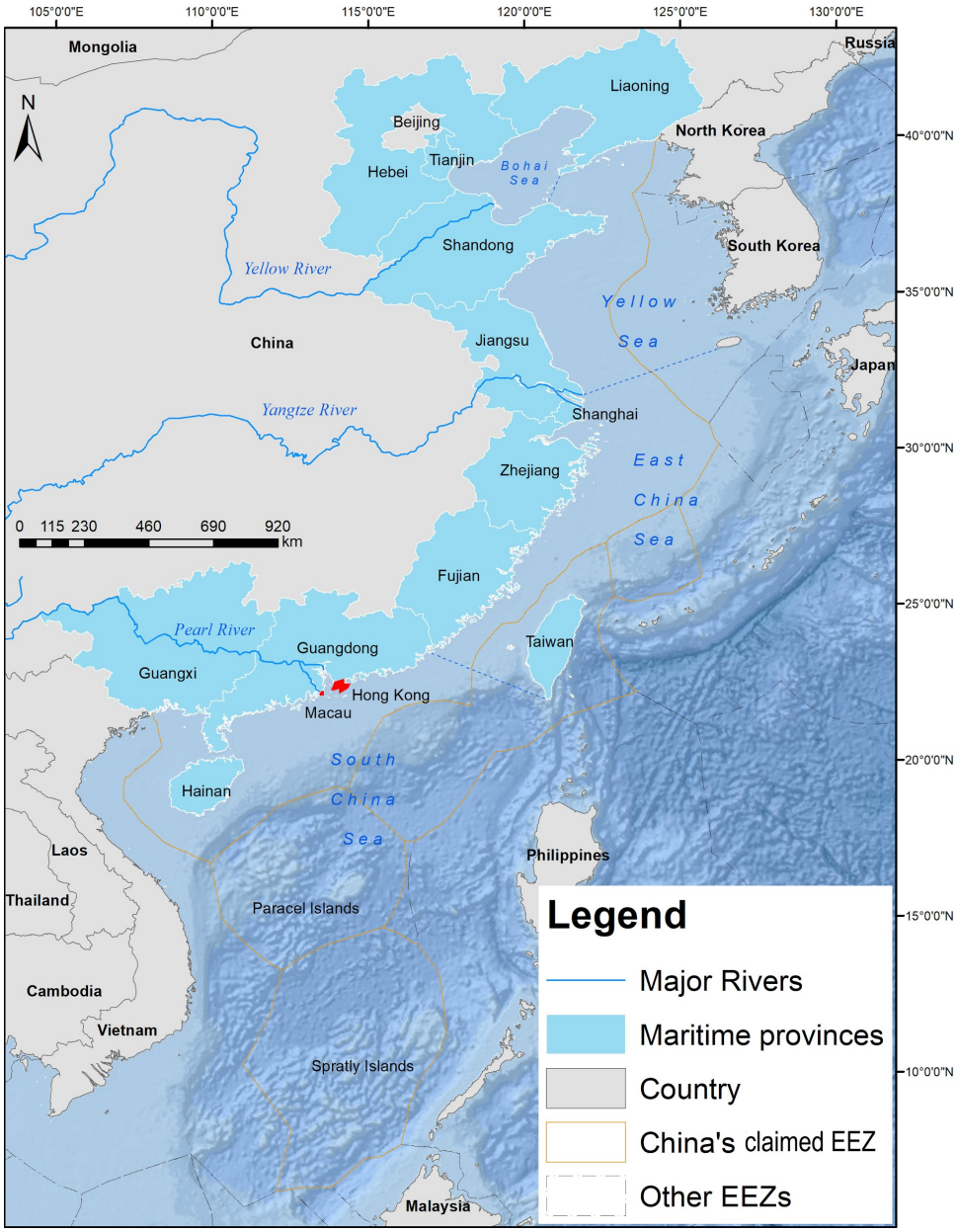

Figure 1. China's four seas and it's claimed Exclusive Economic Zone (EEZ).

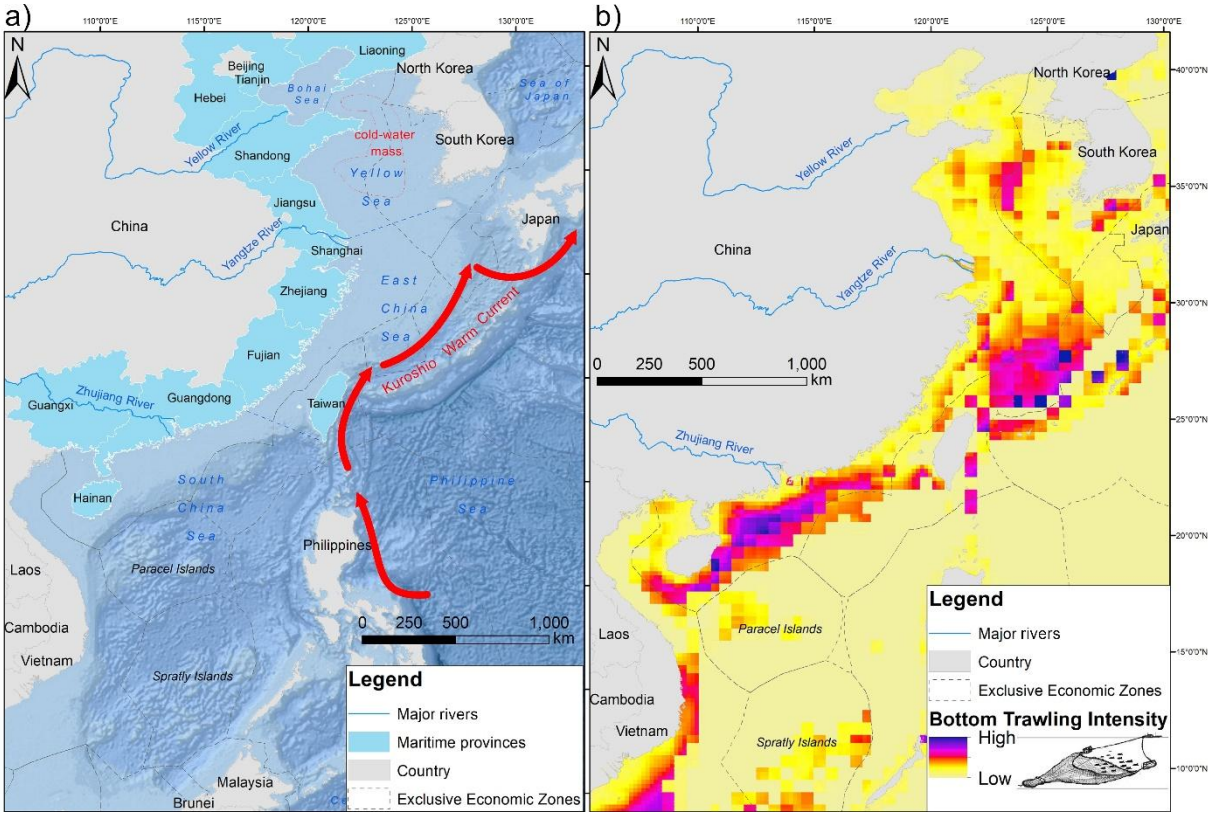

Figure 2. China's coastal seas and bottom trawling intensity.

3. Data collection and analysis

3.1 Literature review

To better understand the history of China's BTF, we searched both qualitative and quantitative data about this topic (e.g., vessels, gears, operation styles, stock status, development phases) from three sources: (i) a recent systematic study of Chinese fishing gears in the Bohai Sea and Yellow Sea (in Chinese) [47], (ii) relevant peer-reviewed papers from China's 'Web of Science' – the China Knowledge Resource Integrated Database (a.k.a., CNKI, http://cnki.net/, 1979 – 2018), using the Chinese keyword '拖网' (i.e., trawl; in Chinese, this word could cover any studies related to trawl, trawler, and trawl fisheries), and (iii) studies about Chinese BTF in English peer-reviewed literature from the Web of Science (subject: "China" AND "trawl" AND "fish"). The collected data provided useful information about the fishing capacity (vessels and horsepower) of Chinese bottom trawlers (BTs) and other catchers.

3.2 Data collection and reconstruction of fishing capacity and yield statistics of China's marine fisheries

We collected annual statistics of China's marine fisheries (including distant-water fisheries) to estimate the capacity and yield of its BTF and all marine capture fisheries. To this end, we first collected capacity statistics (total number and horsepower of various vessels) between 1951 and 2017 from Chinese Fishery Statistical Yearbooks[1] (CFSYs, see 3.2.1). Although there were many non-motorized fishery vessels (e.g., wind-powered boats) in China in the early decades from 1950s – 1990s, we here only focused on motorized vessels as the latter was measured and were reported more consistently by China throughout the history while the former was only available in the early decades and there were likely not many non-motorized fishing boats conducting bottom trawling based on our literature review [48,49].

Given data paucity for BTs and all marine catchers in CFSYs, we then used various models (e.g., timeseries models) to reconstruct the capacity of China's BTs and all catchers, first for all waters that China fished (see 3.2.2 & 3.2.3), and then for its distant-water fisheries (DWF; section 2.4). Additional capacity records were drawn from the China Knowledge Resource Integrated Database (1950 – 2019, see 3.1). Whenever data were available, we validated our model-based estimates with independent studies from peer-reviewed literature. Notably, were we did not count other technological creep (e.g., uses of fish finder, GPS, and smaller mesh size) in measuring fishing capacity [47,48], which is usually difficult to estimate and a common issue all fishing capacity studies [5,50].

We collected yield data of China's BTs and marine catchers from the reconstructed fishery database (1950 – 2014) of the Sea Around Us Project, Institute for the Oceans and Fisheries, The University of British Columbia (see 3.2.4). We made some important improvement on these reconstructed timeseries by correcting estimates from 1950 to 1984; we then extrapolated the data to the missing years from 2015 to 2017 based on various models (see 3.2.5).

3.2.1 Collecting capacity statistics from Chinese Fishery Statistical Yearbooks (CFSYs)

The original capacity data collected from CFSYs (yearly statistics available from 1951 – 2017) included the national annual fishery statistics of two metrics of interest – the total number of vessels and total horsepower. Here we merely focused on motorized bottom trawlers (BTs) throughout the study. Although we could not find these statistics directly for BTs, there were such statistics available for trawlers (拖网渔船, largely bottom trawlers) at the national level available from 2003 – 2017 [51]. For distant-water BTs, we gathered the statistics of (1) 'distant-water catchers' (远洋捕捞渔船, fishing vessels that operate in distant waters beyond China's 4 seas) that were available at the national level from 1986 – 2002, and (2) 'distant-water vessels' (远洋渔船, distant-water catchers and fishery auxiliary vessels) that were available from 1986 – 2017 (Table 1). As we explained above (see 2.1), China's concept of 'distant water' is different from

[1] Note we here did not include CFSY of year 2018 because the data in this year were not published yet (until late 2019) at the time we completed the reconstruction analysis. But the impact on our estimates would be low given this only include a single year data point.

the common definition, which is the water beyond a nation's EEZ; in contrast, China considered fisheries in C4S (which covers its claimed EEZ but also part of the EEZs of neighboring countries) as 'domestic fisheries', and all other fisheries beyond C4S are 'distant water fisheries' [46].

The statistics on the above proxies (e.g., trawlers, distant-water catchers) for China's BTs (both domestic and distant-water ones) were the best data we could currently obtain at the national level from China's own sources. These national-level statistics were based on yearly statistical reports from China's maritime provinces/municipalities. We acknowledged that there were large numbers of illegal and unregistered fishing boats in China, but most of the illegal vessels were small boats [52], and thus BTs (which usually require relatively high engine power and large vessels) likely do not take a large share of them. However, future studies are needed to better examine this problem.

Table 1. Terminology of Chinese fishing vessels defined by China.

Term	Term in Chinese	Definition
Trawlers	拖网渔船	Motorized trawling vessels powered by engines; including both pelagic trawlers and bottom trawlers
Distant-water catchers	远洋捕捞渔船	Motorized fishing vessels that specifically operate in distant waters beyond C4S
Catchers	捕捞渔船	Motorized fishing vessels that specifically used to catch fishery stocks
Production vessels	生产渔船	Motorized fishery vessels that were used either to specifically catch fishery stocks or in mariculture
Distant-water vessels	远洋渔船	Motorized distant-water catchers and fishery auxiliary vessels
Motorized vessels	机动渔船	Comprised of production vessels and motorized fishery auxiliary vessels that do not fish but provide fishery logistics

Given the paucity of fishery capacity data for BTs at the national level, we reconstructed the capacity timeseries based on the collected data in the following sections.

3.2.2 Reconstructing capacity statistics for China's bottom trawlers

We assumed that all trawlers in China conducted (but might not only) bottom trawling, which was likely the case both based on our own observations in the field and literature review [53,54]. Given China has only reported its capacity statistics for trawlers since 2003, we then need to fill the gap between 1950 and 2002.

We used a variety of methods (, autoregressive models, time-trend regression models, and constant ratios) to fill the gaps. Our first option was to build timeseries models, e.g., auto regressive integrated moving average (ARIMA; 'auto.arima' function in the 'forecast' r package) [55]. However, this demand consecutive and relative long-term timeseries datasets to construct robust models. We found this was very challenging in our study for most of our data were quite scarce (not recorded continuously; see details below). We were only able to use timeseries models for some extrapolations.

To do interpolation and extrapolations when the timeseries model could not derive reliable estimates (e.g., negative values; see below), we employed time-trend regression models (i.e., using year as the regressor) and ratio statistics. The time-trend models here referred to two categories of modeling techniques: 1) local polynomial models, e.g., locally estimated scatter-plot smoother (LOESS; 'loess.as' and 'loess' functions in the 'fANCOVA' r package) [56], and 2) generalized additive models (GAM; 'gam' function in the 'mgcv' r package) [17,57]. The former depends on consecutive timeseries and was used when the ARIMA model did not derive reasonable backcasts or forecasts (e.g., negative values; see details below). The latter did not require consecutive data and was used for 1) interpolation on missing years between two years, and 2) extrapolation for a short period (e.g., 2 years backward or ahead) if the

resultant estimates were acceptable. The ratio statistics, on the other hand, were ratios of the capacity statistics (e.g., total number of vessels) between the focal variable (e.g., trawlers) and a proxy/predictor (e.g., all catchers) which had available data within the time frame. We used the ratio statistics when the focal variable had very few data points to apply robust time-trend regression models, but its proxy had plenty of data and they were significantly correlated (examined with cross correlation tests, 'ccf' function in the r package 'tseries') [58]. Ideally, the ratio should be well fitted by ARIMA or time-trend regression models to predict the ratios in missing years. We recorded the 95% confidence intervals of the estimates derived from each of the above approaches to analyze the uncertainty during the reconstruction process.

The reconstruction was done for three periods given the data availability and the assumed development periods of China's BTs as narrated in the Results of the manuscript. The first period was from 1950 to 1978, which was before the nation launched the 'economic reform and market opening up' policy (announced in late Dec. 1978). During this period, marine fishing vessels were owned and operated by the state-owned companies or commune-owned production communities/groups (in Chinese, 生产社队, see CFSY by MOA before 1978). After 1978, fishing vessels started to be privatized and small trawlers were built and entered the fisheries [59,60]. This presumably has a tremendous impact on the relationships between several proxy variables and trawlers and upon the trends of the total vessels and horsepower of trawlers. Meanwhile, we couldn't gather capacity statistics for the proxy variables in 1979 and we considered this year as a transition from the first period (1950 – 1978) to the later period (1989 – 2002) and need a smoothing model to connect the two in a reasonable way. Therefore, we split the timeseries into three periods accordingly: 1950 – 1978, 1979, and 1980 – 2002. We first demonstrated the reconstruction processes from 1950 – 1978 and 1980 – 2002, respectively, and then used the data from both periods to interpolate for capacity statistics of trawlers in 1979.

1st Period (1950 – 1978): Before the economic reforms and vessel privatization

Major assumptions for this period: (1) there was a linear relationship between China's trawlers and large marine catchers (LMC, i.e., fully-motorized fishing vessels in contrast to those powered by wind or a combination of wind and engines, a.k.a., '生产渔轮', *shēng chǎn Yú Lún*) in terms of the total number (or horsepower) of vessels [61], (2) there was a linear relationship between LMC and the large marine fishery vessels (LMFV, a.k.a., '渔轮', *Yú Lún*, including LMC and fully-motorized fishery assistant ships such as fish carriers) in terms of the total number (or horsepower) of vessels [62], and (3) all China's trawlers were bottom trawlers given bottom trawling was the dominant type of fishing practice of trawlers [53,54].

We learned that China's motorized trawlers during this period were all LMC with high horsepower (mainly vessels with an engine horsepower > 250 hp or 184 kW) [54]; every fishing vessel of LMC conducted trawling at least before 1958 [62], and exclusively non-trawling LMC (mainly purse seiners, transformed from trawlers) only emerged in 1960s with some records of the total number of these vessels in a few years since then [53,54]. We therefore estimated capacity statistics of trawlers from those of LMC, which themselves were derived with following reconstruction processes.

