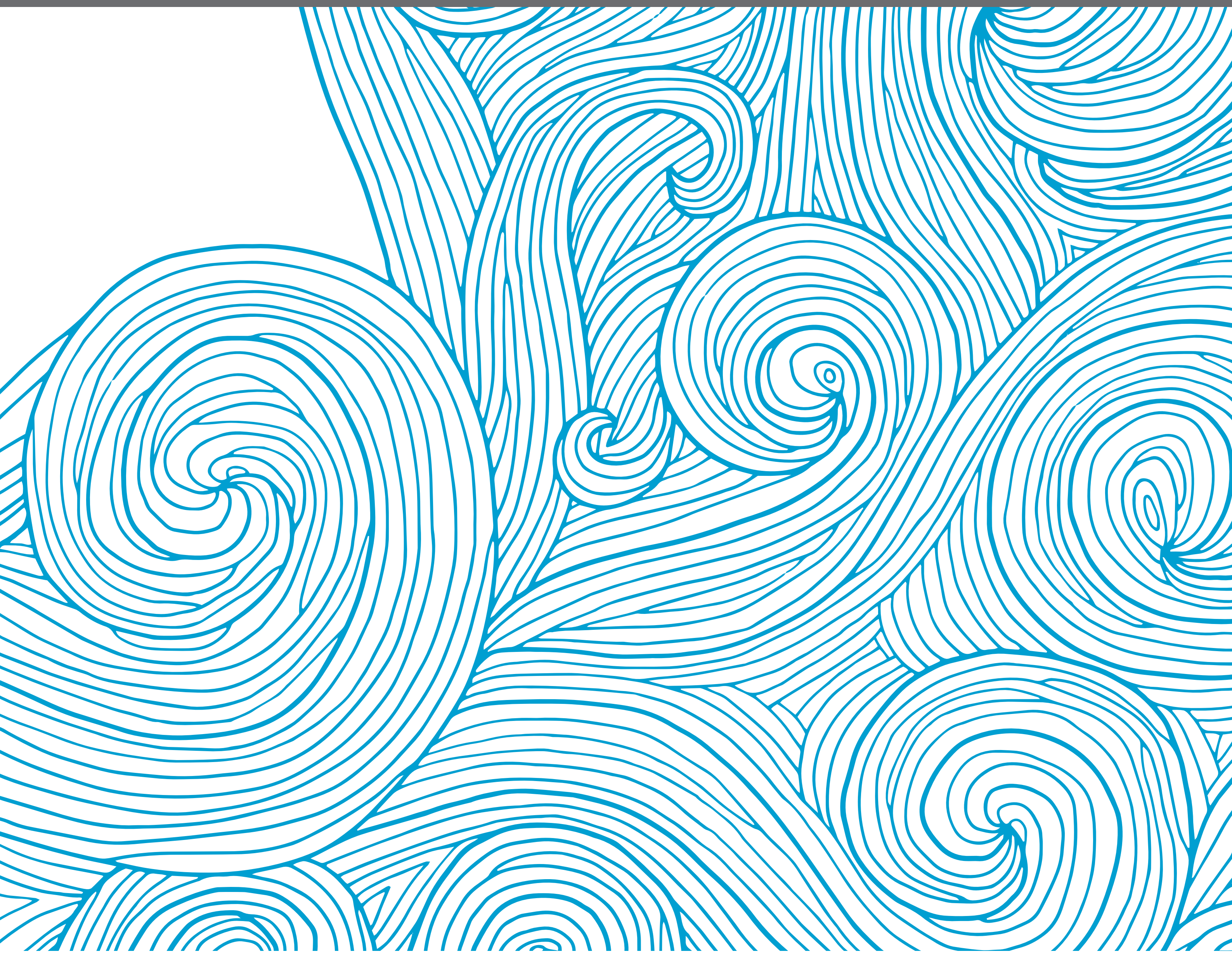
THE STATUS OF MARINE FISHERIES IN EAST ASIA, 东亚地区渔业状况

EDITED BY: Daniel Pauly, Cui Liang and Weiwei Xian

PUBLISHED IN: Frontiers in Marine Science



frontiers Research Topics

Frontiers eBook Copyright Statement

ISSN 1664-8714
ISBN 978-2-88971-915-0
DOI 10.3389/978-2-88971-915-0

About Frontiers

Frontiers is more than just an open-access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

Frontiers Journal Series

The Frontiers Journal Series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the Frontiers Journal Series operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

Dedication to Quality

Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews.
Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view. By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the Frontiers Journals Series: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area! Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers Editorial Office: frontiersin.org/about/contact

THE STATUS OF MARINE FISHERIES IN EAST ASIA, 东亚地区渔业状况

Topic Editors:
Daniel Pauly, Sea Around Us, Institute for the Oceans and Fisheries, University of British Columbia, Canada
Cui Liang (梁翠), Institute of Oceanology, Chinese Academy of Sciences (CAS), China
Weiwei Xian (线薇薇), Institute of Oceanology, Chinese Academy of Sciences (CAS), China

