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Status of fisheries in 13 Asian Large Marine Ecosystems

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ABSTRACT

Thirteen Asian Large Marine Ecosystems (LMEs) ranging from the Arabian Sea LME in the West to the Western Bering Sea LME in the East are reported on in terms of their fisheries, catch trends and associated indicators such as the primary production required to maintain fishery catches, trends in the mean trophic levels of the catch, stock-status plots and others. Effective management of these LMEs is crucial for maintaining marine ecosystem system health and the goods and services the LMEs provide. Such management must be able to rely on credible catch data. The catch data used here were based on the national catch reconstructions performed by the *Sea Around Us*, as also documented in www.searoundus.org, but these could not fully compensate for the deficiencies of the fisheries statistical systems of several major countries in Asia, as reflected in exaggerated catch levels and uninformative catch compositions.

1. Introduction

Managing fisheries at the Large Marine Ecosystems (LMEs) level is necessary for fish undertaking long distance migrations and trans-boundary stocks, especially where distant-water fleets are operating (Bonfil et al., 1998; Sherman et al., 2003; Sherman and Hempel, 2008; Pauly et al., 2014). Recent efforts have been made by different stakeholders from more than one hundred economically developing countries for implementing ecosystem-based management at the LME scale (Sherman, 2014). Intergovernmental organizations such as the Food and Agriculture Organization of the United Nations (FAO) also contributed to facilitate the establishment of multi-sectoral (including fishery sector) governance systems within LMEs, for example, the Bay of Bengal Large Marine Ecosystem (BOBLME) Project (Bianchi et al., 2016). Also, a number of international, regional and bilateral environmental agreements and other legal instruments have been adopted by the multi-national organizations of the bordering countries such as ROPME (Regional Organization for the Protection of the Marine Environment) in the Arabian Sea LME (Heileman et al., 2008b). Non-profit organizations also help to address coastal fisheries problems in Asia. For example, the WorldFish Center collaborated with the fisheries agencies in several Asian countries to implement a project called TrawlBase (1998–2001) to recover data whose analysis would assist in developing policies for the sustainable management of their coastal fish stocks (Silvestre et al., 2003; Heileman and Chuenpagdee, 2008). Although there are multilateral efforts aiming to improve the current situation regulation of fisheries and better manage LMEs, competing claims over marine resources often leads to the failure of these regulations, for example in the South China Sea LME (Spijkers et al., 2018). Effective management of LMEs would not only enhance marine ecosystem health, but would also maintain the goods and services which LMEs can provide, for example, fisheries catch in the countries bordering these LMEs. These ecosystem goods and services are particularly important for developing countries, which are highly dependent on fisheries for food and jobs; this also applies to most of the thirteen Asian LMEs examined here (Fig. 1).

To implement well-designed fisheries management strategies for LMEs, the status of their biodiversity and the major trends of their fisheries should be available. However, information on the catches and other fisheries related quantities are usually not available at the LME level. Indeed, the first published report that contained such fisheries catch and related indicators at the LME level was the book edited by Sherman and Hempel (2008), which presented time series of landings submitted by its member countries to the FAO as spatialized data (i.e. distributed over half degree latitude x half degree longitude grid cell) and assigned to LMEs by the *Sea Around Us* (Pauly et al., 2008; Sumaila et al., 2011). Also, a report which documented the catches (also based on the FAO database) and other parameters required for deriving sustainability indicators for all LMEs in the world was published (Pauly and Lam, 2016).

In the meantime, however, the *Sea Around Us* completed a global effort to improve the comprehensiveness of the global marine fisheries

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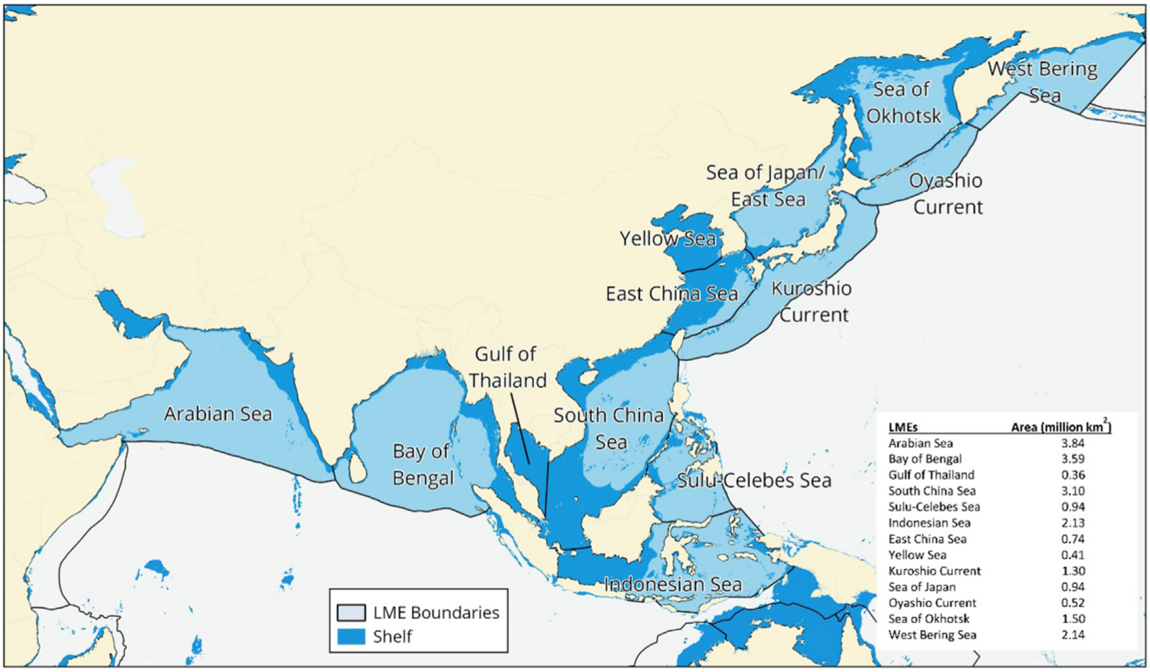