China reported the capacity statistics (i.e., total number and horsepower) of LMC only from 1978 to 1986 [63], and thus we had to estimate these capacity statistics from 1950 to 1977. The best predictors we found were the number and horsepower of LMFV available from 1951 to 1983, in the Compilation of Fishery Statistics in the East China Sea Region (in Chinese: 东海区海洋渔业统计资料汇编 1951 - 1983) [64]. We first tried ARIMA to extrapolate the number and horsepower of LMFV to 1950 based on the available data, but this derived negative values in 1950 (-51, -55221 hp). We then used LOESS instead and derived a reasonable estimate on the number of LMFV (mean ± SE: 199±32) for we learned that the total number of LMC in 1950 was between 100 and 300 claimed by an independent study [62]. However, the estimated total horsepower based on a LOESS had a negative lower bound of 95% CI (-3392 hp). To correct this error, we assumed that the mean horsepower of LMFV in 1951 was equal to that in 1950, and derived an estimate of total horsepower of LMFV in 1950 based on the mean horsepower and the estimated total number of LMFV in 1950 (mean ± SE: 18166±2931 hp).

We then estimate the number and horsepower of LMC to the period between 1950 and 1977 based on two relatively consistent ratios between LMC and LMFV in terms of total number (mean ± SE: 0.918±0.005, N = 6) and mean horsepower (mean ± SE: 0.951±0.007, N = 6) of vessels respectively. We first used

ARIMA to extrapolate the two ratio estimates from 1950 to 1977. This derived an ARIMA (0,0,0) model with a non-zero mean (i.e., constant means with low and random noises). Therefore, we used the loess model instead of ARIMA. The extrapolation uncertainty (95% CI) was estimated by resampling an equal number (N = 36) of elements 1000 times (i.e., bootstrapping) from the training dataset to rerun the loess model.

Based on the estimation for LMC, we fill the gaps of the capacity statistics of BTs from 1950 to 1978. First, we assigned the total number and horsepower of LMC to those of BTs in the early years (1950 – 1963) when all LMC were trawlers [53,62] (Fig. 3a). We then derived the total number of BTs from 1964 to 1978 based on the total number of LMC and the number of LMC conducting purse seining (the only non-trawling fishing practice for LMC during this period; Fig. 3a) [53]. Second, we assumed that the mean horsepower of BTs was equal to the mean horsepower of LMC given those LMC conducting purse seining were transformed from trawling vessels [62]. Therefore, we calculated the total horsepower of trawlers by multiplying the total number of BTs and the mean horsepower of LMC in each year and recorded the confidence intervals (Fig. 3b).

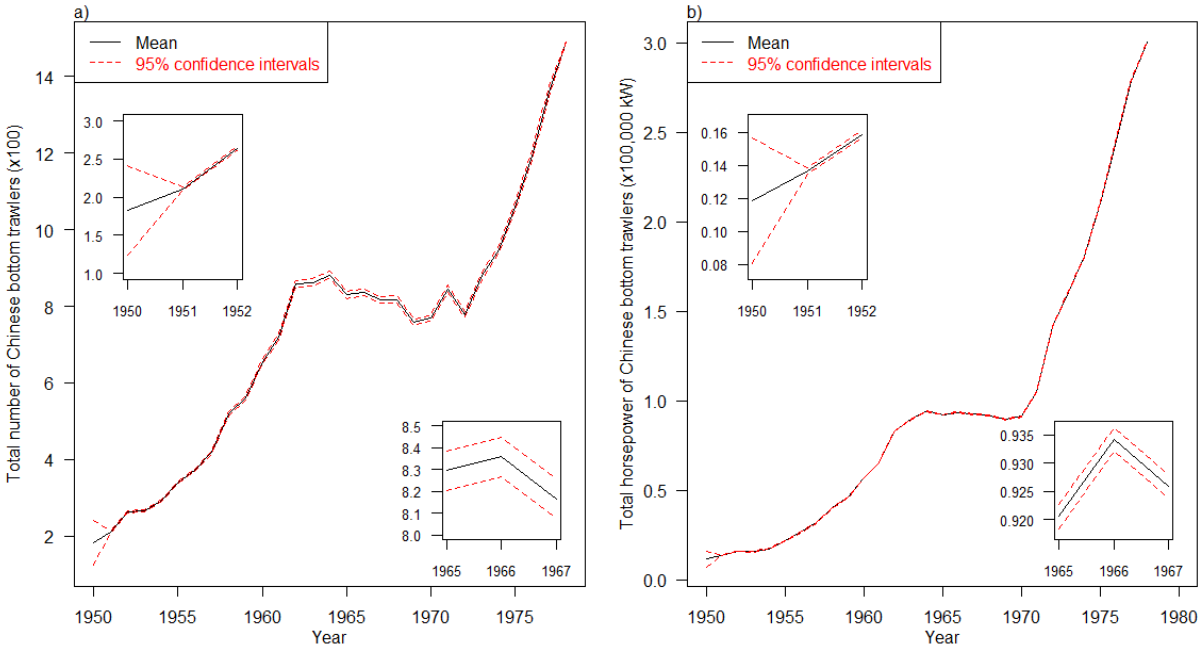

Figure 3. Capacity statistics for bottom trawlers from 1950 to 1978: a) total number of vessels, and b) total horsepower of vessels. The inserted small graphs demonstrated the model estimates in two time frames (1950 – 1952, and 1965 – 1967) with finer resolutions.

2nd Period (1980 – 2002): After economic reforms and vessel privatization

Major assumption: the ratio of trawlers in three major fishery provinces (Zhejiang, Fujian, and Guangdong) to those of the whole nation (in terms of total number or mean horsepower) was consistent throughout the history (here, 1980 – 2017).

Given there were no national-level information available for fishery capacity of China's trawlers, we searched local reports on the number and horsepower of trawlers in coastal provinces/municipalities. This was done by searching a few Chinese characters: 拖网 (trawl, and can also refers to trawlers in Chinese), 渔船 (fishing vessels) in the 'Full Text' in the China Knowledge Resource Integrated Database (a.k.a., CNKI, http://cnki.net/, 1950 – 2019). Here, we searched data from peer-reviewed journals, thesis & dissertation, conference proceedings, newspaper, yearbook, and monographic serials all in Chinese. We also got access to a hard-copy official publication, the Compilation of Fisheries Statistics of South China Sea from 1980 to 2005 (in Chinese: 南海渔业统计资料汇编 1980 - 2005) [61], which was not available through internet, with the assistance from Chinese colleagues. Whenever there was a conflict on the same

statistic in the same year between different sources, we chose the earliest record or record from the more robust source (e.g., independent scientific surveys rather than government reports) as a way of data quality control.

Eventually, we found some relevant data that spanned from 1980 to 2017 of three maritime provinces: Zhejiang, Fujian, and Guangdong. Given all three provinces had missing records for some years, we first filled these missing values and then scaled up to the national level based on the following steps.

Zhejiang province

Before 2003, the capacity statistics for trawlers in Zhejiang was only available in 1981 (total number of trawlers = 6234, BFMOA 2006). But there were data available in some years for the total number of three proxies: shrimp trawlers (available in 1980, 1982 – 1986, 1994, 1995, 2000, 2008, 2012, 2014), single trawlers (targeting fish species, available in 1996 – 2008), and marine catchers (available in 1980, 1984, 1994, 1995, 2003 – 2017) [51,64–71]. We also estimated the number of shrimp trawlers in Zhejiang for other four years (2001 – 2004) based on the total catch by shrimp trawlers in Zhejiang divided by the catch per shrimp trawler in Zhoushan (one of the major fishing cities of Zhejiang) [69].

We tried a variety of models to fill the gaps of shrimp trawlers and single trawlers. We first interpolate gaps for shrimp trawlers in Zhejiang with two GAM models (R^2 = 0.963 and 0.986, Figs 3a&b). The first GAM model used all available data (N = 16) to do the interpolation, which derived acceptable estimates in all years except 1981 (negative values in lower bound of the 95% CI, Fig. 4a). We therefore selected a subset of original data (N = 6) to construct a local GAM model which derived positive statistics (mean ± SE: 279±103) for year 1981 (Fig. 4b). We then tried two models (ARIMA with auto fit and loess with optimal selection) to extrapolate gaps between 1950 and 1995 and between 2009 and 2017 for single trawlers in this province (Fig. 5). Eventually, we used the extrapolations from the loess model (Fig. 5b) as we learned that the number of single trawlers increased after the economic reform and vessel privatization (since 1980) and presumably decreased under the double-control and trawl-reduction policies (since 2003) [39,72,73].

We tried to estimate the total number of trawlers in Zhejiang from the counterpart of shrimp trawlers and single trawlers. We first calculated the ratio between the subgroup (shrimp trawlers + single trawlers) and all trawlers in terms of total number in Zhejiang in the available years (1981, 2003 – 2014; N = 13). Given the uncertainty in the estimates of the subgroup in some years, we used GAM models with bootstraps (N = 1000 resamples from the subgroup estimates) to estimate the ratio between 1980 and 2002 (Fig. 6a). The mean and 95% confidence intervals were used to estimate the total number of trawlers in Zhejiang. We found that the GAM models (N = 1000) had an acceptable explanation power (adjusted R^2: median = 0.76) but a high standard deviation (0.32; Fig. 6b). The estimated total number of trawlers in this province based on the derived ratio demonstrated high variances (Fig. 7). It was therefore necessary to explore alternative proxies to do the estimation.

We also tried to estimate trawlers in Zhejiang based on the number of catchers in the province and the ratio between the two. First, we used a GAM to interpolate the number of catchers in missing years between 1980 and 2002 (adjusted R^2 = 0.996; Fig. 8a). Second, we used another GAM to estimate the ratio of trawlers to catchers in Zhejiang (by total number of vessels) in the missing years (adjusted R^2 = 0.901; Fig. 8b). The uncertainty in both model predictions were retrieved. Eventually, we estimated the total number of trawlers in Zhejiang based on the estimates from these two models (Fig. 9). We calculated the uncertainty (95% CI) in each estimated year based on the square root of the sum of the weighted uncertainty [74].

We compared the derived estimates of the total number of trawlers in Zhejiang based on the two different methods described and chose the latter given its smoother fitting and lower standard deviations (Fig. 6 vs. Fig. 9).

We then estimated the total horsepower of trawlers in Zhejiang based on a regression model. The horsepower of trawlers was only available from 2003 to 2017 [51] and could be estimated from relevant data in 1981. The latter was estimated based on a compilation of fisheries statistics in the East China Sea region [64]. This compilation only documented the trawlers' data for 1981; it split the horsepower of trawlers in Zhejiang (and other provinces in the East China Sea region) into 11 levels (e.g., < 60 hp, 60 – 79 hp, 80 – 119 hp, etc.) and provided the number of trawlers in each level. We estimated the total horsepower by summing up the product of the mean horsepower of each horsepower level multiplied by the number of trawlers in each level. We therefore used a GAM (with the year as the explanatory variable) to fill the gaps based on these data points (N = 16, adjusted R^2 = 0.991; Fig. 10). We also had available information of the mean horsepower of shrimp trawlers in 2000, which can be used as a reference point to validate the estimated total horsepower in the same year. We did this by multiplying the mean horsepower of shrimp trawlers in 2000 with the estimated total number (mean and 95% CI) of trawlers in 2000. This resulted in an estimated total horsepower of 2.55 million kW (95% CI = 2.31 – 2.80 million kW), close to the GAM-based estimate of 2.78 kW (95% CI = 2.71 – 2.86 million kW). Given the former estimation was based on mean horsepower of shrimp trawlers, the GAM estimation for all trawlers in 2000 was acceptable. However, more data are needed to validate the estimation.

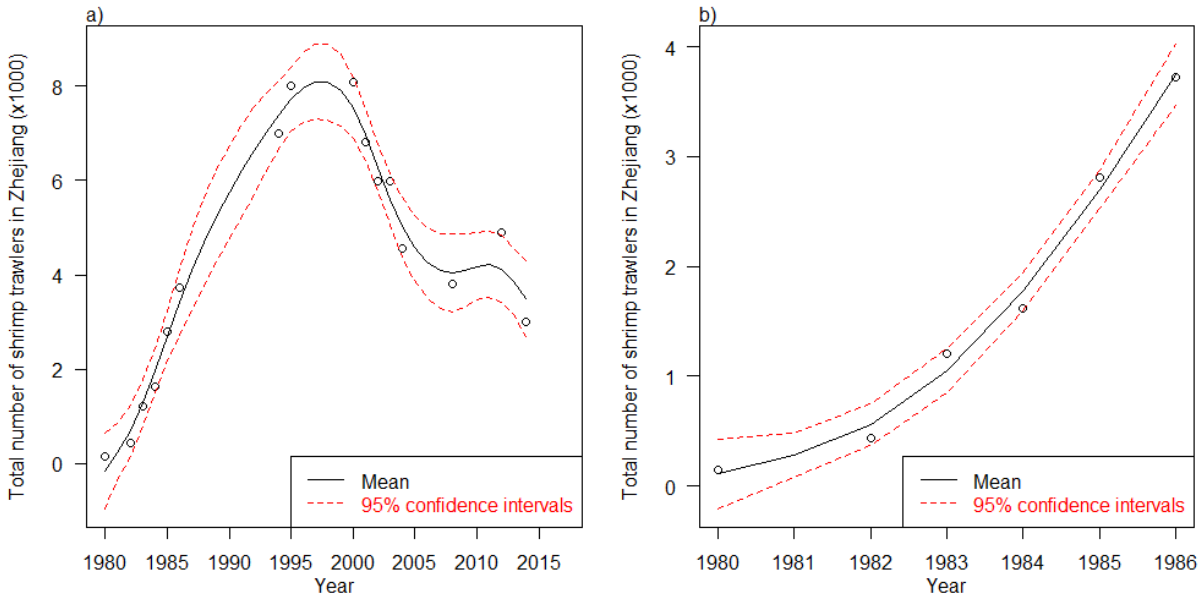

Figure 4. Total number of shrimp trawlers in Zhejiang based on two generalize additive models: a) using full dataset, and b) using subset data.

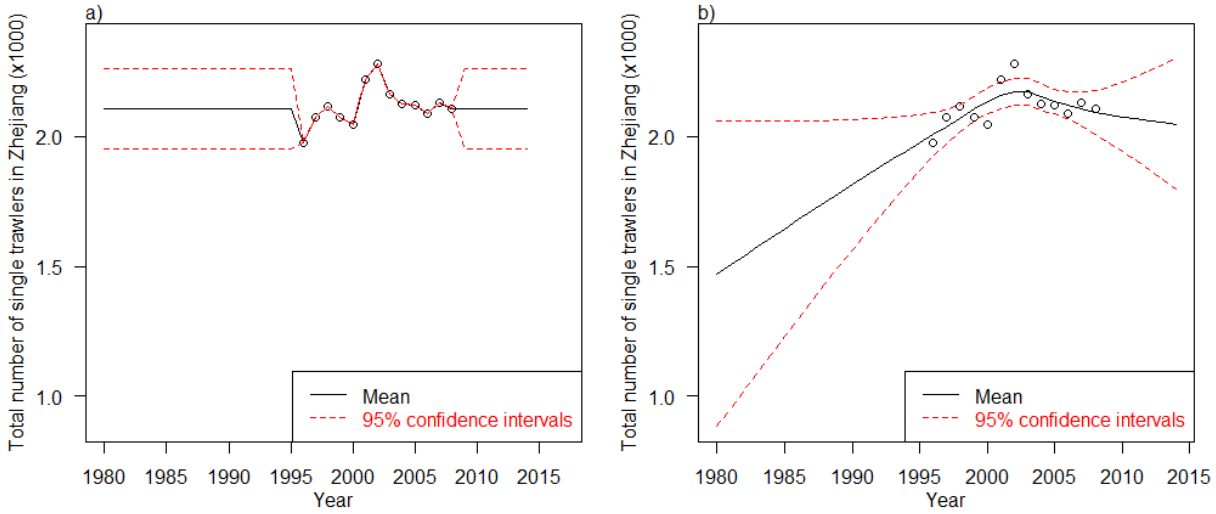

Figure 5. Estimation for the total number of single trawlers in Zhejiang based on two models: a) Autoregressive Integrated Moving Average (ARIMA (0,0,1) with non-zero mean), and b) local polynomial regression model (loess, span = 0.75, degree = 1).