Citation: Pauly, D., Liang, C., Xian, W., eds. (2022). The Status of Marine Fisheries in East Asia, 东亚地区渔业状况. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-88971-915-0

Table of Contents

frontiers in Marine Science

EDITORIAL
published: 25 November 2021
doi: 10.3389/fmars.2021.787217

Editorial: The Status of Marine Fisheries in East Asia

Daniel Pauly[1]*, *Cui Liang*[2,3,4] *and Weiwei Xian*[2,3,4]

[1] Sea Around Us, Institute for the Ocean and Fisheries, University of British Columbia, Vancouver, BC, Canada, [2] CAS Key Laboratory of Marine Ecology and Environmental Sciences, Institute of Oceanology, Chinese Academy of Sciences, Qingdao, China, [3] Laboratory for Marine Ecology and Environmental Science, Qingdao National Laboratory for Marine Science and Technology, Qingdao, China, [4] Center for Ocean Mega-Science, Chinese Academy of Sciences, Qingdao, China

Keywords: stock assessments, catch time-series, length frequency data, China, Korea, Japan

Editorial on the Research Topic

The Status of Marine Fisheries in East Asia

East Asia includes some of the countries with the highest domestic fisheries catch in the world, notably China and Japan. The status of their fisheries matters to the world because these countries also deploy huge fishing fleets into the high seas and the Exclusive Economic Zones of other countries, tasked with compensating for stagnating or even declining local fisheries resources.

Rebuilding East Asian fishery resources is a challenge, however, because their status is often unknown. This situation is due, at least in part, to the fact that time series of data suitable for analysis requiring sophisticated, but data-demanding methods, being scarce or not available in the region.

This dissatisfying state of affairs is now gradually being overcome, notably through the development, by Froese et al. (2017, 2018), of stock assessment methods that require less data, but still produce results that are reliable results enough to inform fisheries management.

These approaches consist of:

(1) the "CMSY/BSM" method (Froese et al., 2017), which relies essentially on time-series of catches—preferably spanning two decades or more—and ancillary data to estimate time series of abundance or "biomass" for the assessed populations or "stocks";
(2) the "LBB' method (Froese et al., 2018), which uses length-frequency samples, i.e., multiple measurements of fish lengths, to infer the status of a fish populations or stocks, and
(3) A reconceptualization of classical yield-per-recruit (Y/R) analysis (Beverton and Holt, 1957) such that can provide estimates of the ratio of current to unexploited biomass.

These methods were introduced to Chinese scientists via a highly successful training course held in Qingdao during June 16–20, 2019. The course was taught by the authors and Dr. M.L. Deng Palomares, with Dr. Rainer Froese participating remotely.

During the course, multiple stock assessments were run which eventually evolved into the bulk of the articles presented here. A few articles that were written previously and/or independently of the course are also included.

Altogether, 161 East Asian marine stocks were assessed, of which 132 pertained to finfishes and 29 to invertebrates, especially squids. Of these, 83 stocks were exploited along the coast of the Chinese Mainland (Liang, Xian, Pauly et al.; Liang, Xian, Liu et al.; Wang, Wang, Liu et al.; Wang X. et al.; Zhai and Pauly(a); Zhai et al.; Zhang L. et al.), 22 from around Taiwan (Ju, Chen et al.; Ju, Tian et al.; Liang Xian, Liu et al.), 50 around Japan (Liang, Xian, Liu et al.; Ren and Liu; Wang, Wang, Liang et al.; Wang, Liang et al.; Zhang S. et al.) and 6 around South Korea (Liang, Xian, Liu et al.).

OPEN ACCESS

Edited and reviewed by:
*Yngvar Olsen,
Norwegian University of Science and Technology, Norway*

****Correspondence:***
*Daniel Pauly
d.pauly@oceans.ubc.ca*

Specialty section:
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

Received: *30 September 2021*
Accepted: *26 October 2021*
Published: *25 November 2021*

Citation:
Pauly D, Liang C and Xian W (2021) Editorial: The Status of Marine Fisheries in East Asia. Front. Mar. Sci. 8:787217. doi: 10.3389/fmars.2021.787217

As is the case for all stock assessment methods, the CMSY/BSM and LBB methods rely on reliable input data, i.e., catch (and catch-per-unit-effort) time series for CMSY/BSM and length-frequency data for LBB. Problematic inputs, and unrealistic constraints ("priors") will lead to biased parameter estimates, and a few of the 161 estimates presented here will be biased up- or downward. However, there is no reason to assume a systematic bias.

Overall, these assessments jointly represent the most comprehensive evaluation of *the Status of Marine Fisheries in East Asia*, and they paint a very sobering picture. Thus, if one gives each stock a similar weight, one can compute from these assessments, for each region, the average biomass (or fish resource abundance) currently remaining as a percentage of its inferred biomass or abundance in the absence of fishing.

These mean percentages are 25% for the Chinese Mainland, 16% for Taiwan, 30% for Japan and 26% for South Korea; all of these averages are well below 50%, the level the classical stock assessment model of Schaefer (1954, 1957) requires for Maximum Sustainable Yield to be generated (Pauly and Froese, 2020). The regional means were derived from several ratio estimates that were higher, i.e., there are stocks in East Asia that are not overfished. However, there were far more stocks that had extremely low values of current to unfished biomass, with the result that the mean ratio for East Asia was 25%.