LMEs	Area (million km^2)
Arabian Sea	3.84
Bay of Bengal	3.59
Gulf of Thailand	0.36
South China Sea	3.10
Sulu-Celebes Sea	0.94
Indonesian Sea	2.13
East China Sea	0.74
Yellow Sea	0.41
Kuroshio Current	1.30
Sea of Japan	0.94
Oyashio Current	0.52
Sea of Okhotsk	1.50
West Bering Sea	2.14

Fig. 1. The thirteen Asian LMEs that are included in this study.

catch dataset through bottom-up catch reconstructions for all maritime countries of the world (Pauly and Zeller, 2016a). The reconstructed catch data revealed that global catch is about 50% higher than reported by the FAO, peaked at 130 million tonnes in 1996, and has been declining since. The catch reconstructions, moreover, were done by sector and thus provide a solid ground for evaluating the performance of the industrial sector (which also generates most of the discards, ignored by FAO, but included in the reconstructions), in comparison with the small-scale sector and its components (i.e. artisanal, subsistence and recreational fisheries). These more detailed catch data (which can be freely downloaded from www.seaaroundus.org) provide a picture of fisheries in LMEs that is more nuanced than that based on FAO data, and should better inform the decision processes regarding management strategies for LMEs.

In this study, we reassessed the catch and other fisheries related parameters (Pauly et al., 2008) in 13 Asian LMEs based on the reconstructed catch data from the *Sea Around Us* (Pauly and Zeller, 2016a). These 13 LMEs (Fig. 1) encompass a total area of 15.7 million km^2, of which 37% is shelf area (i.e. 5.8 million km^2). Some of these LMEs are in very productive and biologically diverse regions, for example, the Gulf of Thailand, South China Sea, Sulu-Celebes Sea and Indonesian Sea LMEs. Among these LMEs, seven are classified as the highest risk LMEs based on the Transboundary Water Assessment Programme (TWAP) risk scores (Kleisner et al., 2016).

The reassessment was done using a spatial approach initiated by Watson et al. (2004), further developed in Zeller et al. (2016) and in more detail in several chapters of Pauly and Zeller (2016b), which maps catches onto spatial cells that can then be regrouped into higher spatial aggregates, e.g. the Exclusive Economic Zone (EEZs) of countries (see www.seaaroundus.org), or the 13 LMEs so far defined in the Asian ocean region.

Since these aggregates of spatial cells can then be combined with other data (for example, the ex-vessel price of the fish caught, or their trophic level), one can then easily derive other time series, such as indicators of the degree to which LMEs may be degraded or impacted by fisheries. In this paper, we present the methods of obtaining fish catch time series, along with a set of derived time series ecosystem indicators for all LMEs in Asia, and then further discuss the status and management implication in each of these LMEs.

2. Methods

2.1. Reported catch (landings)

Annual catch data were extracted from the *Sea Around Us* database of reconstructed catches, which cover the years 1950–2014, distributed onto 180,000, 30′ latitude × 30′ longitude spatial cells of the world ocean (Watson et al., 2004; Zeller et al., 2016). Reconstructing catch data utilized a wide variety of data sources and information to estimate all of the fisheries components such as subsistence catch, recreational catch and discards that are missing from the official reported data (Pauly and Zeller, 2016a). This allocation process produced spatial time series of landings data from 1950 to 2014 that were aggregated into our 13 LMEs, and which distinguished between landings by distant-water and domestic fleets, and between different fishing sectors.

The catch reported to FAO from its members countries is lower than the reconstructed catch (FAO, 2016; see Supplementary Figs. 1 and 2). The small-scale fishery sectors, i.e. artisanal, subsistence and recreational received little attention in data collection systems, so their catches are underrepresented in, or absent from, official catch statistics, as are discards and illegally caught fish (Pauly, 2006; Zeller et al., 2015). Thus, the total reconstructed catch from 1950 to 2014 was about 1.9 times and 1.3 times of the total reported catch in the Indian Ocean and Pacific Ocean LMEs, respectively., which is comparable to the ratio of global reconstructed to the reported catch (i.e. about 1.5 times). The “catch reconstruction” approach utilized a wide variety of data and information sources to estimate the catch of those sectors that are missing from the official reported data. In the Indian and Pacific Ocean LMEs, the reported catch still tends to increase, but this is mainly due to the over-reporting by a few countries.

Although catch data are seldom associated with a measure of uncertainty, we quantified the uncertainty of the reconstructed catch data from Asian LMEs using the ‘pedigrees’ approach described in Pauly and Zeller (2016a). Uncertainty scores were obtained from the first authors of catch reconstructions, who evaluated the quality of the time series from each fisheries sector (industrial, artisanal, subsistence and recreational) for each of three time periods (1950–1969, 1970–1989 and 1990–2014). These 'scores' are (1) 'very low', (2) 'low', (3) 'high' and (4) 'very high' (Supplementary Table 1). Then, the overall mean weighted percentage uncertainty of each EEZ of each fishing sector in each year within the Asian LME areas was computed. These values were then input into a Monte-Carlo model and run for 10,000 times. For each year, we obtained the medium, 2.5th and 97.5th percentiles of the distribution of the estimated catch derived from Monte-Carlo simulations. Then, the medium, 2.5th percentile and 97.5th percentile of the total catch of all LMEs within Indian and Pacific Oceans are calculated, respectively (Supplementary Figs. 1 and 2).