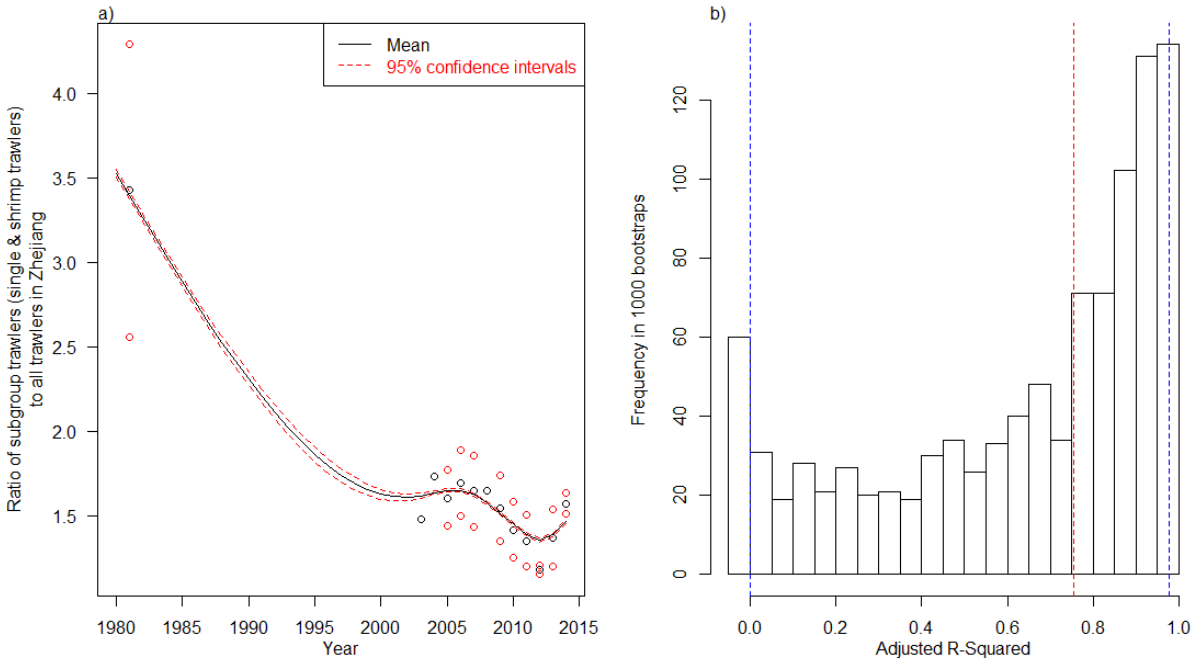

Figure 6. Estimation of the ratio of subgroup trawlers (shrimp trawlers & single trawlers) to all trawlers in Zhejiang based on a generalized additive model (using year as the predictor): a) the model fit plot (mean and 95% CI) depicted with the uncertainty of the ratio (mean as black circles, 95% CI as red circles), b) frequency distribution of the adjusted R-squared values derived from the bootstrap process (N = 1000), which drew randomly an equal sample size of points with replacement from the original ratio sample.

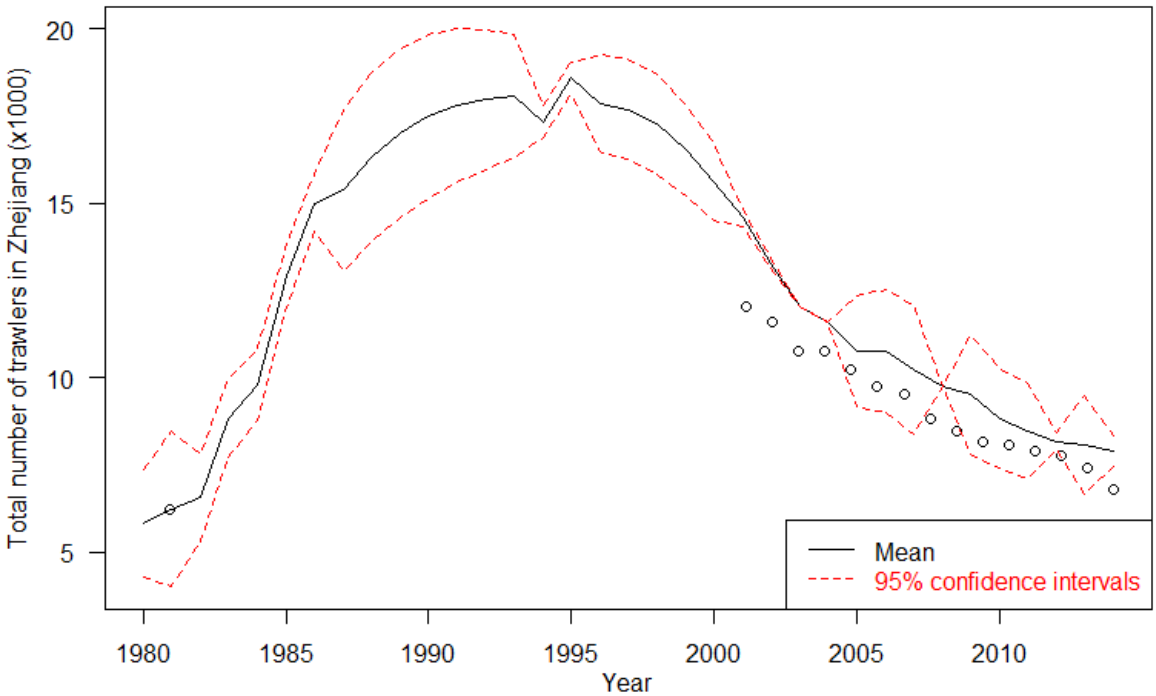

Figure 7. Estimation of the total number of trawlers in Zhejiang based on the estimations of subgroup trawlers (shrimp trawlers & single trawlers). Black circles depict the original data points.

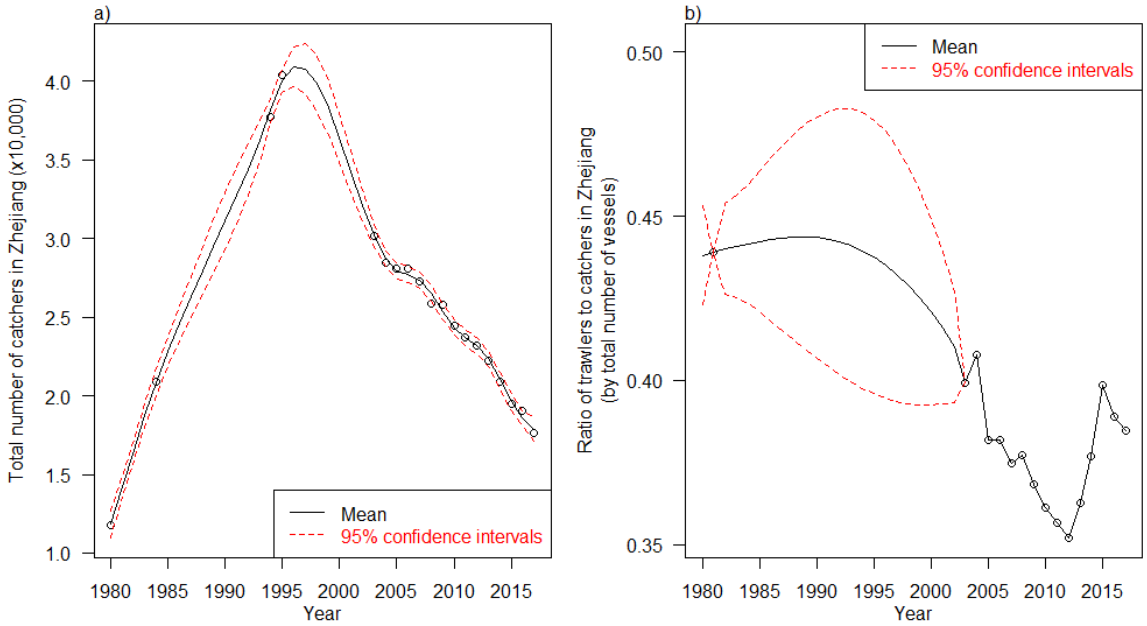

Figure 8. Estimation of a) the total number of catchers in Zhejiang based on a generalized additive model (GAM), and b) the ratio of trawlers to catchers (by total number of vessels) in Zhejiang based on a GAM. Black circles depict the original data points.

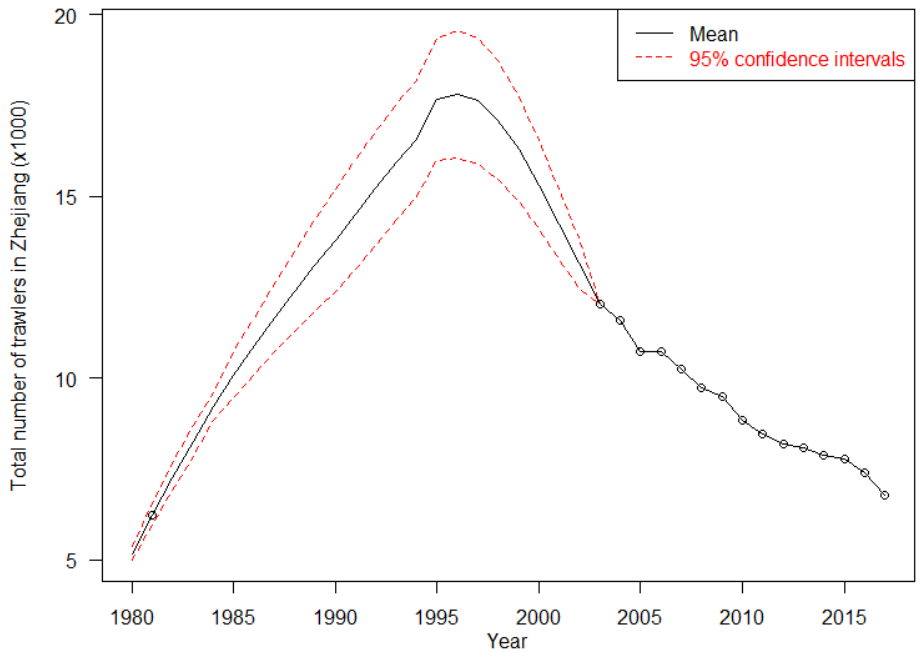

Figure 9. Estimation of total number of trawlers in Zhejiang based on the ratio between trawlers and catchers and the total number of trawlers in Zhejiang. Black circles connected with lines depict the original data points.

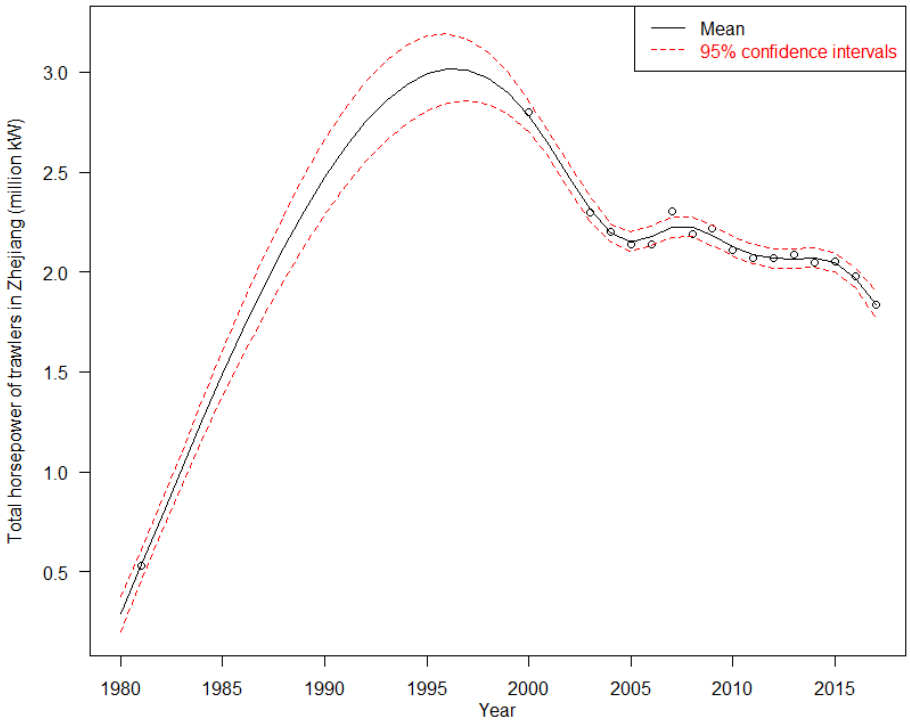

Figure 10. Estimation of total horsepower of trawlers in Zhejiang based on a generalized additive model.

Fujian province

For Fujian province, we used two regression models respectively to estimate the total number and horsepower of trawlers. First, we had available data for total number of trawlers in most years (1981, 1985, 1990 – 2002) during the examined period (1980 – 2002) and from 2003 to 2017 [51,64,69]. We built a GAM (year as the explanatory variable) to fill the gaps based on this dataset (N = 30, adjusted R^2 = 0.926; Fig. 11a). Second, we derived the total horsepower of trawlers for three years (1981, 1999, and 2001) based on available information. The first was based on the horsepower group statistics as mentioned above from a compilation of fisheries capacity statistics in the East China Sea region [64]

The second and third were based on the mean horsepower of bottom trawlers and the total number of trawlers in Fujian [75]. We learned that the ratio of bottom trawlers to all trawlers in the two years were 0.994 and 0.998 [70,75], therefore the mean horsepower of bottom trawlers and the counterpart of all trawlers in Fujian should be approximately the same. Based on these three estimates and the data from 2003 to 2017 (N = 18) [51], we construct a GAM to fill the gaps (adjusted R^2 = 0.983; Fig. 11b).

We made some corrections to the above estimation in Fujian with reference to the reported capacity data of production vessels (both fishing vessels and aquaculture vessels) in Fujian. First, we found that the extrapolated number and horsepower of trawlers in 1980 had negative lower bounds of the 95% CI (Fig. 12), and the mean values (total number = 387, total horsepower = 38,830 kW) higher than the reported values (total number = 79, total horsepower = 36,414 kW) of production vessels [51]. We therefore corrected the 1980's estimates in Fujian. We first calculated the ratio between trawlers and production vessels in Fujian in terms of total number in 1981 and assumed that this ratio was the same as in 1980. This allowed us to estimate the total number (N = 4) of trawlers in 1980 in Fujian based on the ratio (0.049) and the reported number of the production vessels in 1980. We assumed that the mean horsepower of trawlers did not change from 1980 to 1981. Therefore, the total horsepower (594.4 kW) of trawlers in 1980 in Fujian was estimated based on the total number of trawlers in 1980 and mean horsepower (148.6 kW) of trawlers in 1981. Second, the estimated total number and horsepower of trawlers in 1983 (total number = 928, total horsepower = 137,489 kW) were higher than the reported counterparts of production vessels in the same year (total number = 184, total horsepower = 60,896 kW) [51]. We first corrected the number (N = 8) of trawlers in 1983 based on the mean ratio (0.046) between trawlers and productions in 1981 and 1985 (the closest years with available data). We then corrected the total horsepower (1186.4 kW) of trawlers in 1983 based on the estimated total number of trawlers in 1983 and the mean horsepower (148.2 kW) of trawlers in 1983, which was derived from the original model estimation.

Guangdong

Likewise, we first used GAMs to directly estimate the total number and horsepower of trawlers in Guangdong province. For Guangdong, there were missing values for the number and horsepower of trawlers in five years (1980 - 1982, 1984, and 1985) during this period (1980 – 2002) [51]. We built a GAM (predictor: year) for the total number (N = 34, adjusted R^2 = 0.974; Fig. 12a) and total horsepower (N = 34, adjusted R^2 = 0.974; Fig. 12b), respectively. The resulted estimates were all positive except the lower bounds of the total number of trawlers in 1980 and 1981. We then used the estimates to fill the gaps in total number (in 1982, 1984, and 1985) and total horsepower (1980 - 1982, 1984, and 1985) of trawlers. To correct the estimate on total number in these two years, we then used another GAM based on the ratio between trawlers and catchers in Guangdong in terms of total number of vessels. This alternative GAM resulted in a model slightly less powerful than the previous one but still explained a very high amount of deviance (95%; Fig. 13a). More importantly, based on this ratio-based model, the derived estimate of total number (mean and 95% CI) of trawlers were all positive (the lowest value of the lower bound of the 95% CI = 48; Fig. 13b), in contrast to the previous GAM. We then used the derived estimates in 1980 and 1981 to replace the previous corresponding estimates of total number of trawlers in Guangdong.