That overfishing is prevalent in East Asia was previously known (Srinivasan et al., 2012; Li et al., 2017). However, most of these assessments include estimates of the parameters also required to compute the time needed for overfished stocks to recover, given a reduction of fishing pressure (see Demirel et al., 2020). Thus, this makes it possible for fisheries scientists in East Asia to straightforwardly compute fishing quotas allowing for increasing stock sizes by a factor of two in the average, but which would allow for the social cost of a reduction of fishing effort to be smaller than the benefits gained from abundant stocks embedded in functioning ecosystems.

Indeed, at least for the Chinese Mainland, Zhai and Pauly(b) found, based on the conversion of 19 food web models into particle-size distribution spectra, that the functioning of coastal marine ecosystem of East Asia are gradually eroded due to the fisheries-induced disappearance of large fish species and miniaturization of the remaining species.

Thus, rebuilding stocks in East Asia would not only benefit fisheries economically, in terms of their catches, but also re-establish the functioning, rich marine ecosystems that enable fisheries to flourish in the longer term.

东亚地区渔业状况

东亚包括一些世界上国内渔业捕捞量最高的国家,特别是中国和日本。为弥补国内停滞甚至衰退的渔业资源,东亚国家会向公海和其他国家的专属经济区派出庞大的捕捞船队,因此,它们的渔业状况备受世界关注。

重建东亚渔业资源颇具挑战，因为其资源状态往往是未知的。造成这种情况的部分原因在于，复杂的资源评估方法需要大量的时间序列数据，而这种数据在东亚地区通常很少见或不存在。

目前，通过德国渔业学家Rainer Froese及其同事开发的几种数据缺乏条件下的渔业种群评估方法，这种状况正逐渐被改善。这些方法需要较少的渔业数据作为输入，但仍能产生较为可靠的结果来为渔业管理提供参考。

这些方法包括:

(1) "CMSY/BSM"方法(Froese et al., 2017),它主要依赖于渔获量的时间序列（时间跨度最好超过二十年）以及辅助数据来估计被评估种群或群体的丰度或生物量。
(2) "LBB"方法(Froese et al., 2018),该方法使用测量得到的体长频率数据,来推断渔业种群或群体的状态。
(3) 对经典的单位补充量渔获量分析(Beverton and Holt, 1957) 进行概念重建,以估计当前生物量与未开发生物量的比值 。

这些方法通过2019 年 6 月18–20 日在青岛举办的培训课程被介绍给来自多所高校和科研院所的中国渔业学者。该课程主要由Maria Lourdes D. Palomares博士和Daniel Pauly博士教授,Rainer Froese 博士远程参与。在培训课程期间,上述方法被用于东亚地区众多渔业种群或群体的资源评估,并最终形成了本集刊的大部分文章。集刊中另有部分文章独立于本次培训课程,也在后期进行了增补。

本集刊共对161个东亚海洋种群进行了评估,包括132种鱼类,29种无脊椎动物 。在这些被评估的种群中,有83个种群主要在中国大陆沿海被开发(Liang, Xian, Pauly et al.; Liang, Xian, Liu et al.; Wang, Wang, Liu et al.; Zhai and Pauly (a); Zhai et al.; Zhang L. et al.),22个种群主要被台湾地区开发(Ju, Chen et al.; Ju, Xian et al.; Liang, Liu et al.), 分布于日本海域的种群50个(Liang, Xian, Liu et al.; Ren and Liu; Wang, Wang, Liang et al.; Wang, Liang et al.; Zhang S. et al.), 韩国海域6个(Liang, Xian, Liu et al.)。

与所有种群评估方法的情况一样,CMSY/BSM 和LBB 方法依赖于可靠的输入数据,即CMSY/BSM的渔获量（和单位努力量渔获量）时间序列和LBB 的体长频率数据。存疑的输入数据和约束条件（"先验值"）将导致参数估计出现偏差。在这161个评估种群中,会有部分种群的评估结果因输入数据的质量问题被高估或低估,但目前的研究未发现系统性误差的存在。

总体而言,本集刊中的文章共同组成了目前对东亚海洋渔业状况最全面的评估。如果给每个评估种群一个相同的权重,可以从这些评估结果中计算出每个区域当前剩余生物量（或资源丰度）与未开发生物量（或丰度）比值的平均值。中国大陆的平均百分比为25%,台湾为 16%,日本为30%,韩国为26%。所有这些平均值都远低于50%,即Schaefer (1954, 1957) 的经典资源评估模型要求生成最大可持续产量的水平(Pauly and Froese, 2020)。虽然评估结果显示东亚区域有尚未过度捕捞的种群,但由于存在大量剩余生物量与未开发生物量比值极低的种群,因此东亚区域该比值整体为25%左右。