To assess the impact of fishing on each of the LMEs, the catch time series were then used to derive seven indicators, i.e. (i) size of the ecological footprint; (ii) marine trophic index (MTI); (iii) the fishing-in-balance index (FiB) (iv) region-based marine trophic index (RMTI); (v) stock status by number and biomass of exploited stocks; (vi) catch from bottom impacting gear types, and (vii) fishing effort. Details are provided in the following.

2.2. Ecological footprint

Since the degradation of marine ecosystems is determined mainly by the removal of biomass, the primary production required by the catch (PPR), expressed as a fraction of the observed primary production in the area where the catch was taken (Pauly and Christensen, 1995), corresponds to the ecological footprint of the fishery.

The PPR of fisheries depends on the taxonomic composition of the catch and on their trophic level. The PPR to produce a given amount of a high-trophic level fish (such as tuna) is much higher than that required for the same amount of a low-trophic level fish (such as sardines) because the transfer efficiency from one trophic level to the next is low, usually 10 per cent (Pauly and Christensen, 1995; Ware, 2000). To compute the PPR for a given tonnage of fish catch, the catch and the mean trophic level (TL) of each taxon in the catch, and an estimate of transfer efficiency (TE) were combined using the equation (Pauly and Christensen, 1995):

$$PPR = \sum_{i=1}^{n} \left(\frac{catch_i}{9}\right) \bullet \left(\frac{1}{TE}\right)^{(TL_i-1)}$$

Since we used a TE of 10 per cent, the equation becomes:

$$PPR = \sum_{i=1}^{n} \left(\frac{catch_i}{9}\right) \bullet 10^{(TL_i-1)}$$

where $catch_i$ is the catch of each taxon i in each LME and n is the total number of taxa being caught in a particular LME. TL_i is the trophic level of species i, whereas TE_i is the trophic transfer efficiency, which is the proportion of prey production converted to predator production. A conservative 9:1 ratio is used for converting wet weight to carbon (Strathmann, 1967). Global estimates of primary production were derived an algorithm described by Platt and Sathyendranath (1988), which estimates depth-integrated primary production based on chlorophyll pigment concentration from remotely-sensed SeaWiFS data (www.seawifs.gsfc.nasa.gov) and photosynthetically active radiation as calculated in Bouvet et al. (2002). The estimated primary productivity in 1998 is assumed to be representative of the entire period. The PPR of all species (or groups of species) in each LME were then summed. The ecological footprint was then estimated by dividing the total primary production required by the total observed primary production in each LME, with both catches and primary production expressed in the same weight units.

2.3. Marine Trophic Index (MTI)

The MTI is an indicator used by the Convention on Biological Diversity (Pauly and Watson, 2005). The MTI expresses the mean marine trophic level (mTL) of the fisheries catches in an area, and when mTL trends are considered, this indicator links to 'fishing down the food web' (Pauly et al., 1998; Christensen and Pauly, 1993; Pauly and Christensen, 1995). Its computation requires careful examination of specific conditions in LMEs. It is generally expected that a decline in MTI may indicate a fishery-induced decline in the biodiversity of the top predators. The MTI tracks changes in mTL, defined for year k as:

$$MTI = \quad mTL_k = \frac{\sum (Y_{ik} \bullet TL_i)}{\sum (Y_{ik})}$$

where Y_{ik} is the catch of species i in year k, and TL_i the trophic level of species (or group) i, the latter usually obtained from diet composition studies documented in FishBase (www.fishbase.org) for fishes, and in SeaLifeBase (www.sealifebase.org) for marine invertebrates. Here, the change in value of the MTI in the 2000s from that in the 1950s is used as the indicator. Negative values represent a decrease in the mean trophic level in an LME, and the lower the value of this indicator, the higher the risk category the LME is placed in.

2.4. Fishing-in-Balance index (FiB)

The effect of geographic expansion on the trophic level of catch was first expressed using an indicator called the Fishing-in-Balance (FiB) index (Bhathal and Pauly, 2008). This indicator was developed to express the fact that, in each ecosystem, when low-trophic level fish (e.g. forage fish) are targeted, catches can be expected to be higher than that when high-trophic level fish (e.g. tuna) are targeted (Pauly et al., 2000). Thus, there is a direct relationship, mediated by the transfer efficiency (TE, see above), between catch and trophic level. Specifically, the FiB index will remain constant when a decline in the mean trophic level of the catch is compensated for by an appropriate increase in catch, and vice-versa. Otherwise the FiB index change, which is then indicative of geographic expansion or other changes in the fishery (Pauly et al., 2000).

The FiB Index is defined for any year k:

$$\mathrm{FiB} = \log(\mathrm{Y_k}^*(1/\mathrm{TE})^{\mathrm{TL}}{}_{\mathrm{k}}) - \log(\mathrm{Y_0}^*(1/\mathrm{TE})^{\mathrm{TL}}{}_{0})$$

where Y is the catch, TL is the mTL in the catch, TE is the transfer efficiency between trophic levels, and 0 refers to the year used as a baseline. The FiB is calculated from the geometric mean of each of the terms, thereby preserving the relationship between ecologically equivalent amounts of fish at different trophic levels. This index may: 1) remain constant (equal 0) if the fishery is 'balanced', that is, all trophic level changes are matched by 'ecologically equivalent' changes in catch; 2) increase (positive index value) if there are (a) bottom-up effects (for example, increase in primary productivity) or (b) geographic expansion of the fishery to new fishing grounds (typically offshore) which, in effect, expands the ecosystem exploited by the fishery; or 3) decrease (negative index value) if discarding occurs that is not represented in the catch, or if the ecosystem functioning is impaired by the removal of excessive levels of biomass (Kleisner et al., 2011).