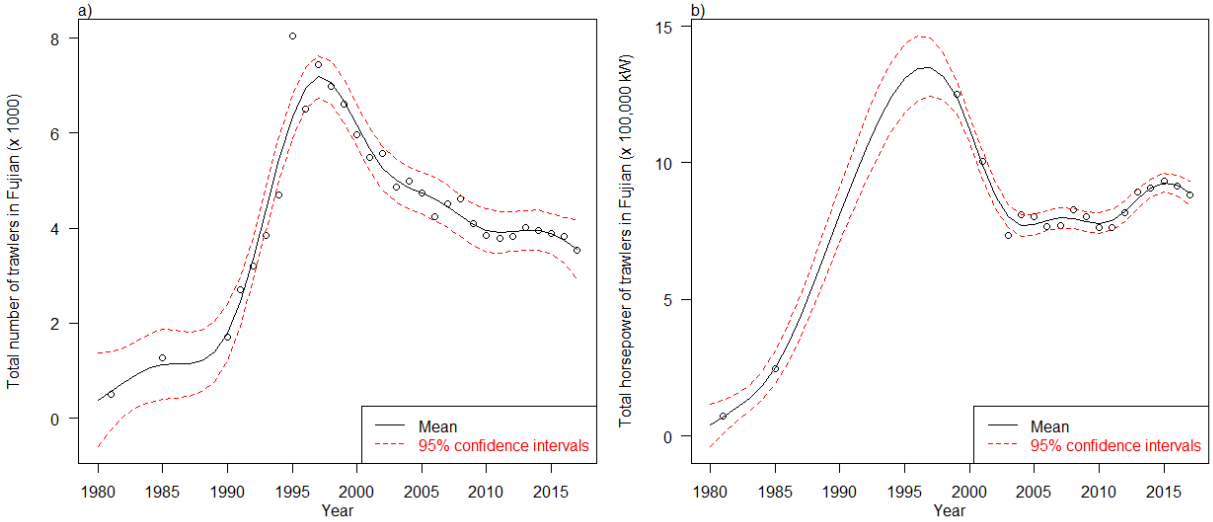

Figure 11. Estimated total number and total horsepower of trawlers in Fujian.

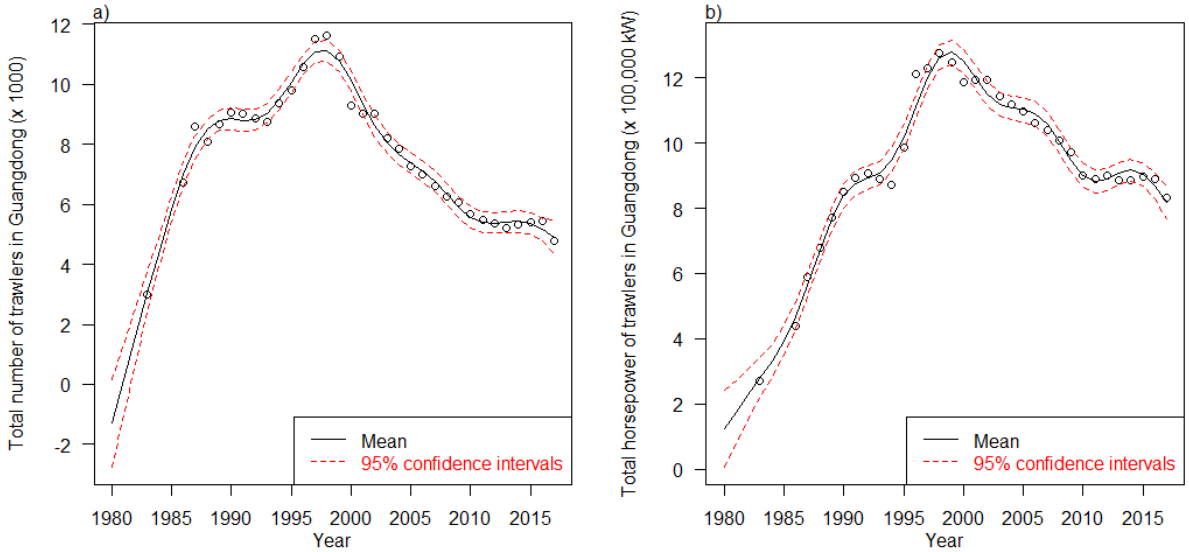

Figure 12. Estimation for a) total number and b) total horsepower of trawlers in Guangdong province based on generalized additive models (GAMs).

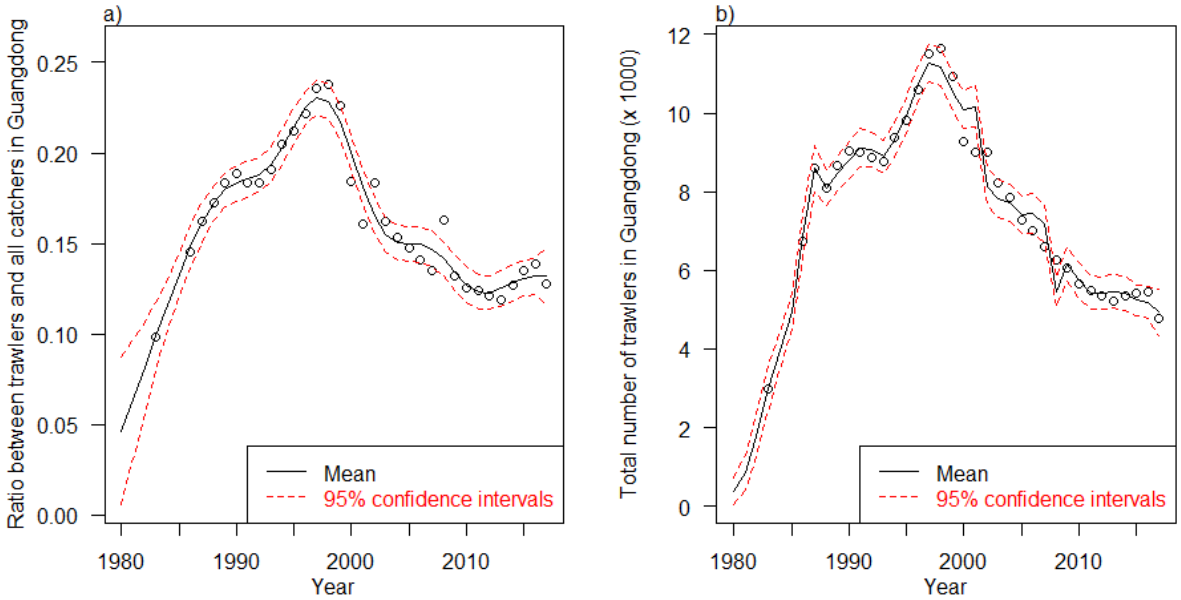

Figure 13. Estimation of a) the ratio between trawlers and all catchers (in terms of total number of vessels) in Guangdong province based on a generalized additive model (GAM), and b) the total number of trawlers in Guangdong province based on the estimated ratio and total number of catchers in Guangdong province.

Scaling up to the nation (i.e., China)

We estimated the total number and total horsepower of trawlers in China based on the estimates from Zhejiang, Fujian, and Guangdong provinces derived from above analyses, and ratios between China's trawlers and the trawlers from the three provinces from 2003 to 2017. We first extrapolated the ratios to the period between 1980 and 2002. For the total number of trawlers, we identified an ARIMA (0,0,0) with a non-zero mean, which extrapolated the ratio between 1980 and 2002 (mean ± SE: 2.083 ± 0.111). For the total horsepower, we identified an ARIMA (0,1,0) with drift (mean ± SE: -0.0136 ± 0.0073) to extrapolate the ratio backward. We then used these ratios and the available data of the trawlers from the three provinces to derive estimates of trawlers in China from 1980 to 2002 (Fig. 14). Given there was a suspicious rapid rise on the estimated total horsepower of trawlers from 2002 to 2003, we also used LOESS (adjusted R^2 = 0.918) to estimate the ratio and re-estimated the total horsepower of trawlers (Fig. 14b).

We compared the resulted trajectories of the total number of trawlers and their horsepower with other independent statistics as a manner of validation (Fig. 15). These statistics included the reported capacity data (total number and horsepower) of (i) China's marine production vessels (fishing vessels and aquaculture vessels that were OPERATED in each year, excluding those idle vessels from the tally) from 1980 – 2002 [51], (ii) trawlers owned by coastal provinces (Shanghai, Zhejiang, and Fujian) in the East China Sea in 1981 [64], and (iii) trawlers owned by coastal provinces (Guangdong, Guangxi, and Hainan) in the South China Sea in 2001 [61]. We found that the total number China's trawlers (estimated based on the ARIMA) did not surpass the counterpart of China's marine production vessels (Fig. 15a); the former was higher than the total number of trawlers of provinces in the East China Sea in 1981 and the counterpart in the South China Sea in 2001 (Fig A14a). The total horsepower of China's trawlers, estimated from both ARIMA and LOESS, did not surpass the counterpart of production vessels (Fig. 15b). The former was higher than the total horsepower of trawlers of provinces in the South China Sea in 2001. The horsepower of trawlers in the East China Sea in 1981 (805,759 kW) was lower than the total horsepower of China's trawlers derived from the LOESS (mean = 837,851 kW), but higher than the estimated based on ARIMA (mean = 745,052 kW). Given this, we used the LOESS-based estimate on total horsepower for China's trawlers. Additionally, both number and horsepower of trawlers started to decline in ~ 1997 (Fig. 15), which might be caused by the Double Control policy (control total number and horsepower of fishing

vessels) enacted in that year. In general, we considered our estimates on the number (based on the ARIMA) and horsepower (based on LOESS) of China's trawlers were acceptable.

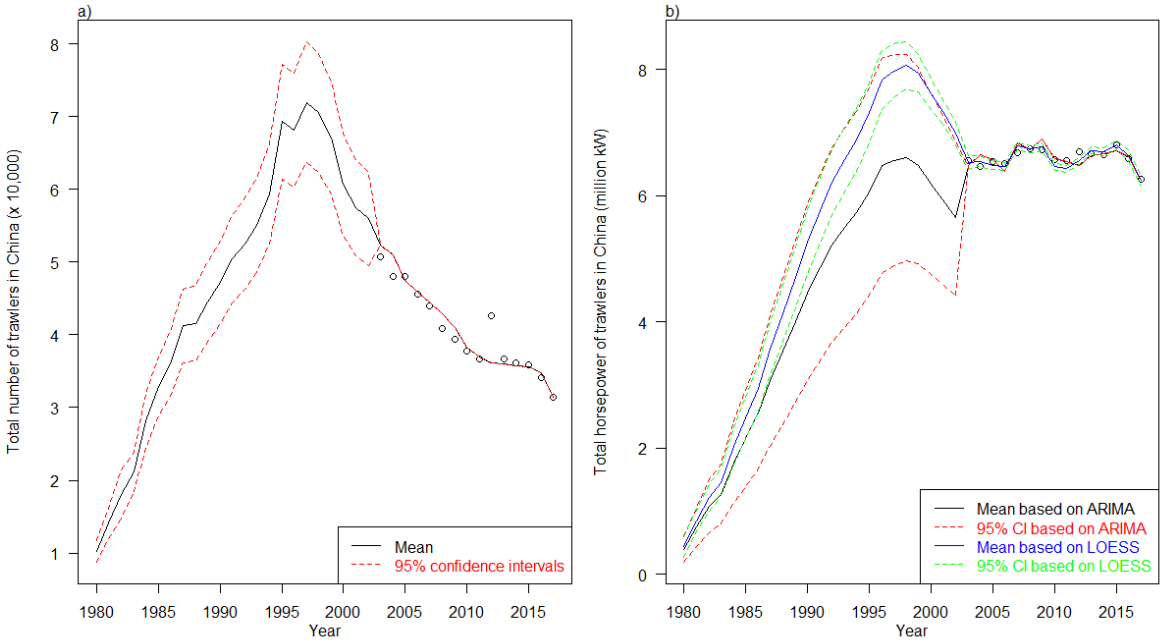

Figure 14. Estimation of a) total number and b) total horsepower of China's trawlers from 1950 – 2017. The black circles connected with lines denote exiting data points from 2003 – 2017. ARIMA, auto regressive integrated moving average; LOESS, locally estimated scatterplot smoothing.

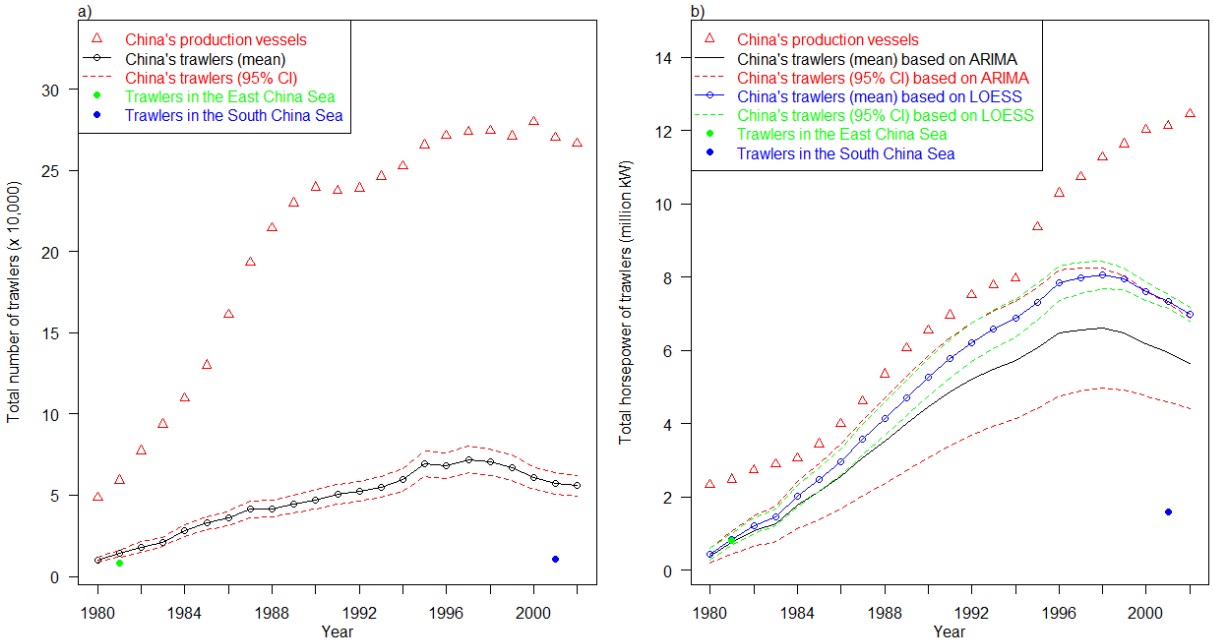

Figure 15. Estimated a) total number and b) total horsepower of China's trawlers, in contrast to the reported data of China's production vessels (fishing vessels and aquaculture vessels that were operated in each year) from 1980 – 2002, trawlers owned by provinces in the East China Sea in 1981, and trawlers owned by provinces in the South China Sea in 2001. ARIMA, auto regressive integrated moving average; LOESS, locally estimated scatterplot smoothing.

3rd Period (1979): transition between planned economy to market economy

We estimated the number of trawlers in 1979 based on the mean values the data from 1978 and 1980 estimated above from the first and second periods. The uncertainty of the estimates in 1980 was carried backward to 1979 as the values in 1978 were based on reported data and had no uncertainty estimates. This ended up with a rapid increase in the total number (from 1489 to 5845 ± 763; Fig. 16) and a relatively smoother increase in the total horsepower (from 300,303 to 367,895 ± 85,056 kW; Fig. 17) from 1978 to 1979. On average, the mean horsepower per trawler declined from 202 kW in 1978 to 63 kW in 1979. This was likely possible given that fishing vessels started to be privatized in 1979 driven by economic reforms, and many small motorized trawlers (with lower mean horsepower) were built and entered the fisheries [76].

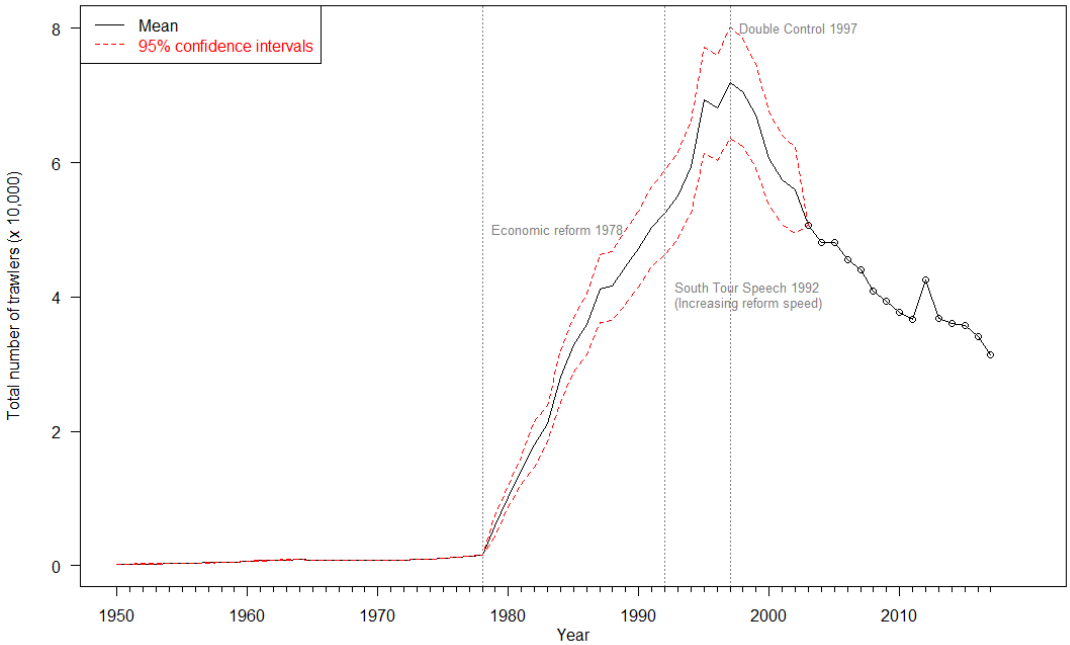

Figure 16. Trajectory of total number of trawlers in China from 1950 – 2017, depicted with the estimated mean, 95% confidence intervals, reported data (2003 – 2017, black circles connected with lines), along with some relevant policies.