尽管东亚地区普遍存在过度捕捞现象早已被熟知(Srinivasan et al., 2012; Li et al., 2017), 本集刊中的结果还提供了新的信息,例如在捕捞压力降低情况下,用于计算过度捕捞种群恢复时间所需要的参数的估计值(Demirel et al., 2020)。这使得东亚的渔业学家可以计算科学的捕捞配额,从而使种群数量平均增加两倍,增加的种群数量带来的收益将超过减少捕捞压力导致的社会成本损失。

事实上，在将19 个食物网模型转换成粒度分布谱之后，Zhai and Pauly(b) 发现，以中国大陆地区为代表的东亚沿海海洋生态系统的功能正在逐渐被侵蚀，渔业活动引起的大

型鱼类物种的消失和剩余物种的小型化是造成这种现象的主要原因。因此，重建东亚种群不仅会在渔获量方面为渔业带来经济利益，而且还将重建功能健全、物种丰富的海洋生态系统，使渔业能够长期繁荣发展。

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

REFERENCES

Beverton, R. J. H., and Holt, S. J. (1957). *On the dynamics of exploited fish populations. Ministry of Agriculture, Fisheries and Food*. London: Fishery Investigations.

Demirel, N., Zengin, M., and Ulman, A. (2020). First large-scale Eastern Mediterranean and Black Sea stock assessment reveals a dramatic decline. *Front. Mar. Sci.* 7:103. doi: 10.3389/fmars.2020.00103

Froese, R., Demirel, N., Coro, G., Kleisner, K. M., and Winker, H. (2017). Estimating fisheries reference points from catch and resilience. *Fish. Fish.* 18, 506–526. doi: 10.1111/faf.12190

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A. C., Dimarchopoulou, D., et al. (2018). A new approach for estimating stock status from length-frequency data. *ICES J. Mar. Sci.* 75, 2004–2015. doi: 10.1093/icesjms/fsy078

Li, J., Cao, K., Ding, F., Yang, W., Shen, G., and Li, Y. (2017). Changes in trophic-level structure of the main fish species caught by China and their relationship with fishing method. *J. Fish. Sci. China* 24, 109–119. doi: 10.3724/SP.J.1118.2017.16164

Pauly, D., and Froese, R. (2020). MSY needs no epitaph- but it was abused. *ICES J. Mar. Sci.* 78, 2204–2210. doi: 10.1093/icesjms/fsaa224

Schaefer, M. B. (1954). Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Inter Am. Trop. Tuna Comm. Bull.* 1, 23–56.

Schaefer, M. B. (1957). A study of the dynamics of the fishery for yellowfin tuna in the eastern tropical Pacific Ocean. *Inter Am. Trop. Tuna Comm. Bull.* 2, 243–285.

Srinivasan, U. T., Watson, R., and Sumaila, U. R. (2012). Global fisheries losses at the exclusive economic zone level, 1950 to present. *Mar. Policy* 36, 544–549. doi: 10.1016/j.marpol.2011.10.001

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

[CHINESE TRANSLATION] EDITORIAL: 东亚地区渔业状况

东亚包括一些世界上国内渔业捕捞量最高的国家，特别是中国和日本。为弥补国内停滞甚至衰退的渔业资源，东亚国家会向公海和其他国家的专属经济区派出庞大的捕捞船队，因此，它们的渔业状况备受世界关注。

重建东亚渔业资源颇具挑战，因为其资源状态往往是未知的。造成这种情况的部分原因在于，复杂的资源评估方法需要大量的时间序列数据，而这种数据在东亚地区通常很少见或不存在。

但目前，这种状况正逐渐被改善，特别是通过德国渔业学家Rainer Froese及其同事开发的渔业种群评估方法。这些方法需要较少的渔业数据作为输入，但仍能产生较为可靠的结果来为渔业管理提供参考。

这些方法包括：
（1）"CMSY"方法 (Froese et al. 2017)，它主要依赖于渔获量的时间序列（时间跨度最好超过二十年）以及辅助数据来估计被评估种群或群体的丰度或生物量。

（2）"LBB"方法 (Froese et al. 2019)，该方法使用测量得到的体长频率数据，来推断渔业种群或群体的状态。

（3）对经典的单位补充量渔获量分析 (Beverton and Holt 1957) 进行概念重建，以估计当前生物量与未开发生物量的比值。

这些方法通过 2019 年 6 月 18-20 日在青岛举办的培训课程介绍给来自多所高校和科研院所的中国科学家。该课程主要由Maria Lourdes D. Palomares博士和Daniel Pauly博士教授，Rainer Froese 博士远程参与。在培训课程期间，上述方法被用于东亚地区众多渔业种群或群体的资源评估，并最终形成了本集刊的大部分文章。集刊中另有部分文章独立于本次培训课程，也在后期进行了增补。

本集刊共对161个东亚海洋种群进行了评估，包括132种鱼类，29种无脊椎动物。在这些被评估的种群中，有83个种群主要在中国大陆沿海被开发 (Liang et al. 2020a, 2020b; Wang et al. 2020a, 2021; Zhai and Pauly 2019; Zhai et al. 2020; Zhang et al. 2020a)，22个种群主要被台湾地区开发 (Ju et al. 2020a, 2020b; Liang et al. 2020b)，分布于日本海域的种群50个 (Liang et al. 2020b; Ren and Liu 2020; Wang et al. 2020b, 2020c; Zhang et al. 2020b)，韩国海域6个 (Liang et al. 2020b)。