The LMEs are categorized by the positive difference between the mean TL in the 2000–2014 period and the 1950s, a larger difference being indicative of greater potential for ecosystem degradation. Larger differences in this value imply that the fisheries expanded offshore in the LME in question.

2.5. Region-based Marine Trophic Index (RMTI)

MTI and FiB illustrate changes in the average trophic level over time and provide an indication of geographic expansion or contraction of fished areas. However, it is difficult to visually combine the message from MTI and FiB. Thus, a Region-based Marine Trophic Index (RMTI) was developed (Kleisner et al., 2014) which combines the logic of the equations for the MTI and the FiB index. Thus, when calculating the

RMTI, we assume that the fishery proceeds in a sequential manner, where one region is 'fully exploited' before the fishery moves to the next. This assumption is reasonable since, given the high fuel costs of offshore fisheries, fishing activities will remain confined to coastal fishing grounds as long as possible, before moving offshore.

When estimating RMTI, two assumptions are made: (1) the fish stocks in the initial region continue to be fished following the year of expansion, and (2) fishing in the initial region continues to be in balance or contracting given the TE in that region. Here, however, we abstain from presenting the relevant equations and refer to Kleisner et al. (2014). An exemplary application of the RMTI to the East China Sea was presented by Liang and Pauly (2017), whose first author also distributes a spreadsheet on how to implement the RMTI.

2.6. Stock status by number and catch biomass of exploited stocks

Stock status plots (SSPs) use catch time series to assign individual stocks to different development stages, based on their catch levels relative to the peak catch of the time series (Froese and Kesner-Reyes, 2002; Pauly et al., 2008; Kleisner et al., 2013). For example, the 'overexploited' stage occurs after a time series peaks, for catch levels between 10% and 50% of the peak catch, in contrast to the 'collapsed' stage, which also occurs after the peak, but at catch levels lower than 10% of peak catch. The 'exploited' stage occurs when catch levels are higher than 50% of the peak catch, whereas the 'developing' stage occurs before a time series peaks, when catch levels are lower than 50% of peak catch. The 'collapsed' stage occurs when catch level decline to less than 10% of peak level. Finally, if catch levels are between 10% and 50% of the peak and occur after the time series peaks, this stage is classified as 'rebuilding'.

The algorithm is applied to numbers of stocks (taxa) and to catch tonnage per taxon to highlight the annual proportions of stocks and total catch in a particular stage. An increase in the percentage of stocks that are classified as 'overexploited' or 'collapsed' are indicative of a lack of sustainability, especially when the bulk of the catch tonnage is from taxa with these designations.

We defined a stock to be a taxon (at either species, genus, or family level) that occurs in the catch records for at least five consecutive years, over a minimum of a 10-year time span, and that has a total catch in an area of at least 1000 t over the time span analyzed. The number of stocks by status in a particular LME in a given year is then computed, and is presented here as time-varying percentages in stock-status plots.

Actually, to assess more accurately the stock status of exploited species, 'stock assessments' must be performed, which combine structural population models with age composition and other data to estimate their population size. However, because of these onerous requirements, until recently, assessed fisheries only contributed to 16% of the global catch and occurred predominantly in developed countries (Ricard et al., 2012). Therefore, Costello et al. (2012) developed a multivariate regression approach to assess the status of unassessed fisheries by identifying predictors of the stock status (B/B_{MSY}) from assessed fisheries, including in the regions covered here. Moreover, the *Sea Around Us* provides on its website (since mid-2018) stock assessments based on the CMSY methods (Martell and Froese, 2013; Froese et al., 2017) for nearly all Marine Ecoregions of the world (Spalding et al., 2007) which include the major species in all LMEs discussed here. An analysis of the results of these assessments will be presented elsewhere.

2.7. Catch from bottom-impacting gear types

Annual catches by LME and bottom-impacting gear types, including dredges and bottom trawls, were extracted from the *Sea Around Us* database, and are here considered as a proxy for habitat impacts (Watson et al., 2006). Then, the percentage of catch from bottom-trawling gear to the total catch was calculated for each LME. A 10-year average (2005–2014) of this percentage was used to provide a single indicator value per LME. The higher this percentage was, the greater habitat impact can be expected.

2.8. Fishing effort

Fishing effort data for the period 1950–2006 were obtained from the FAO, the European Union, the Regional Fisheries Management Organizations managing tuna stocks, and CCAMLR (Anticamara et al., 2011; Watson et al., 2013). Data from these different sources were standardized based on engine power (watts) and fishing days. Fishing effort was then estimated by country, vessel gross registered tonnage class, and vessel/gear types from the sources mentioned above. Non-fishing vessels such as patrol ships, research vessels, and mother-ships/carrier vessels were excluded from the analysis. Gaps in the database, which involved mainly countries with small catches and fleets, were filled by using effort data from EEZs with similar catch profiles, which acted as surrogates for data-poor EEZs (Anticamara et al., 2011).

An indicator of ecosystem degradation can be computed as the rate of change in effort from the mean of the 1980s to the mean of the 2000s, with higher rates of change implying greater potential for degradation of natural living resources or ecosystems. The rate of change in the total effective effort in the last decade is used as the indicator. Values range from − 1.6 to 129 million kilowatts days per year.

3. Results

3.1. Fishing pressure

The trend of catch data in the LMEs of the Indian Ocean and Pacific Ocean are shown in Fig. 2. Annual catch in the three LMEs in the Indian Ocean increased tremendously since the 1950s, and peaked at about 16 million tonnes in 2004 (Fig. 2a), then fluctuated between 15 and 16 million tonnes. The catch reported to FAO by its member countries increased steadily from 1950 to 2014, in contrast to the reconstructed catch, which stagnated in the last decade.