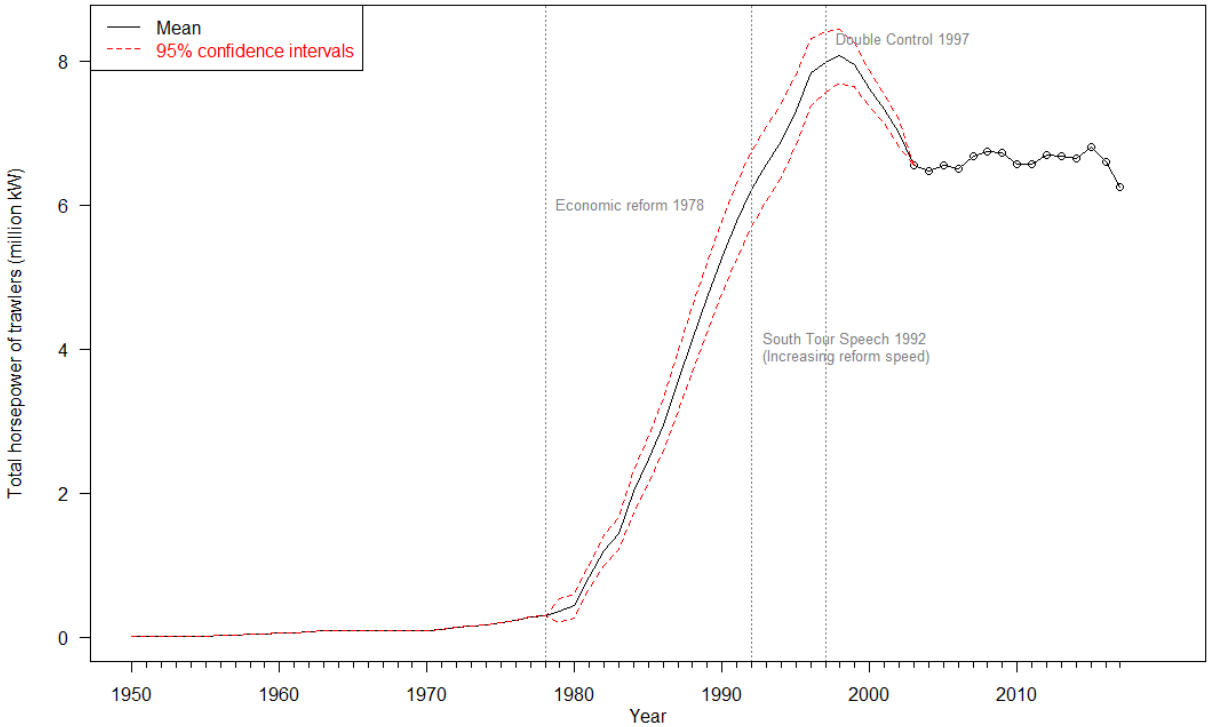

Figure 17. Trajectory of total horsepower of trawlers in China from 1950 to 2017, depicted with the estimated mean, 95% confidence intervals, reported data from 2003 to 2017 (black circles connected with lines), along with some relevant policies (text in black, green, and red).

3.3 Reconstructing fishing capacity for China's motorized marine catchers

We used the statistics of fishery production vessels (FPVs, 1980 – 2017) and marine fishery vessels (MFVs, 1951 – 2017) to estimate capacity data for marine catchers between 1950 and 2002 [51]. Our attempt was to estimate the ratios between catchers and MFVs, which had the most wholistic dataset that can be relied on. However, we only had available data to calculate the ratios from 2003 to 2017. We could just use these ratios to construct ARIMA or LOESS models and extrapolate the ratios before 2003. However, these models derived unrealistic ratios (mean ratios higher than 1 and negative bounds of 95% CI) in many years. To solve this problem, we did a stepwise estimation by first estimating the ratios between FPVs and MFVs, and then estimating ratios between catchers and FPVs from 1950 and 2002.

First, we extrapolated the capacity data of MFVs to 1950 based on the 1) estimated capacity data (mean ± SE) of BTs in 1950 and 2) constant ratios (1.089 by number, and 1.516 by horsepower) of MFVs to BTs in the following three years (1951, 1952, and 1953) – assuming these ratios were the same as in 1950. We did not use ARIMA or LOESS to fill the gap in MFVs given these models derived negative lower bounds of 95% CI in an initial trial.

Second, we estimated the ratios (in terms of number and horsepower respectively) between FPVs and MFVs between 1950 and 2002 with ARIMA and LOESS models based on the available data from 1980 to 2017. The ARIMA (0,1,0) derived ratios with unrealistic higher bounds of 95% CI (higher than 1; Figs 18a & 19a); the LOESS derived reasonable ratios without significantly surpassing 1 (maximum value = 1.03) for all years and the models fitted the data well (adjusted R^2 = 0.910 and 0.950 for number and horsepower respectively; N = 30; Figs 18b & 19b). We then applied the LOESS-based estimates for the ratios between FPVs and MFVs.

Third, we reconstructed the ratios between catchers and FPVs between 1950 and 2002. We used GAMs to fill the gaps based on available data from 2003 to 2017 and two other reference points. The first one was in 1950, when we assumed that all FPVs were catchers given China's mariculture vessels were probably not developed yet in this early year [77]. The second point was in 1981, when we could estimate the ratios based on the reported data of FPVs and the ratios between catchers and trawlers. We assumed that the ratios between catchers and trawlers in China in 1981 (in terms of number and horsepower, respectively) was the same as in the East China Sea in the same year. The latter was available from the compilation of statistics in the East China Sea (3.58 and 1.83, respectively in terms of number and horsepower) [64]. The resulted GAMs had good fit to the data (adjusted R^2 = 0.996 and 0.992 for number and horsepower respectively; N = 16; Fig. 20).

We considered our estimates on the capacity data of China's marine catchers were acceptable in contrast to the estimates and reported data of relevant fishery vessels. These datasets included 1) the reported number and horsepower of all marine fishery vessels in China from 1951 to 2017 [51], 2) the reported number and horsepower of catchers from Guangdong from 1980 to 2002 [61], 3) the reported number and horsepower of catchers from Hainan in 1988 and from 1990 to 2002 [61], 4) the reported number of catchers from Zhejiang in 1980, 1984, 1994 and 1995 [64]. We found that the total number and horsepower of China's marine catchers were higher than the counterparts of catchers from Guangdong, Hainan, and Zhejiang, and higher than the counterparts of trawlers (Figs 21 & 22). However, we did find that the number and horsepower of catchers did not match well with the counterparts of bottom trawlers in 1950 to 1953. The mean number of catchers was equal to that of bottom trawlers in 1950, 1951, and 1952, but their standard errors varied in these years. We corrected these by adjusting the standard errors of the number of catchers to the same of bottom trawlers, assuming all catchers were bottom trawlers in these years, which was likely true as suggested by some studies [53,54]. Accordingly, the horsepower of catchers was adjusted to be equal to that of bottom trawlers in these years. In 1953, the total number of catchers was 267±5, while the total number of bottom trawlers was 265±1. This made the number of other catchers to be negative in lower bound of 95% CI. Therefore, we corrected the SE of the former to 1 (same as the latter, making the number of other catchers to be a reasonable value 2±1. The horsepower of other

catchers in 1953 based on the estimates of catchers and bottom trawlers was 7376±581 kW. This was unrealistic given the mean horsepower per vessel would be very high (3688±581 kW), which was not possible in this early year. Therefore, we assumed that the two other catchers had the same mean horsepower as the bottom trawlers and recalculated the horsepower of catchers. This assumption was likely true given other catchers were converted from trawlers in the early years since 1953 [53].

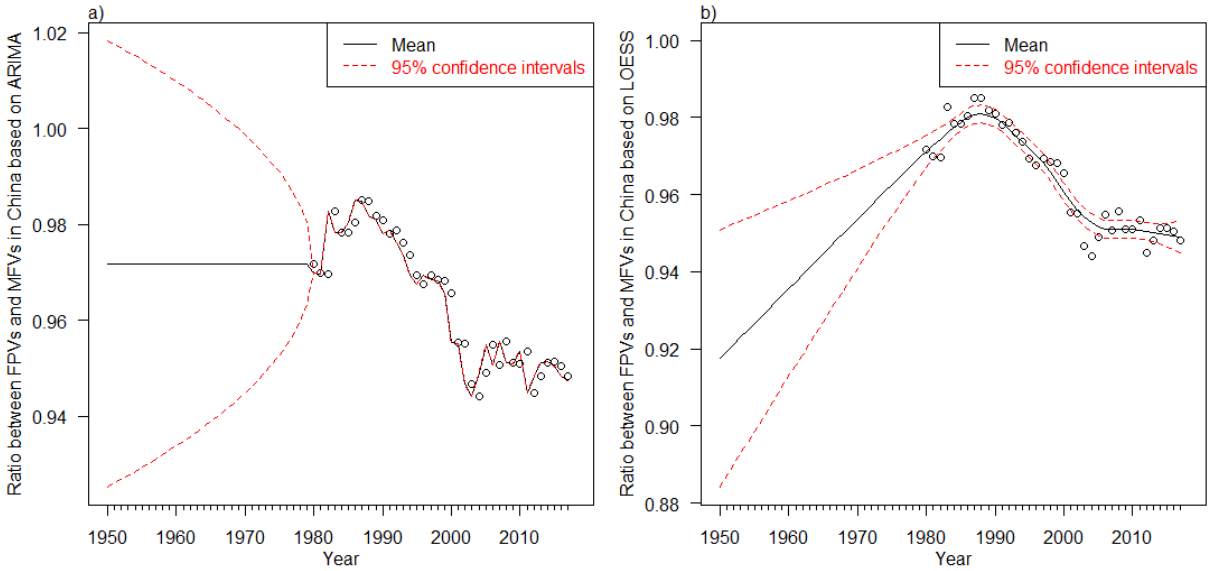

Figure 18. Estimated ratios between fishery production vessels (FPVs) and marine fishery vessels (MFVs) in terms of total number of vessels based on two types of models: a) auto regressive integrated moving average (ARIMA), and b) locally estimated scatterplot smoothing (LOESS).

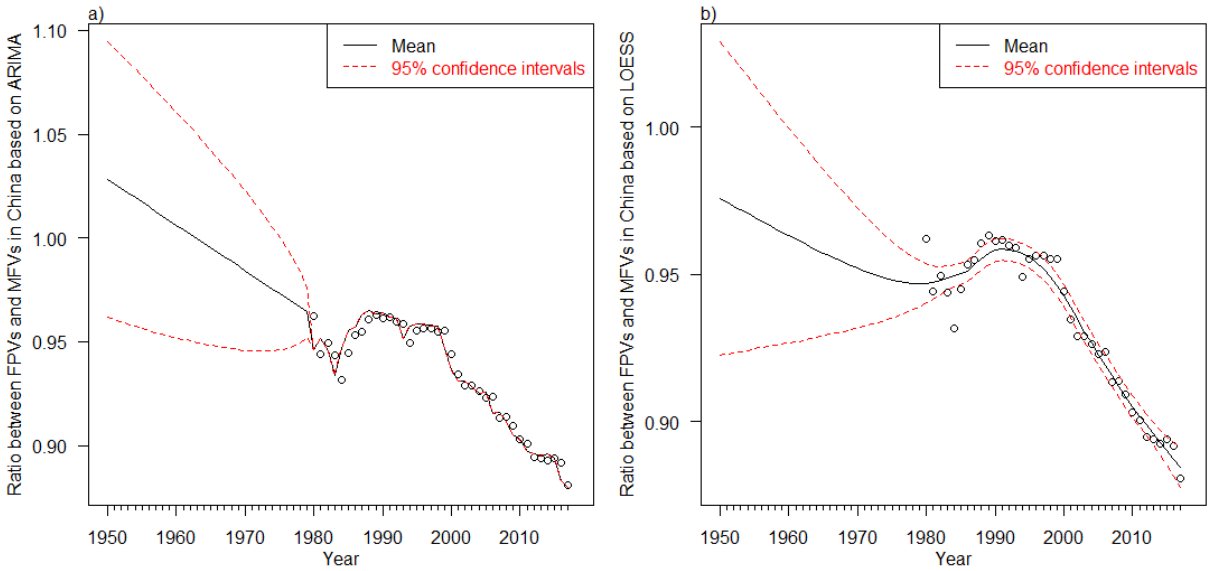

Figure 19. Estimated ratios between fishery production vessels (FPVs) and marine fishery vessels (MFVs) in terms of total horsepower of vessels based on two types of models: a) auto regressive integrated moving average (ARIMA), and b) locally estimated scatterplot smoothing (LOESS).

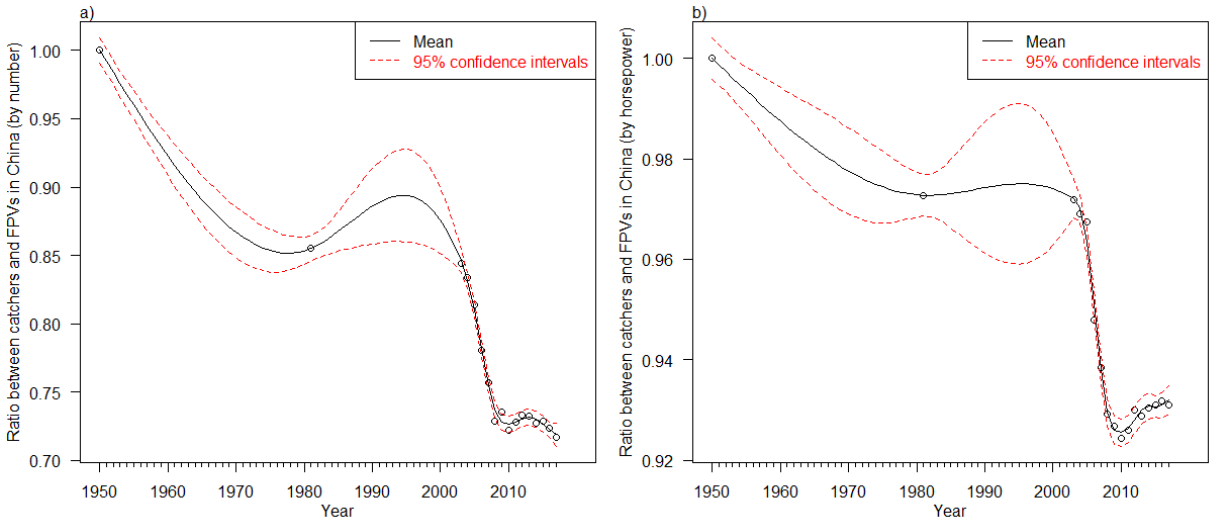

Figure 20. Estimated ratios between catchers and fishery production vessels (FPVs) in China in terms of a) total number of vessels, and b) total horsepower, based on generalized additive models.

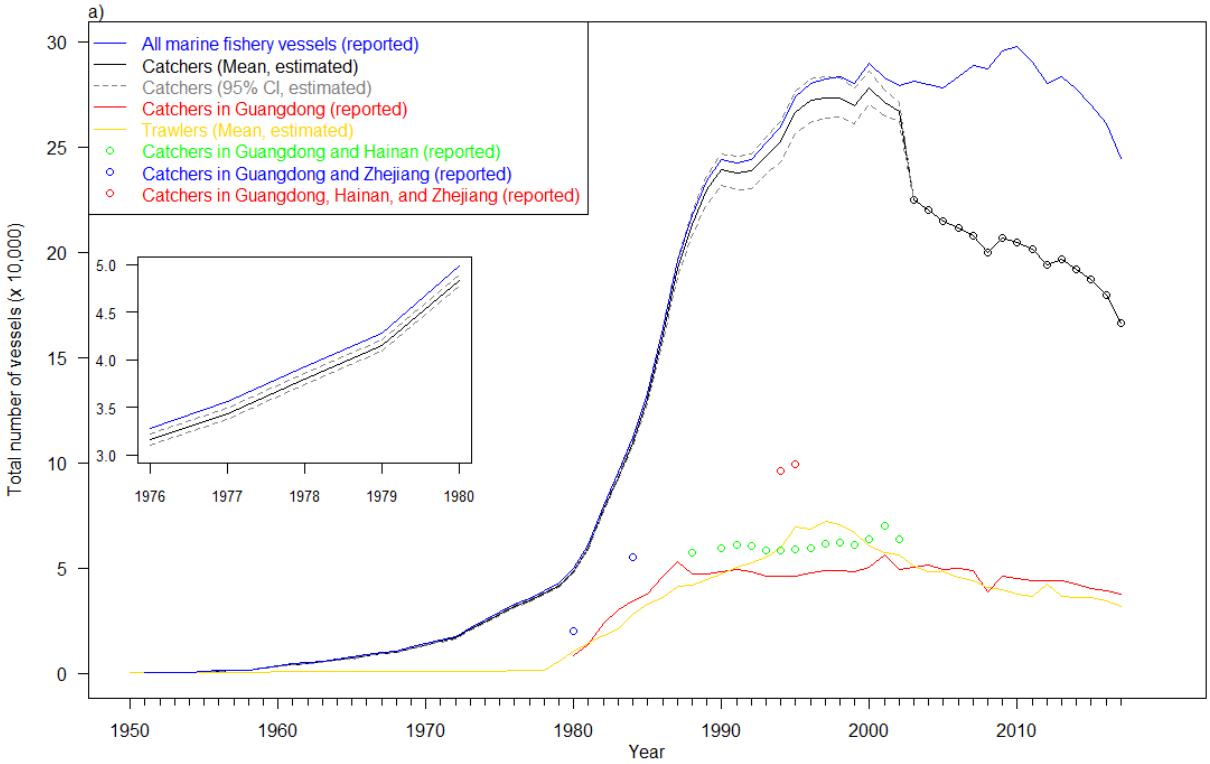

Figure 21. Trajectory of total number of China's marine catchers from 1950 to 2017, including the estimated data from 1950 to 2002, in contrast to the data of marine fishery vessels, trawlers, and catchers from Guangdong, Hainan, and Zhejiang provinces. The inserted smaller graph shows a part the trajectories (1976 – 1980) in a finer resolution.