与所有种群评估方法的情况一样，CMSY/BSM 和 LBB 方法依赖于可靠的输入数据，即 CMSY (BSM) 的渔获量（和单位努力量渔获量）时间序列和 LBB 的体长频率数据。存疑的输入数据和约束条件（"先验值"）将导致参数估计出现偏差。在这161个评估种群中，会有部分种群的评估结果因输入数据的质量问题被高估或低估，但目前的研究未发现系统性误差的存在。

总体而言，本集刊中的文章共同组成了目前对东亚海洋渔业状况最全面的评估。如果给每个评估种群一个相同的权重，可以从这些评估结果中计算出每个区域当前剩余生物量（或资源丰度）与未开发生物量（或丰度）比值的平均值。中国大陆的

平均百分比为 25%，台湾为 16%，日本为 30%，韩国为 26%。所有这些平均值都远低于 50%，即Schaefer (1954, 1957) 的经典资源评估模型要求生成最大可持续产量的水平 (Pauly and Froese 2020)。虽然评估结果显示东亚区域有尚未过度捕捞的种群，但由于存在大量剩余生物量与未开发生物量比值极低的种群，因此东亚区域该比值整体为25%左右。

尽管东亚地区普遍存在过度捕捞现象早已被熟知 (Srinivasan et al. 2012; Li et al. 2017)，但本集刊中的结果还提供了新的信息，例如在捕捞压力降低情况下，用于计算过度捕捞种群恢复时间所需要的参数的估计值 (Demirel et al. 2020)。这使得东亚的渔业学家可以计算科学的捕捞配额，从而使种群数量平均增加两倍，增加的种群数量带来的收益将超过减少捕捞压力导致的社会成本损失。

事实上，在将19 个食物网模型转换成粒度分布谱之后，Zhai and Pauly (2020) 发现，以中国大陆地区为代表的东亚沿海海洋生态系统的功能正在逐渐被侵蚀，渔业活动引起的大型鱼类物种的消失和剩余物种的小型化是造成这种现象的主要原因。因此，重建东亚种群不仅会在渔获量方面为渔业带来经济利益，而且还将重建功能健全、物种丰富的海洋生态系统，使渔业能够长期繁荣发展。

REFERENCES

Beverton, R. J. H., and Holt, S. J. (1957). On the dynamics of exploited fish populations. Ministry of Agriculture, Fisheries and Food. Fishery Investigations, London, Series II, XIX. 533 p.

Demirel, N., Zengin, M., and Ulman, A. (2020). First large-scale Eastern Mediterranean and Black Sea stock assessment reveals a dramatic decline. Front. Mar. Sci. 7: 103. doi: 10.3389/fmars.2020.00103.

Froese, R., Demirel, N., Coro, G., Kleisner, K. M., and Winker, H. (2017). Estimating fisheries reference points from catch and resilience. Fish Fish 18, 506-526.

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A.C., Dimarchopoulou, D., et al. (2018). A new approach for estimating stock status from length-frequency data. ICES J. Mar. Sci. 75, 2004-2015. doi: 10.1093/icesjms/fsy078.

Li, J., Cao, K., Ding, F., Yang, W., Shen, G., and Li, Y. (2017). Changes in trophic-level structure of the main fish species caught by China and their relationship with fishing method. J. Fish. Sci. China 24(1), 109-119.

Pauly, D., and Froese, R. (2020). MSY needs no epitaph- but it was abused. ICES J. Mar. Sci. doi:10.1093/icesjms/fsaa224.

Schaefer, M. B. (1957). A study of the dynamics of the fishery for yellowfin tuna in the eastern tropical Pacific Ocean. Inter-Am. Trop. Tuna Comm., Bull. 2, 243-285.

Schaefer, M. B. (1954). Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. Inter-Am. Trop. Tuna Comm., Bull. 1, 23-56.

Srinivasan, U. T., Watson, R., Sumaila, U. R. (2012). Global fisheries losses at the exclusive economic zone level, 1950 to present. Mar Policy 36, 544-549.

frontiers in Marine Science

ORIGINAL RESEARCH
published: 26 November 2019
doi: 10.3389/fmars.2019.00724

Yield-per-Recruit, Utility-per-Recruit, and Relative Biomass of 21 Exploited Fish Species in China's Coastal Seas

Lu Zhai[1]* and Daniel Pauly[2]

[1] Fisheries College, Ocean University of China, Qingdao, China, [2] Sea Around Us, Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, BC, Canada

OPEN ACCESS

Edited by:
Simone Libralato, Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Italy

Reviewed by:
Claudio Vasapollo, Italian National Research Council (CNR), Italy
Brett W. Molony, Oceans and Atmosphere, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia

***Correspondence:**
Lu Zhai
zhailu0708@hotmail.com

Specialty section:
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

Received: 09 August 2019
Accepted: 08 November 2019
Published: 26 November 2019

Citation:
Zhai L and Pauly D (2019) Yield-per-Recruit, Utility-per-Recruit, and Relative Biomass of 21 Exploited Fish Species in China's Coastal Seas. Front. Mar. Sci. 6:724. doi: 10.3389/fmars.2019.00724