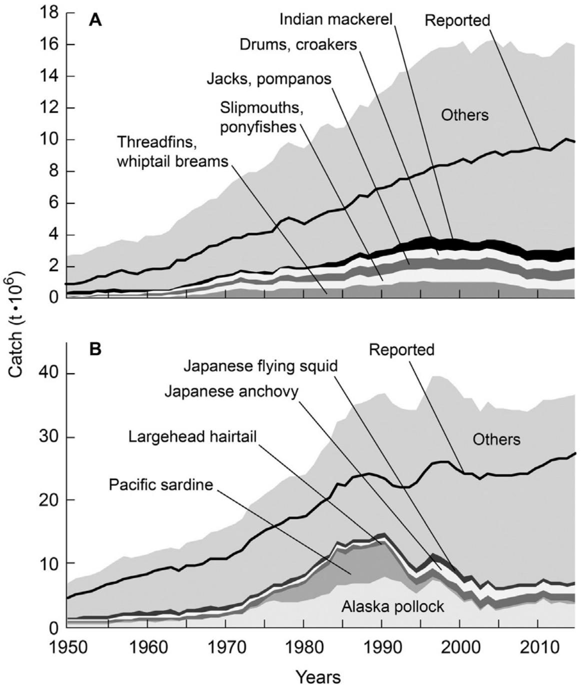

Fig. 2. Reconstructed catch (1950–2014) of the top 10 taxa in (a) 3 LMEs in the Indian Ocean; (b) 10 LMEs in the Pacific Ocean. Adapted from www.seaaroundus.org.

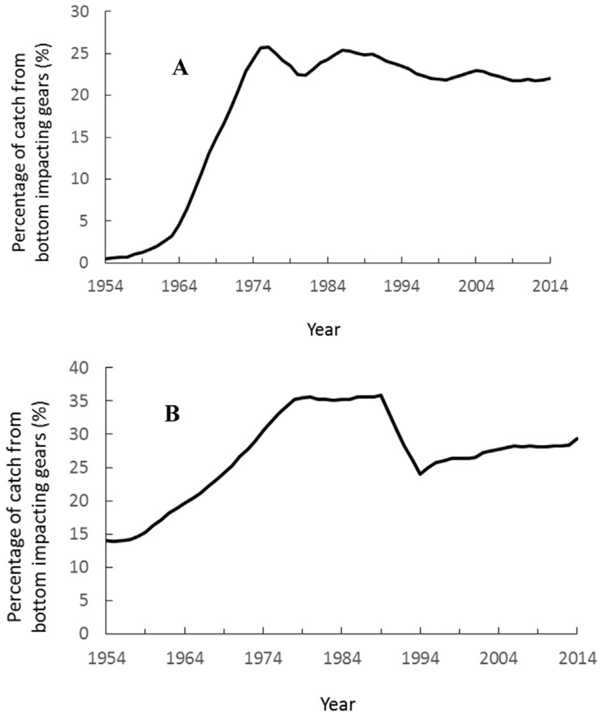

Fig. 3. Running mean percentage (5-year interval) of annual catch from bottom impacting gears to the total catch in (a) 3 LMEs in the Indian Ocean; (b) 10 LMEs in the Pacific Ocean from 1950 to 2014.

The total reconstructed catch in the 10 LMEs in Pacific Ocean also increased massively from the 1950s, and peaked at about 40 million tonnes in 1996 (Fig. 2b). From 2005 to 2014, the annual reconstructed catch fluctuated between 34 and 37 million tonnes.

The relative contribution of the total LME catch that is caught by bottom-impacting gear (mainly trawls and some dredges) is an indicator of potential ecosystem degradation from fisheries (Fig. 3). In the 3 LMEs in the Indian Ocean, the trawled catch increased gradually from very low percentages in the 1950s to its peak at 25% in mid-1970s (Fig. 3a). Then, this percentage fluctuated around 21–25%. Destructive fishing including trawl fishing and the use of explosives and poisons was found to be severe in several regions, for example, Gulf of Thailand LME (Talaue-Mcmanus, 2018; Wilkinson et al., 2005). In the Pacific Ocean LMEs, the percentage of trawled catch gradually increased from the 1950s, and reached a peak at 35% in 1980s. Thereafter, this indicator dropped, and fluctuated around 25–30% in the past two decades (Fig. 3b).

Nominal fishing effort is defined here as the cumulative power of the engines of the vessels in all fishing fleets operating in a LME, adjusted for the likely number of fishing days of each fleet segment. Effective effort is the nominal effort adjusted for the gradual technological improvements in fish finding and catch handling. Here, the technological improvement factor was set at 2.5% per year, based on a prior meta-analysis of published efficiency increases in Pauly and Palomares (2010). The effective effort in the 13 LMEs considered here increased since 1950, slowly at first and sharply from 1994 to 1998; thereafter, it continued to increase rapidly (Fig. 4).

3.2. Stock-status plots

The plots in Fig. 5a and c show the percentage of stocks of a given status by year in three Indian Ocean LMEs and 10 Pacific Ocean LMEs, respectively. They show a rapid increase in the percentage of exploited, overexploited and collapsed stocks in the Asian LMEs. Fig. 5b and d allow for assessing the status of stocks in term of the catches they contribute to the fisheries of Indian Ocean LMEs and Pacific Ocean LMEs, respectively. Combined, the two types of stock-status plots suggest that the impact of fishing on stock numbers is much higher than its impact on catch tonnage. This confirms the common observation that fisheries tend to affect biodiversity (as reflected in the taxonomic diversity of catches) more strongly than they affect the biomass of important stocks (as reflected in the catch amounts) (Pauly and Lam, 2016). In other words, fisheries eliminate small, less productive stocks, and gradually concentrate on a few productive stocks (Roberts, 2010).