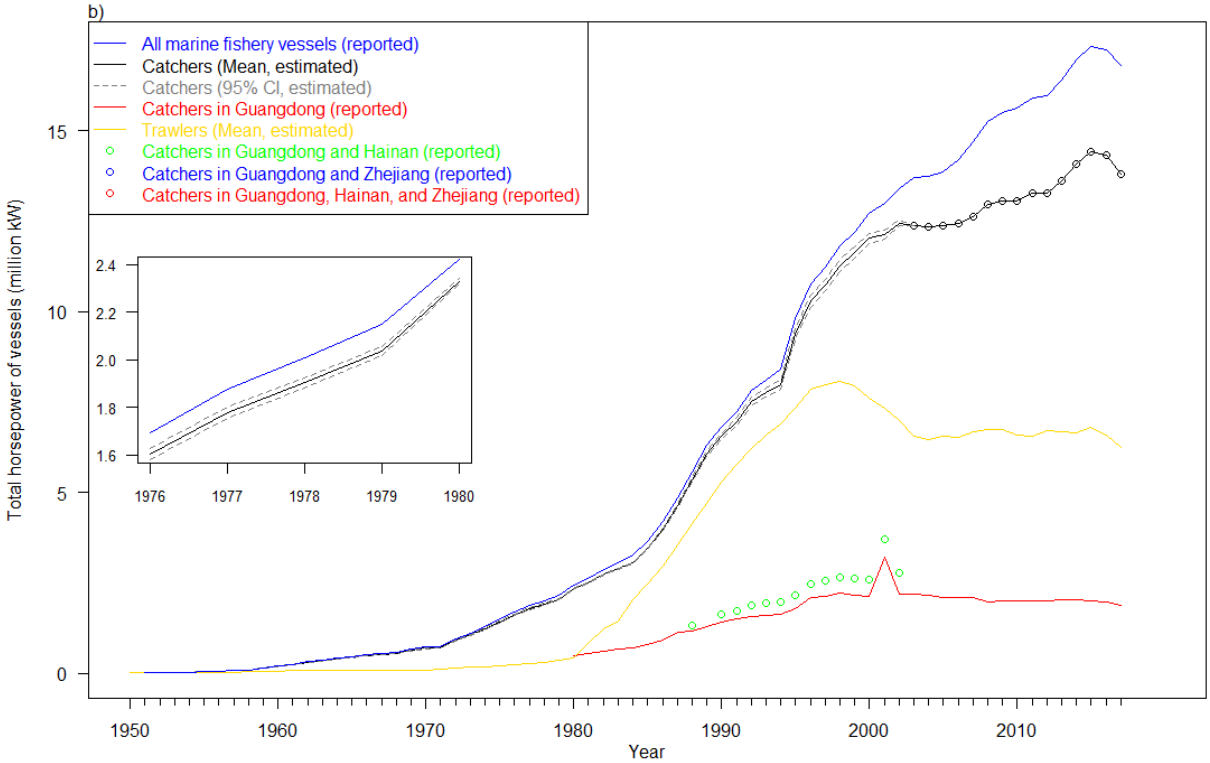

Figure 22. Trajectory of total horsepower of China's marine catchers from 1950 to 2017, including the estimated data from 1950 to 2002, in contrast to the data of marine fishery vessels, trawlers, and catchers from Guangdong, Hainan, and Zhejiang provinces. The inserted smaller graph shows a part of the trajectories (1976 – 1980) in a finer resolution.

3.4 Reconstructing fishing capacity for China's distant-water catchers and bottom trawlers

We reconstructed capacity statistics (total number and horsepower) of China's distant-water catchers (DWCs) and distant-water bottom trawlers (DWBTs) based on the following datasets. The first one was China Fisheries Statistical Yearbooks (CFSYs) [51], which included yearly records of the 1) total number and horsepower of China's distant-water vessels (DWVs) from 1986 – 2017, and 2) total number and horsepower of China's DWCs from 1986 – 2002. We also searched relevant statistics from China Knowledge Resource Integrated Database (a.k.a., CNKI, http://cnki.net/, 1950 – 2019) using the keywords "远洋" (meaning "distant-water") and "渔业" (meaning "fisheries"). This helped us finally collect useful records on the following statistics. First, we gathered the number and horsepower of China's DWF vessels (including DWF catchers plus other fishery assistant vessels) and DWF catchers in 1985, during which only 12 catchers (all are BTs) and one fishery transportation vessel were deployed in West Africa [78]. Second, we collected records of the number of DWF BTs in eight years (1985, 1987, 1988, 1990, 1992, 1997, 2007, and 2017) and total horsepower of DWF BTs in two years (1985, 1992) from published literature [78–83].

We first estimated the capacity statistics of China's DWCs from 2003 to 2017 based on the counterparts of DWVs and the ratios between the two. The ratio between DWCs and DWVs in terms of number of vessels were available from 1985 to 2002 based on the collected data. We first used ARIMA to forecast the ratios from 2003 to 2017 in terms of total number and horsepower respectively. For the ratio in terms of total number of vessels, we identified the best ARIMA was an ARIMA (1, 0, 0) with non-zero mean (mean ± SE: 0.9321±0.0094) that poorly fitted the data (N = 18; Fig. 23a). For the ratio in terms of total horsepower, the best ARIMA was an ARIMA (0, 0, 0) with non-zero mean (mean ± SE: 0.8561±0.0184) which also

poorly fitted the data (N = 18; Fig. 23b). The forecasted ratio in terms of horsepower ranged between 0.699 and 1.014 (Fig. 23b), which was not acceptable given the ratio should be less than 1. Given this, we tried to use LOESS instead. But these LOESS models also did not have good fits (R^2 = 0.409 and 0.115) and showed suspicious decline trends on the ratios from 2003 to 2017 (Fig. 24); the estimated ratios in terms of horsepower were higher than 1 at the higher bound of 95% CI from 2015 to 2017 (Fig. 24b). In the end, we calculated the mean and SE (0.933±0.006 for number, and 0.885±0.019 for horsepower) from the original ratio data and assumed the mean and SE were consistent from 2003 to 2017. Based on the ratio statistics, we determined the total number and horsepower of DWCs from 2003 to 2017 (Fig. 25).

We estimated the number and horsepower of DWBTs from 1985 to 2017 based on the estimates on DWCs and ratios between the two. We first used a GAM (smooth for year: k = 1.785) to fit the number of DWBTs (N = 8), which derived a good fit (adjusted R^2 = 0.987, Fig. 26a). However, there were obvious estimation errors in 1986 (mean ± SE: 19±33) and 1989 (mean ± SE: 123±25), when the total number of DWBTs were negative or higher than the number of DWCs (23 in 1986 and 114 in 1989; Fig. 26a). To correct these errors, we recalculated the values of these two years, respectively, based on the number of DWCs in the same year and the mean ratio (0.931 for 1986, and 0.749 for 1989) between DWBTs and DWCs of the neighboring two years (1985 and 987, and 1988 and 1990). The derived number of DWBTs in these two years were 21 and 85. Given the simplicity of this calculation, estimation uncertainty of these two years was then not able to be determined. For the horsepower of DWBTs, we only had three reference points in 1985, 1988, and 1992, making it difficult to directly build regression models. To fill the gap, we used the ratio between trawlers and all catchers (in terms of the horsepower) of a major Chinese DWF company, the China National Fisheries Co. Ltd. (2003) and its successor the China National Agricultural Development Group Co. Ltd. (2004 to 2017) [51]. We assumed that the ratio between Chinese DWBTs and DWCs (by horsepower) was equal to the counterpart of this company for a given year. We then create a dataset (N = 18) of ratio between DWBTs and DWCs (by horsepower) in 1985, 1988, 1992, and 2003 to 2017. We used a GAM (adjusted R^2 = 0.933, N = 18; Fig. 27) to interpolate the value in missing years and then calculated the total horsepower based on the ratio and the horsepower of DWCs in each year (Fig. 26b).

We validated the above estimates based on independent data from the literature. First, a study counted the total number of Chinese distant-water trawlers and other catchers from 2000 to 2011 around the world and suggested that the mean ratio of observed trawlers to observed catchers in Chinese DWF fleets was 0.606 [33]. Based on our estimation above, the mean ratio of trawlers to catchers in terms of number of vessels in the same period varied from 0.340 to 0.746, which was in line with this study. Second, we learned that the horsepower of a distant-water bottom trawler ranged from 441 – 3676 kW depending on the mode of the vessel (from 1985 to 1993; She and Guo 1993). The mean horsepower of DWBTs based on our estimates between 1985 and 1993 varied between 425±57 and 1025±118 kW, which was acceptable compared with the above record. In general, we considered our estimates on the number and horsepower of Chinese DWBTs were useful, although cautions should be paid as there were not much data available to validate these estimates.

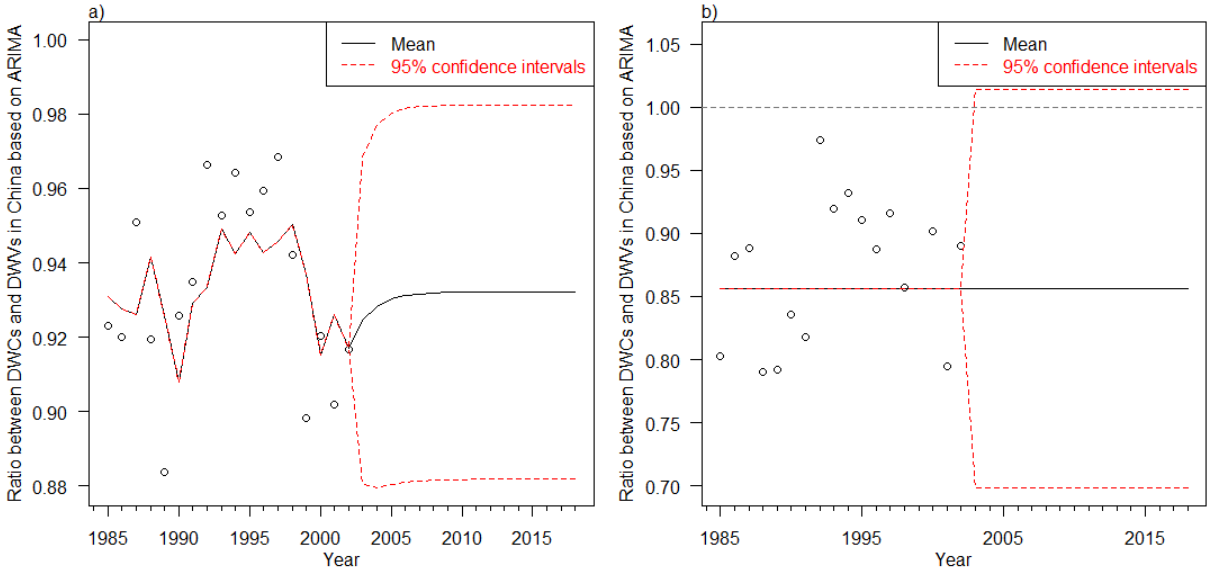

Figure 23. Estimated ratios between distant-water catchers (DWCs) and distant-water vessels (DWVs) in China based on auto regressive integrated moving average (ARIMA), respectively, in terms of (a) total number of vessels, and (b) total horsepower of vessels.

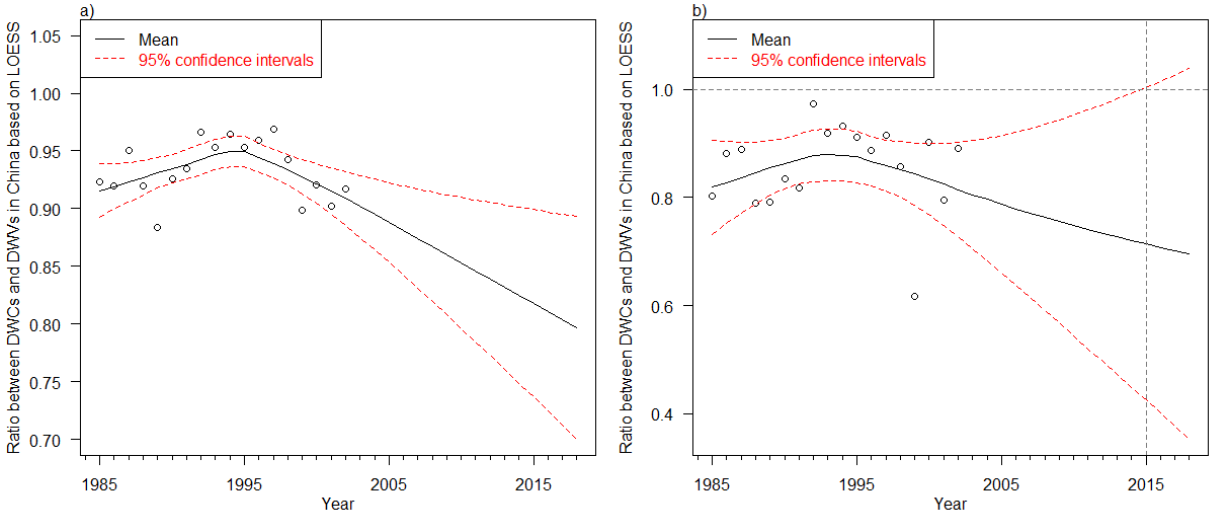

Figure 24. Estimated ratios between distant-water catchers (DWCs) and distant-water vessels (DWVs) in China based on locally estimated scatterplot smoothing (LOESS), respectively, in terms of (a) total number of vessels, and (b) total horsepower of vessels.

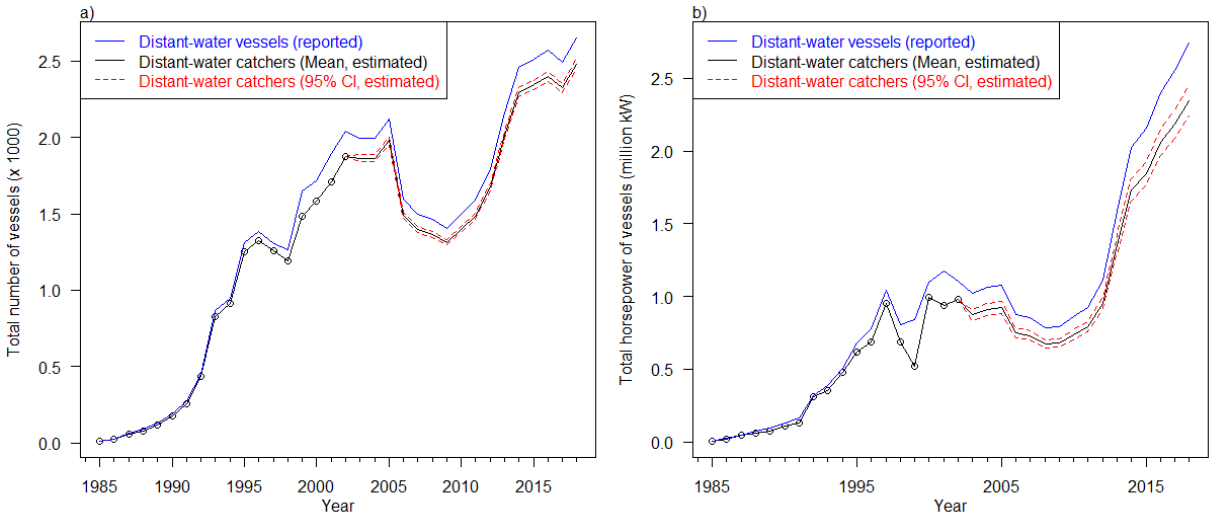

Figure 25. Estimated capacity statistics of distant-water catchers (DWCs, mean and 95% CI): (a) total number of vessels, and (b) total horsepower of vessels. The reported data of distant-water vessels were shown as references to validate these estimations. Circles connected with line were existing timeseries data for DWCs from 1985 to 2002.