Based on growth and related fishery parameters, three approaches, yield-per-recruit (*Y/R*), utility-per-recruit (*U/R*) analyses, and relative biomass (B/B_0) analyses were applied to 21 economically important, trawl-caught species in China's coastal seas to estimate their relative yield, economic value and biomass under different schedules of fishing mortality and mean length at first capture. The results show that all species suffer from overfishing, given the high average fishing mortality ($F \sim 1$ year^{-1}) and small mesh size (~1 cm) used by trawlers. Long-term *Y/R* would double and *U/R* (expressed as price per landed weight) would increase 5-fold if mesh size were increased to about 10 cm. Comparing *Y/R* and *U/R* showed that the benefits of higher prices for larger individuals were detectable only if larger mesh sizes are used, so that individuals are caught only after they have been able to grow. The *Y/R* analyses also allowed estimating the biomass of the 21 assessed populations relative to their unexploited biomass, i.e., B/B_0. Species-specific B/B_0 values ranged from 0.01 to 0.58, with a mean of 0.16 (±0.03), i.e., much lower than the 50% reduction corresponding to Maximum Sustainable Yield (i.e., $B/B_{MSY} = 1$, or $B/B_0 = 0.5$). This confirms the many authors who reported systematic overfishing along China's coastlines, and suggests that rebuilding stocks should be the foremost goal of fisheries management in China.

Keywords: data-poor fisheries, Chinese coastal fisheries, yield per recruit, utility per recruit, biomass estimation, stock assessments

INTRODUCTION

According to statistics of the Food and Agriculture Organization of the United Nations (FAO, 2016), the People's Republic of China (hereafter referred to as "China"), was the top-ranking fishing country in the world with domestic marine catches of about 10 million t in the 2010s (www.fao.org and www.seaaroundus.org).

As part of its Thirteenth Five-Year Plan (2016–2020), China listed the need for improvement of its fishery management systems. Several policies aiming at stabilizing fisheries catches have been proposed, but their implementation has not necessarily been successful. Notably, many of the economic benefits that the policies we supposed to generate have failed to materialize.

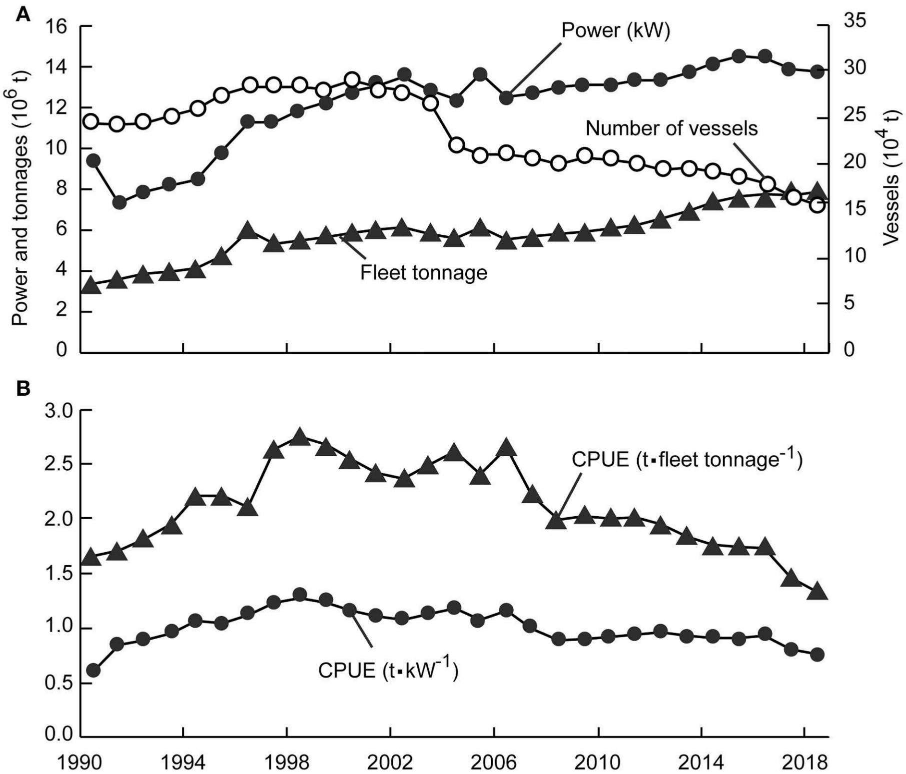


FIGURE 1 | Basic statistics on China's coastal fisheries (1990–2018). **(A)** Three proxies of fishing effort; **(B)** Two measures of catch per unit of effort (CPUE).

One of the most important management measures, the "Double Control" system, was proposed in the early 1990s to regulate fisheries by controlling the number of engine-powered fishing vessels and the cumulative power of the fleet (Shen and Heino, 2014). However, despite a decrease in the number of fishing vessels since 2004, cumulative fleet engine power and tonnages have increased (Anonymous, 1979–2019; **Figure 1A**), and CPUE and total catch continued decreases that began in 1998 (Shen and Heino, 2014; **Figure 1B**).