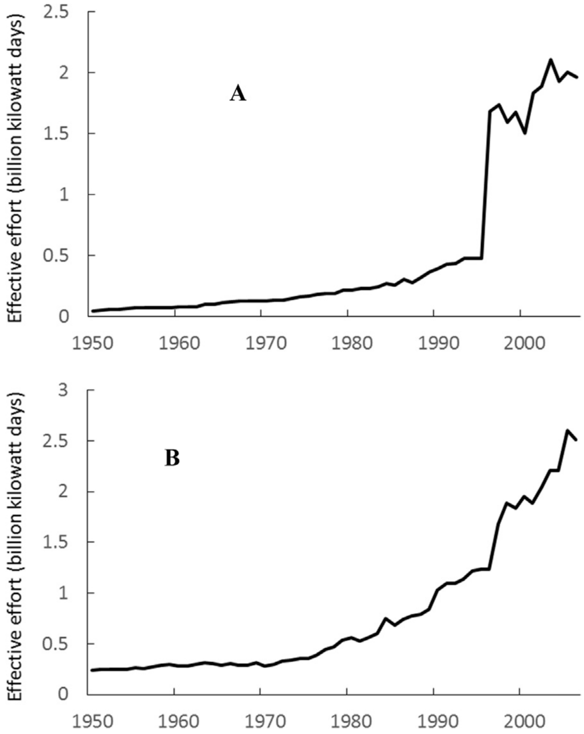

Fig. 4. Aggregate effective fishing effort in (a) 3 LMEs in Indian Ocean; (b) 10 LMEs in Pacific Ocean, 1950–2006 (Anticamara et al., 2011; Watson et al., 2013; Pauly and Lam, 2016).

In Indian Ocean LMEs, over 30% of the stocks are overexploited or collapsed in recent years (Fig. 5A). In Pacific Ocean LMEs, almost 50% of the stocks are overexploited or collapsed in recent years (Fig. 5C). Although the number of collapsed stocks in LMEs is increasing, the number of rebuilding stocks is also increasing, for example in the Pacific Ocean LMEs, an encouraging sign.

3.3. Ecosystem impacts of fishing

The PPR of our 13 LMEs is presented in Table 1, with high values indicating high levels of degradation. A few Asian LMEs including the Gulf of Thailand, South China Sea and East China Sea have ecological footprints greater than 100%. Although more causes could be suggested (e.g. errors in trophic levels assignment, or changes in primary production), this most likely indicates that catches reported from these LMEs were actually taken in other areas (Dulvy et al., 2009), as both Thailand and China have massive distant-water fleets (Pauly et al., 2014; Derrick et al., 2017).

Fig. 6 illustrate both the trend in the mean trophic levels (i.e. the MTI) of a selected LME, from 1950 to 2014 (Fig. 6a), and the need to combine it with the FiB index (Fig. 6b), or to use the RMTI routine before it is interpreted. Thus, while Fig. 6a shows a decline of the mTL down to its lowest value in the late 1980s and then a sudden increase, the FiB index shows a rapid increase from the late 1980s, which suggest the emergence of a new, offshore fishery which would initially target high-trophic level fish, and hence the increase in MTI. This is confirmed