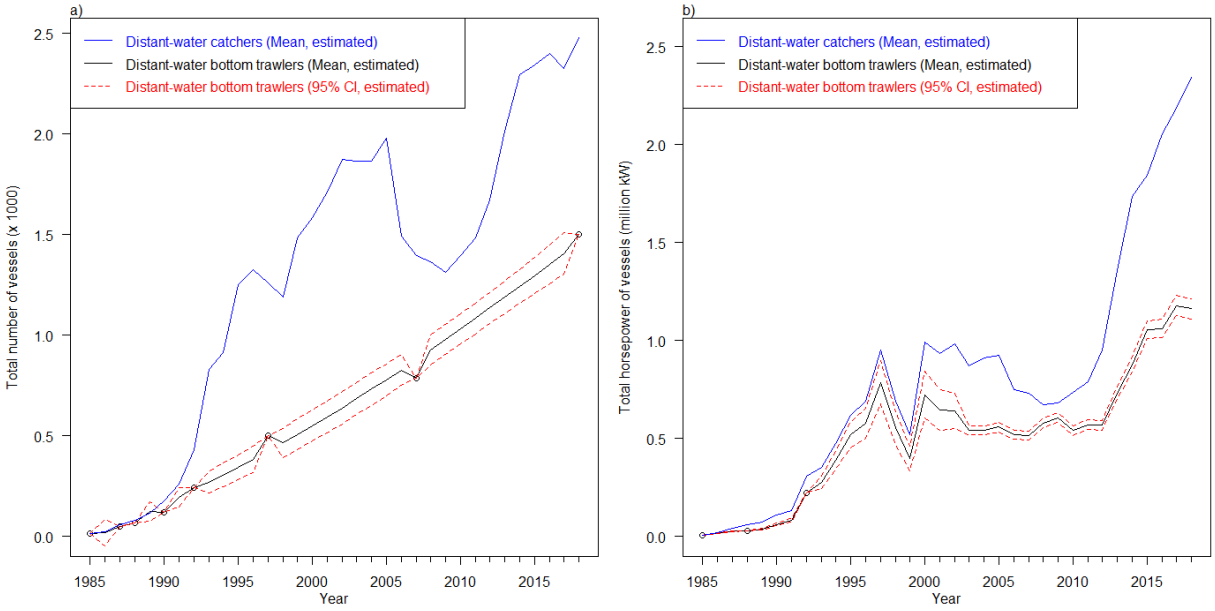

Figure 26. Estimated capacity statistics of distant-water bottom trawlers (DWBTs, mean and 95% CI): (a) total number of vessels, and (b) total horsepower of vessels. The reconstructed data of distant-water catchers (DWCs) were shown as references to validate these estimations. Circles were existing data points for DWBTs.

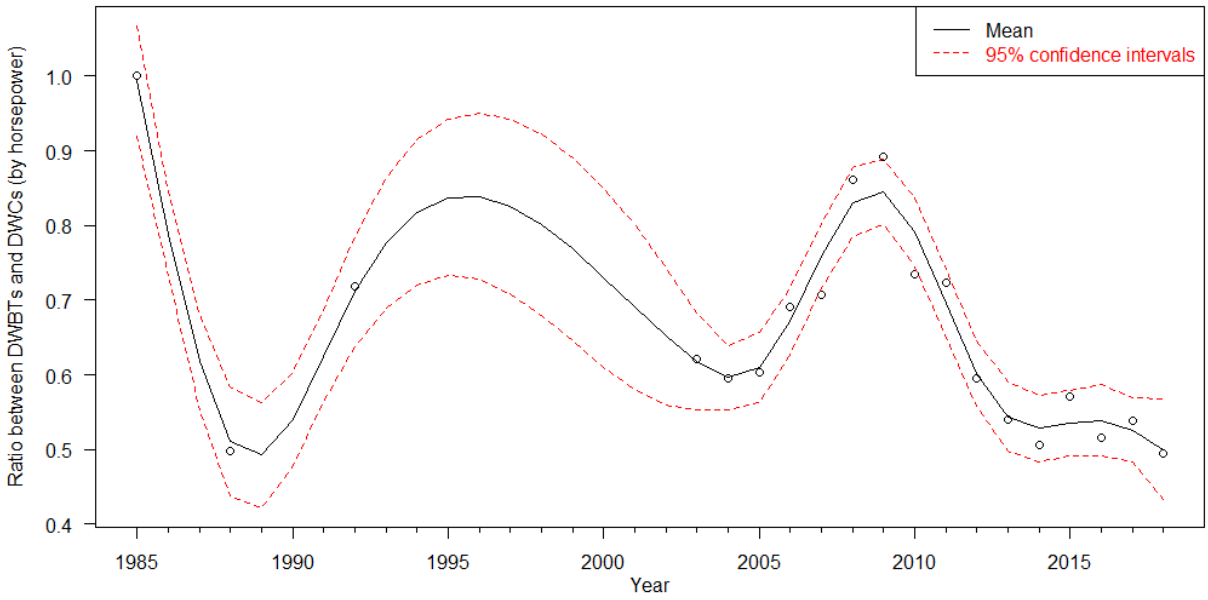

Figure 27. Estimated ratio between distant-water bottom trawlers (DWBTs) and distant-water catchers (DWCs, mean and 95% CI) measured by total horsepower. The estimation was based on a generalized additive model. Circles were the ratio data points based on existing data of the two.

3.5 Collecting yield statistics from Sea Around Us Project

We searched data based on fishing country (here, China) on the website of Sea Around Us Project (SAUP), The University of British Columbia (http://www.seaaroundus.org/data/#/fishing-entity). These original data were reconstructed timeseries yields (catch by tonnage, and landed value from 1950 – 2014) for a variety of gear types, including 'bottom trawl' (i.e., bottom trawls targeting finfish species) and 'shrimp trawl' (i.e., bottom trawls targeting shrimps). We used 'bottom trawl' to replace these two trawl groups and merged all other gear categories into one new category, i.e., 'other gears'. The reconstructed catch contains the catch reported to FAO and estimated unreported catch (including major discards); the landed value was estimated based on the ex-vessel prices and the catch and normalized to 2010 real USD [19,37]. They also included the following attributes of the caught fishery species/taxa: 1) fishing area, 2) year, 3) scientific name, 4) common name, 5) functional group, 6) end use type, etc. Among them, fishing areas refer to specific subregions of EEZs (e.g., Japan main islands) and the high seas (high seas were termed collectively as 'ALL"). We found all the reconstructed catches by China's bottom trawls were within its own and foreign EZZs, and only other gears (e.g., pelagic trawl, purse seine, longline) were operated in the high seas.

We estimated the yields (catch and landed value) for C4S based on the combination of the estimates within the following seven EEZ subregions that were defined by SAUP's database and located in China's four seas: 1) China, 2) Japan (main islands), 3) Korea (North, Yellow Sea), 4) Korea (South), and 5) Viet Nam. Given the latter three EEZ regions included waters beyond C4S, this aggregation approach might slightly overestimate the catch from China's four seas. However, Chinese fishing vessels did not develop distant-water fishing until 1985 and have no access to Japanese, South Korean, and Vietnamese EEZs after the establishment of EEZs in late 1990s, except their agreed co-fishing zones in C4S [39]. Therefore, we are confident that the catch by China's fishing vessels in the above five areas are largely from C4S.

For the yield statistics in China's claimed EEZ, we derived directly from the yield statistics for each of the seven stock assemblage groups: 1) large fish (ML ≥ 90 cm), 2) medium fish (30 cm ≤ ML ≤ 89 cm), 3) cephalopods, 4) shrimps, 5) lobsters & crabs, 6) jellyfish, and 7) small fish (ML < 30 cm) and other invertebrates.

3.6 Correction in spatial disaggregation of the SAUP data

We removed a total of 5642 records of the 'unreported' catches (including 4226 for bottom trawls) beyond C4S (a.k.a., 'distant waters' defined by the Chinese government) from 1950 to 1984, since 'distant water' fishing has not been developed yet by China until 1985 [82,84,85]. Though SAUP was aware of this important timeline in its previous reports [85], we found there were 6353 records of 'unreported' catches mistakenly allocated the to the 'distant waters'. For instance, in 1950, a total of 172.8 t of 'unreported' catches of 'Marine fish not identified' by China shown in the SAUP data was assigned to the EEZ of Sierra Leone, West Africa. We were not clear how these estimates were derived given this was not detailed for China in the SAUP methodology document [18]. One potential explanation related to these false estimates was that they were allocated based on the distant-water catch structure of other fishing powers such as Taiwan (province of China) and South Korea [42], whose distant water fishing started earlier than mainland China (in 1950 and 1960 respectively for Taiwan and South Korea) [86,87]. Given the above reasons, we eliminated these estimates for China's 'distant-water' fisheries from 1950 to 1984.

We reallocated a total of 4184 records of 'reported' catches (including 2127 for bottom trawls) beyond C4S (e.g., Hawaii Northwest Islands, Table 2) from 1950 to 1984 to subregions within C4S. These 'misplaced' records are likely, again, due to spatial disaggregation errors. The catches reported to FAO are based on FAO defined fishing areas and China's reported catches during these early ages are in FAO areas 61 (Pacific, Northwest) and 71 (Pacific, Western Central), which contained large areas of waters beyond C4S. This could explain why the SAUP falsely allocated some of China's 'reported' catches to these distant waters while ignoring the fact that China's fishing fleets did not operate in these waters during this period as mentioned above. To correct this mistake, we re-assigned these records to the most likely regions within C4S based on the proximity and similar latitude rules (Table 2).

Table 2. Fishing areas beyond C4S that were estimated for 'reported' catch (1950 – 1984) by China and their corrected subregions within C4S.

Area Name in SAUP dataset	Reallocated Area name
Japan (Daito Islands)	Japan (main islands)
Hawaii Northwest Islands (USA)	Japan (main islands)
Northern Marianas (USA)	China
Philippines	China
Russia (Far East)	Japan (main islands)
Wake Isl. (USA)	China
USA (Alaska, Subarctic)	Japan (main islands)
Japan (Ogasawara Islands)	Japan (main islands)
Korea (North, Sea of Japan)	Korea (South)

3.7 Forecasting yield statistics from 2015 to 2018

Given that SAUP data ended in 2014, we used ARIMA to forecast the timeseries datasets from 2015 to 2018 ('auto.arima' function in the 'forecast' r package) [55]. We are interested in yields of all Chinese marine fisheries (BTF and other fisheries) from all fishing waters, as well as multiple subregions (e.g., C4S vs. waters beyond C4S) and different gears (BTs vs. other gears). If we forecast the yields individually for different subregions and gears using ARIMA, this may result in mismatches, unrealistic estimates or high uncertainty due to variance propagation when summing the estimates up. To avoid this problem, we used an optimized approach to do the forecasts. First, we estimated yields from all fishing waters: 1) forecasting the catch and landed value for all marine fisheries and BTF using ARIMA; and 2) calculating the counterparts for other fisheries manually. Second, we estimated the yields of BTF in different waters: 1) forecasting the yields for C4S and China's EEZ; and 2) calculating the counterparts for waters beyond C4S and China's EEZ based manually (e.g., catch from waters beyond C4S = catch from all waters – catch from C4S). Third, we calculated the estimates for landed value per unit catch (i.e., mean price level) and other derivatives. For those variables estimated directly from ARIMA, the 95% confidence intervals (CIs) were retained and used to calculate the uncertainty of other variables (using the error propagation formula) [88]. These approached derived acceptable forecasts for all variables across different water bodies (Fig. 28 – 33) except the waters beyond C4S (Fig. 31b & Fig. 33), which had unrealistic estimates of landed values (and the derived mean price level) between 2015 and 2018 (i.e., high uncertainty propagation that derived negative lower bound of the 95% CI). To deal with this problem, we re-estimated the landed value for this water body by first using ARIMA to forecast its mean price level of catches by BTs and then calculated the landed value by multiplying the mean price level with the catch. This ensured that the lower bounds of the 95% CIs of both the mean price level and the derived landed value were positive (Fig. 33). The calculated the mean landed value also matched well with the one calculated by subtracting that of C4S from the counterpart of all waters. We then used these updated estimates for waters beyond C4S.

In the end, the original timeseries (1950 – 2014) and the forecasted timeseries (2015 – 2018) were integrated to derive a full timeseries for each yield statistics.

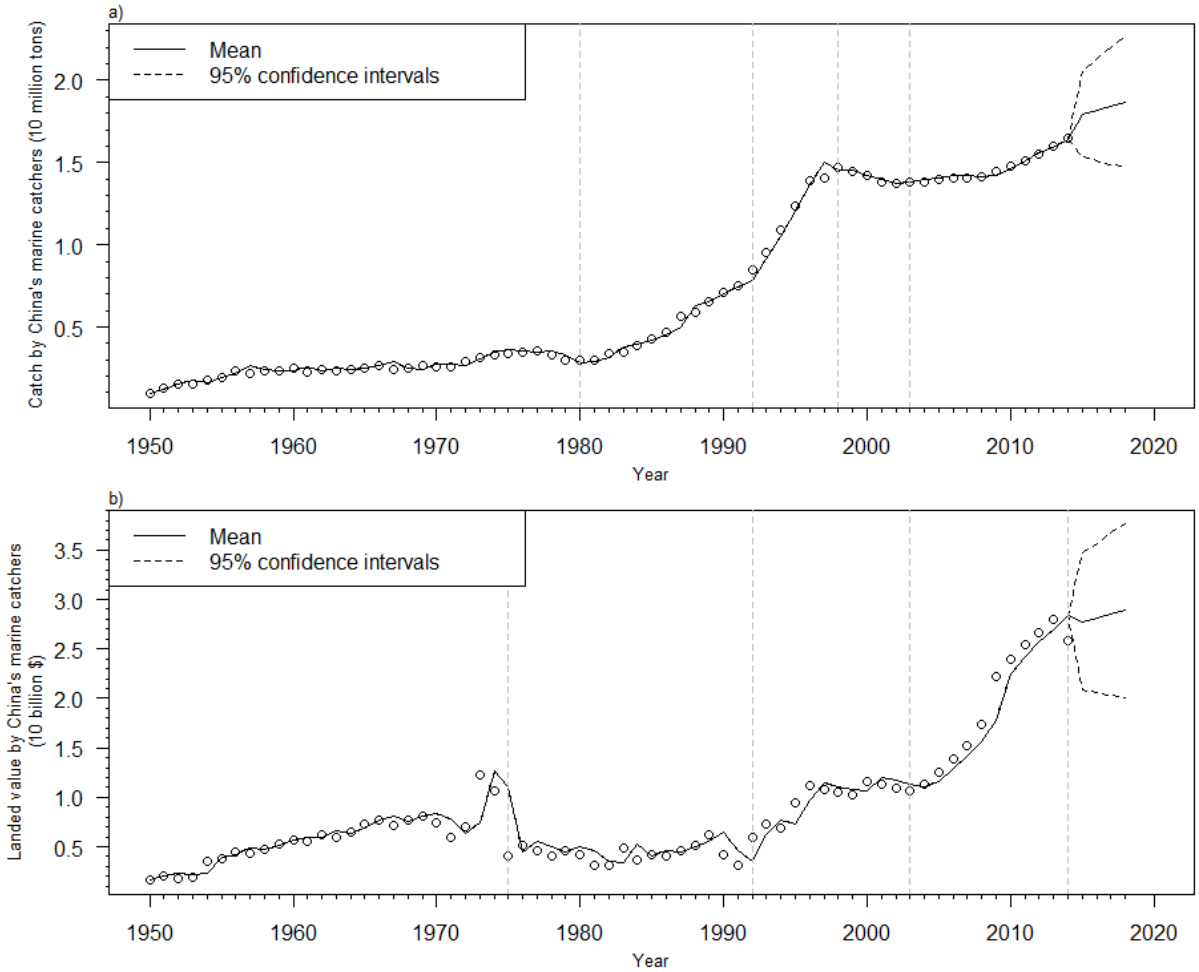

Figure 28. Timeseries (2014 – 2018) of the a) catch and b) landed value produced by China's marine catchers, with forecasted data (mean and 95% CI) from 2015 to 2018. The forecast was based on the auto regressive integrated moving average (ARIMA). Circles were ratios estimated based on the timeseries of reconstructed data (1950 – 2014) by the Sea Around Us Project. The grey dash lines were some reference years when dramatic changes happened or were about to happen on the trajectories.