Mesh size studies in China's coastal have been conducted since 1980s (Ye et al., 1980; Li, 1990); however, the implementation of mesh regulation was initiated only in 2013 (Anonymous, 2013). The regulations allow mesh size ranging from 2.5 to 11 cm for different gear types and species. However, the average mesh size of commercial fishing in practice of China is 1 cm, far less than it legally allowed (Liang and Pauly, 2017a).

As a result, fish are caught that are extremely small and thus are considered "trash fish" and end up as fish feed, either directly, or after reduction to low-value fish meal (Cao et al., 2015). Moreover, the proportion of "trash fish" in the total catches appears to be steadily increasing (Lin et al., 2007), and currently contributes near 4×10^6 t annually (Greenpeace, 2017).

Historically, larger species were dominant in China's coastal seas, and were economically important. This applies *Larimichtyys polyactis* and *Trichiurus lepturus*, whose annual yield was more than 100,000 t, and for *Scomberomorus niphonius* and *Scomber japonicus*, which contributed over 10,000 t annually (Zhang and Liu, 1959). However, under intensive, decade-long fishing pressure, these dominant stocks were replaced by small, low-trophic level species, such as *Engraulis japonicus*, *Setipinna tenuifilis*, *Pholis fangi*, and *Chaeturichthys stigmatias* (Wang et al., 2011; Zhai et al., 2015), inducing a fishing down effect that is now well-documented (Liang and Pauly, 2017b). The degree of overfishing and the economic waste that this implies are key problems for China's fisheries.

Therefore, yield- and utility-per-recruit approaches were applied to 21 species commercially exploited along China's coast, which allowed a combination of fisheries biology and bio-economics to assess the extent of the reduction if their biomass by fishing, and their optimum exploitation levels terms of both yield and value. The ultimate goal of this contribution was to produce evidence required for a review of present policies for fisheries management.

MATERIALS AND METHODS

Methods and Data Sources

We performed utility-per-recruit assessments, which allows consideration of different values per length or age group to be used in a yield-per-recruit context (Die et al., 1988), and hence allows the introduction of simple bio-economics into stock

TABLE 1 | Parameters used for assessing 14 species in China's coastal seas (*a* refers to weight in g; *K* in year^{-1}; L_{inf} and TL_{inf} in cm; *T* in °C).

Species	Survey location	Survey time	*a*	*b*	*K*	t_0	L_{inf}	TL_{inf}	*T*	References
Yellow croaker (*Larimichthys polyactis*)	Liaodong Bay	2012–2013	0.012	3	0.47	−0.30	26.00	29.64	13.80	Liu et al., 2018
Largehead hairtail (*Trichiurus lepturus*)	Bohai Sea and Yellow Sea	1962–1963	0.013	3	0.44	−0.06	50.10	172.91	15.00	Hong, 1980; *T* from (www.fishbase.org)
Fang's gunnel (*Pholis fangi*)	Qingdao coastal water	2008	0.005	3	0.63	−0.63	19.00	20.42	14.50	Huang, 2010
Whitespotted conger (*Conger myriaster*)	Shandong coastal waters	2015–2016	0.002	3	0.60	−0.49	92.80	92.80	15.00	Zhang, 2018; *T* from (www.fishbase.org)
So-iuy mullet (*Planiliza haematocheila*)	Bohai Sea		0.016	3	0.11	−0.82	121.20	124.23	12.47	Geng et al., 2001; *T* from Lin et al., 2001
Red tonguesole (*Cynoglossus joyneri*)	Southern Sea of Korea	2001	0.005	3	0.19	−2.40	28.43	29.06	16.51	Baech and Huh, 2004; *T* from (www.nifs.go.kr/)
Japanese Spanish mackerel (*Scomberomorus niphonius*)	Coastal waters of Shandong Province	2015–2016	0.010	3	0.52	−0.10	76.20	91.69	12.47	Zhang, 2018; *T* from Lin et al., 2001
Bastard halibut (*Paralichthys olivaceus*)	Jiaozhou Bay, Bohai Sea	1980–1986	0.016	3	0.21	−0.10	79.66	101.63	15.00	Zhu et al., 1991; *T* (www.fishbase.org)
Korean rockfish (*Sebastes schlegelii*)	Zhangzidao Artificial Reef, near Dalian	2011–2012	0.025	3	0.21	−0.65	41.25	50.55	20.00	Yin et al., 2016
Silver pomfret (*Pampus argenteus*)	Bohai Sea	2007	0.030	3	0.44	−1.01	26.79	32.80	15.00	Cui et al., 2008; *T* from (www.fishbase.org)
Pointhead flounder (*Cleisthenes herzensteini*)	Bohai, Yellow and East China Seas	1978–1985	0.013	3	0.11	−1.29	47.30	53.70	16.00	Chen et al., 1992; *T* from (www.fishbase.org)
Chub mackerel (*Scomber japonicus*)	Coastal waters of Shandong Province	2015–2016	0.017	3	0.22	−0.12	41.02	44.50	12.47	Zhang, 2018; *T* from Lin et al., 2001
Yellow goosefish (*Lophius litulon*)	Bohai and Yellow Seas	2010, 2013–2014	0.028	3	0.28	−0.44	57.64	66.55	20.00	Yin et al., 2015
Blackhead seabream (*Acanthopagrus schlegelii*)	Taiwan and northern South China Sea	2011–2012	0.033	3	0.22	−1.59	43.70	50.98	22.25	Chu et al., 2011; Law and Sadovy de Mitcheson, 2018

TABLE 2 | Parameters used to estimate relative biomass (B/B_0) for seven fish species in China's coastal seas[a].