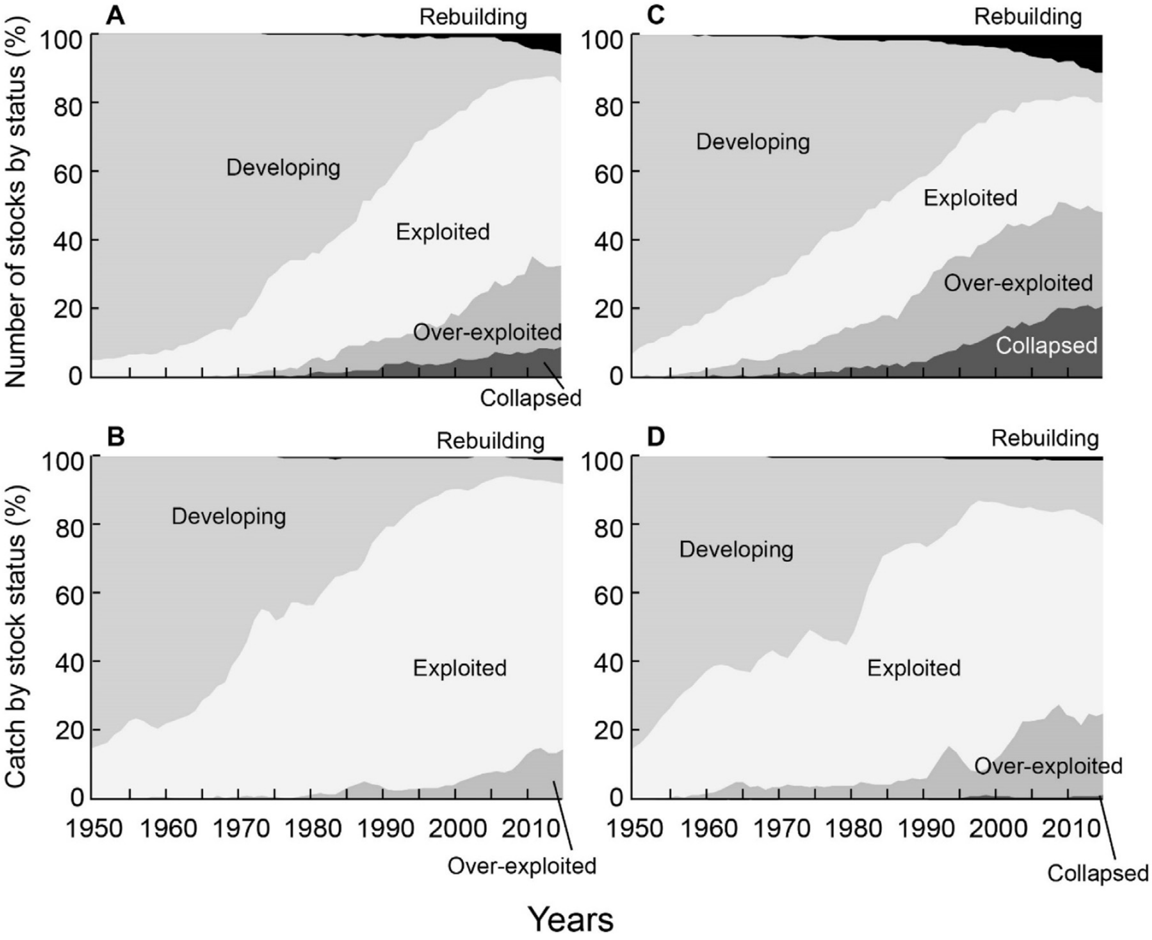

Fig. 5. Stock status plots for the fisheries of three LMEs in the Indian Ocean and 10 LMEs in Pacific Ocean. (a) and (c) show the percentage of stocks of a given status in Indian Ocean LMEs and Pacific Ocean LMEs, respectively, while (b) and (d) show the percentage of catches from stocks of a given status in Indian Ocean LMEs and Pacific Ocean LMEs, respectively.

Table 1
Ecological footprint (PPR/PP, in %) of fishing in 13 LMEs, showing the primary productivity required to sustain their fisheries expressed as percentage of the primary production in their waters.

LME number	LME name	Primary production (mg Cm^{-2} day^{-1})	Ecological footprint (PPR; %)
32	Arabian Sea	1003.13	35.6
34	Bay of Bengal	682.95	56.1
35	Gulf of Thailand	745.27	249.4
36	South China Sea	566.51	118.8
37	Sulu-Celebes Sea	548.89	69.8
38	Indonesian Sea	699.62	45.7
47	East China Sea	945.56	167.2
48	Yellow Sea	1636.03	98.9
49	Kuroshio Current	405.17	4.6
50	Sea of Japan	588.62	91.8
51	Oyashio Current	699.88	47.5
52	Sea of Okhotsk	801.14	64.4
53	West Bering Sea	670.01	11.9

by Fig. 6c, which suggests that a new offshore fishery emerged in the early 1990s, beyond that which expanded the nearshore fishery in the mid-1950s. Altogether, this means that the mean trophic level in East China Sea LME is declining and that its fisheries are geographically expanding, which is confirmed by the detailed analysis of Liang and Pauly (2017) and Liang et al. (2018). Similar results are obtained for the other Asian LMEs.

3.4. Socio-economic and governance consideration

Capacity-enhancing subsidies (Sumaila et al., 2010) and population expansion by the countries adjacent and/or exploiting the fisheries resources of LMEs will put further pressure on the marine resources in these LMEs. Capacity-enhancing subsidies contribute to half of the total fisheries subsidies in Asian countries; this category of subsidies enhance overcapacity and overfishing by increasing profits (Milazzo, 1998).

Those parts of LMEs that are beyond the EEZs of coastal states are subjected to a management regime that is essentially open-access, notwithstanding the work of Regional Management Organizations (RFMO; Cullis-Suzuki and Pauly, 2010). The parts of LMEs that are under national jurisdiction, i.e. within EEZs, should, in principle, do better as both domestic and foreign fishing can be regulated by the coastal countries. However, it appears that only a few developed countries have be able to fully use the governance tools that EEZs represent to rebuild overfished stocks and generally to mitigate the impact of fishing in their waters, and hence in the LMEs that they belong to.

Detailed description on the fisheries status of each LME are given in the Supplementary information.

4. Discussion

Existing national and international institutions, due to their historic sectoral, local, and national focus, are often not able to report fisheries information (catches, values, and associated indicators) at an ecosystem