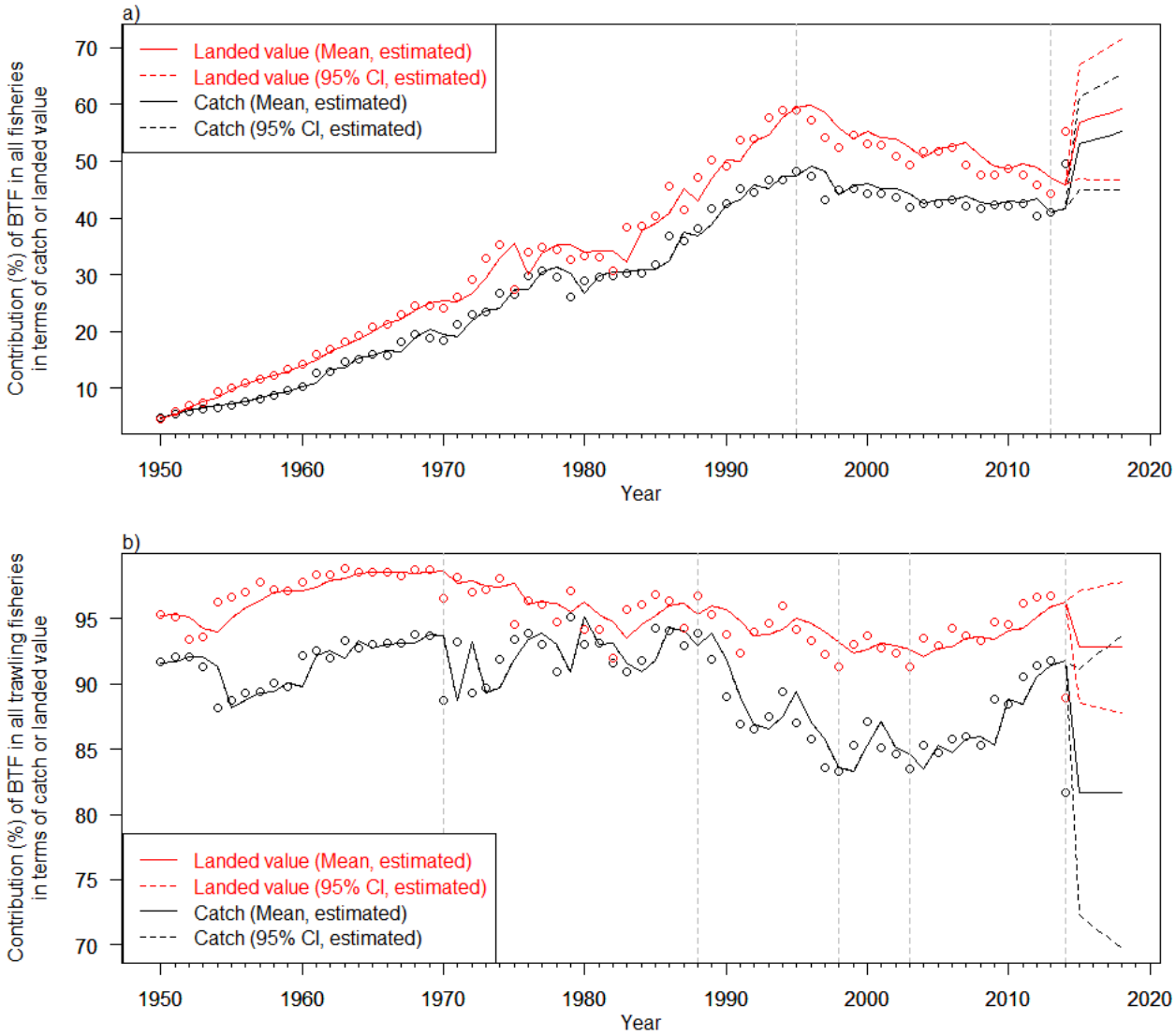

Figure 29. Timeseries (2014 – 2018) of the catch share or landed value share by China's bottom trawlers in a) all marine capture fisheries, and b) trawling fisheries only, with forecasted data (mean and 95% CI) from 2015 to 2018. The forecast was based on the auto regressive integrated moving average (ARIMA). Circles were ratios estimated based on the timeseries of reconstructed data (1950 – 2014) by the Sea Around Us Project. The grey dash lines were some reference years when dramatic changes happened or were about to happen on the trajectories.

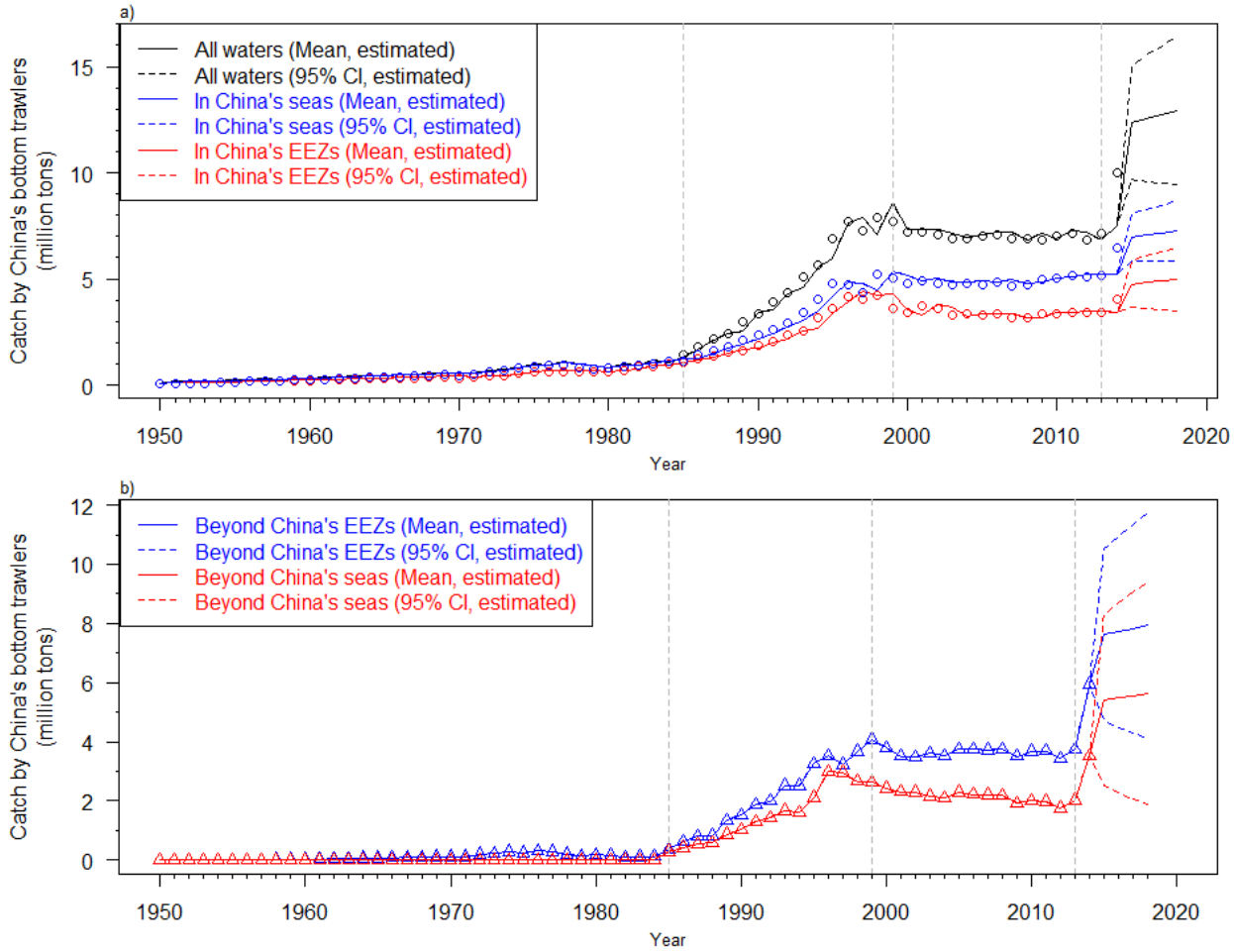

Figure 30. Timeseries (2014 – 2018) of the catch by China's bottom trawlers with forecasted data (mean and 95% CI) from 2015 to 2018 for five water bodies: a) all waters, China's seas (i.e. C4S), and its EEZs; and b) beyond China's EEZs and its four seas. The forecast was based on auto regressive integrated moving average (ARIMA). Circles / triangles were the timeseries of reconstructed catch data (1950 – 2014) by the Sea Around Us Project. The grey dash lines were three reference years when dramatic changes happened or were about to happen on the trajectories: 1985, 1999, and 2013.

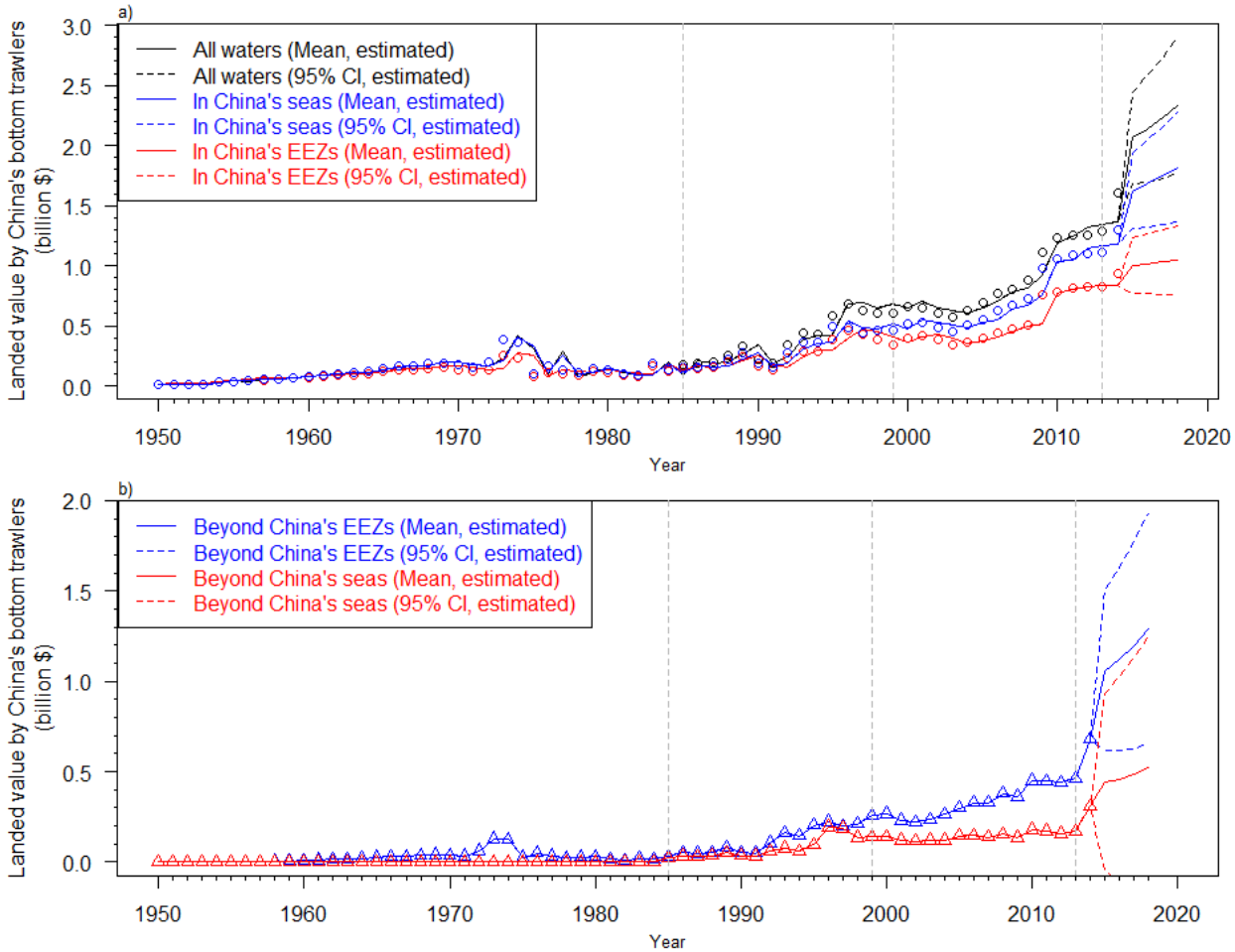

Figure 31. Timeseries (2014 – 2018) of the landed value by China's bottom trawlers with forecasted data (mean and 95% CI) from 2015 to 2018 for five water bodies: a) all waters, China's seas (i.e. C4S), and its EEZs; and b) beyond China's EEZs and its four seas. The forecasts in the panel a were based on the auto regressive integrated moving average (ARIMA); the forecasts in the panel b were based on deductions from panel a. Circles / triangles were the timeseries of reconstructed data (1950 – 2014) by the Sea Around Us Project. The grey dash lines were three reference years when dramatic changes happened or were about to happen on the trajectories: 1985, 1999, and 2013.

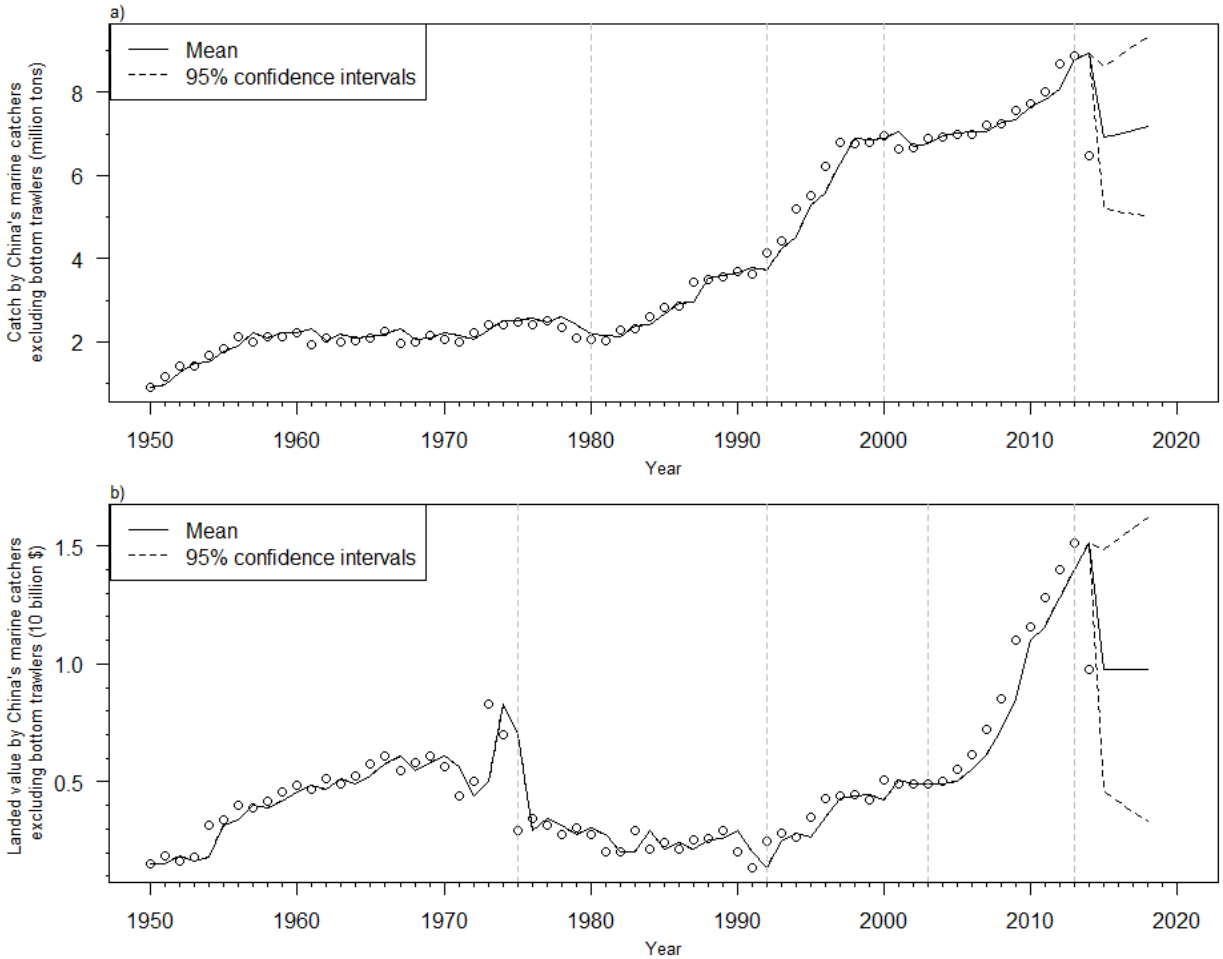

Figure 32. Timeseries (2014 – 2018) of the a) catch and b) landed value produced by China's marine catchers other than bottom trawlers, with forecasted data (mean and 95% CI) from 2015 to 2018. The forecast was based on the auto regressive integrated moving average (ARIMA). Circles were ratios estimated based on the timeseries of reconstructed data (1950 – 2014) by the Sea Around Us Project. The grey dash lines were some reference years when dramatic changes happened or were about to happen on the trajectories.

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