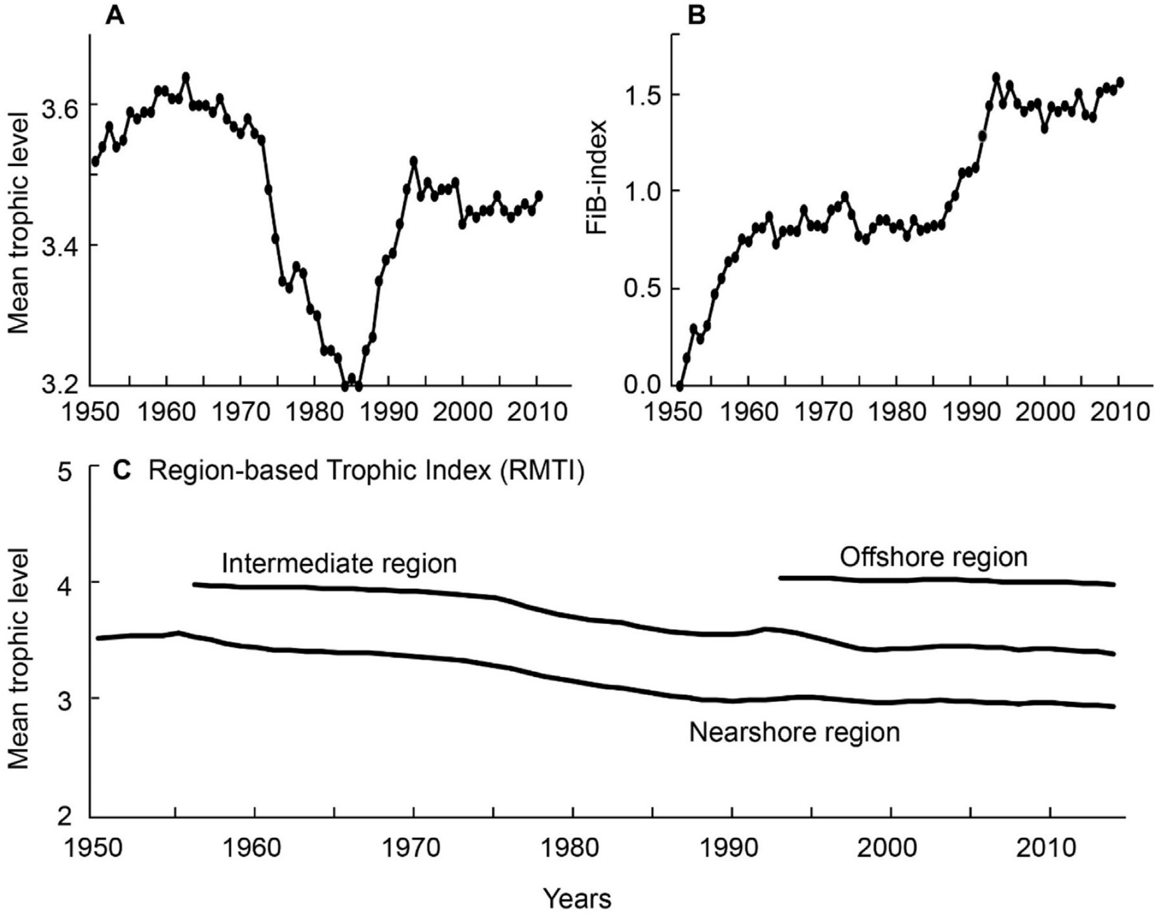

Fig. 6. Major trends in the East China Sea LME, 1950–2014; (a) Marine Trophic Index (MTI); (b) Fishing-in-Balance Index (FiB); and (c) Region-based Trophic Index (RMTI). See text for interpretation.

scale such as LMEs. In contrast, the *Sea Around Us* was specifically established to assess the impacts of fisheries at an ecosystem level. The *Sea Around Us* has therefore developed tools and concepts to present available fisheries data, which via half-degree spatial cells, allows representation of the data at various spatial scales, including that of LMEs.

Many of the national catch reconstructions for Asian countries included catch data associated with high uncertainty, especially for small-scale fisheries. The reporting system of these fisheries is inconsistent to nonexistent, which leads to high uncertainty of the total catch of the Indian Ocean and Pacific Ocean LMEs. The uncertainties of the reconstructed catch are not only limited to the unreported catch, but are also associated with the reported catch in some countries, such as Myanmar, Vietnam, Indonesia and China, which not only reported taxonomically over-aggregated statistics, but exhibited a tendency to exaggerate reported catch (Pauly and Froese, 2012; Pauly and Zeller, 2016b). Clearly, the central governments of these countries need to work closely with the local governments and the FAO to improve the accuracy of their reported data. Also, there is no uncertainty score associated with all the catch amount and the location of large pelagic fishes from the high seas area. Here again, the uncertainties of the reported catch data can be reduced by imposing a more stringent data collection and reporting system in each country to include the catch from small-scale sectors including subsistence and recreational sectors and discards. Also, with the use and increasing accuracy of Automatic Identification System (AIS) data (Natale et al., 2015), the accuracy of the location of the reported catch data is expected to increase.

Since annual catches are used as the primary data for most of the indicators presented (including catch from bottom-impacting gear, value of landings, fish stock status, MTI and FiB Index), the uncertainties associated with the catch statistics will be inherited by these indicators.

The 13 LMEs presented here all suffer from the same problems, i.e. the fleets exploiting their fisheries resources are too large. Based on the indicators presented here and other evidence, they would all benefit from a reduction in their fishing effort and the subsidies governments provide, which would allow stocks they exploit to bounce back. However, a few Asian LMEs including the Gulf of Thailand, South China Sea and East China Sea have very high ecological footprints, suggesting that the marine resources in these LMEs have been heavily overexploited. Although fisheries management needs to reduce the unstainable demand to lower levels in these areas, the various fish population may not be able to rebuild as the ecosystems in which they thrived have been altered. Reduction in fishing pressure is often not enough for the recovery of the depleted stocks because of constraints imposed by several factors including the magnitude of the previous decline, the loss of biodiversity, species life histories, species interactions and climate change (Hutchings and Reynolds, 2004; Worm et al., 2009). Also, the trade-off between the restoration of the marine ecosystems and short-term benefits of the fisheries-dependent communities should be considered when rebuilding the fisheries. Bilateral or multilateral collaboration among bordering countries along the LMEs would be more effective in addressing the overexploitation problem than individual countries acting alone (Heileman et al., 2008a).

These LMEs also do not include any of the large marine reserves which are now understood to be a requirement for the maintenance of marine biodiversity. Therefore, there is a real danger that their biodiversity will be eroded in the next decades, while the role of LMEs in ensuring at least some of the food security and well-being of the people in the countries bordering these 13 LMEs will grow. Clearly, this represents a real challenge at the policy level, because some policy makers will argue that biodiversity has a lower priority than seafood supply.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dsr2.2018.09.002.

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