Common name	Scientific name	*K* (year^{-1})	*M* (year^{-1})	*F* (year^{-1})	L_c/L_{inf}	L_{inf} (cm)
Pacific rudderfish	*Psenopsis anomala*	0.41	0.85	0.98	0.08	21.94
Japanese grenadier anchovy	*Coilia nasus*	0.35	0.68	0.70	0.22	37.61
Osbeck's grenadier anchovy	*Coilia mystus*	0.54	1.12	0.88	0.28	21.31
Japanese anchovy	*Engraulis japonicus*	0.51	1.00	0.93	0.24	15.73
Scaly hairfin anchovy	*Setipinna tenuifilis*	0.31	0.70	0.60	0.12	18.60
Japanese scad	*Decapterus marusadsi*	0.89	1.45	0.44	0.22	27.71
Bombay-duck	*Harpadon nehereus*	0.62	1.12	1.12	0.15	31.32

[a]*From* Liang and Pauly (2017a).

assessments. Here, the values considered were simply the market price per kilogram of the fish in question, which tended to sharply increase with size.

Also, relative biomass (B/B_0) was estimated using a new set of equations, based on Beverton and Holt (1966), and derived by Froese et al. (2018). This method allows estimating B/B_0 under different levels of fishing mortality and L_c values, using the same parameters as for yield-per-recruit analyses, i.e., von Bertalanffy growth parameters (L_{inf}, K), natural mortality (M) and a and b from length-weight relationships (Froese et al., 2018).

Growth parameters can change over time, both because of fishing itself, which removes large individuals and gradually reduce the alleles associated with large sizes in an exploited population (Dieckmann et al., 2005; Enberg et al., 2012), and via ocean warming which will tend to modify growth parameter in the same direction as fishing itself (Cheung et al., 2013). However, these changes are much smaller than the rapid population truncation and size reduction that are due to removal of large individuals by intense fishing, and which are reflected in Y/R and related analyses.

A total of 21 species were analyzed in this paper. The growth parameters (a, b, K, L_{inf}, and t_0) of 14 fish species were assembled (**Table 1**) from the scientific literature and from FishBase (www.fishbase.org) to serve as basis for the 3 approaches

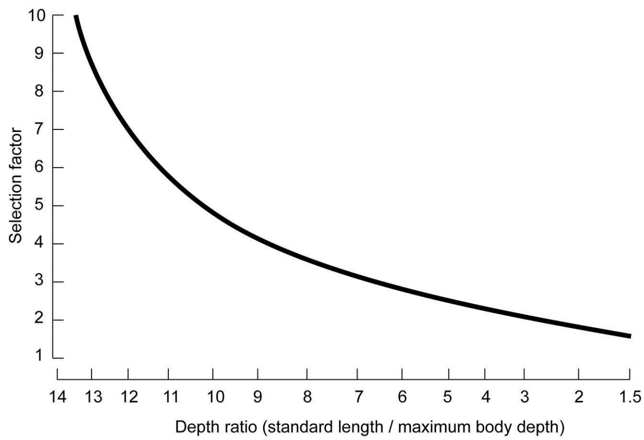


FIGURE 2 | Nomogram for the estimation of selection factors of fishes from their body proportion (modified from Pauly, 1983).

mentioned above. To facilitate computations and between-method comparisons, the multiplicative term in all length-weight relationship ("*a*") where recalculated such that the exponent ("*b*") could be set at a value = 3. Given the cube law (Froese, 2006), $b = 3$ is a good approximation, and deviation from this will have only a negligible impact on the results. For the other 7 species (**Table 2**), *Y/R* analyses had already been performed (by Liang and Pauly, 2017a); thus, Equations (12)–(15) were used to convert the results of their *Y/R* estimates into estimates of B/B_{MSY} and B/B_0, so that they could also be included in overall evaluation of the status of Chinese fisheries (in **Table 7**).

Fish and Fishery Parameters

Fish growth parameters commonly estimated by the von Bertalanffy Growth Function (VBGF; von Bertalanffy, 1934, 1938), as presented by Beverton and Holt (1957), i.e.,

$$L_t = L_{inf}\left(1 - e^{-K(t-t_0)}\right) \quad (1)$$

where L_t is the mean length at age t of the fish in question, L_{inf} is their asymptotic length, i.e., the mean length attained after an infinitely long time, K is a growth coefficient (here in year^{-1}) and t_o is the (usually negative) age the fish in question would have had at a length of zero if they had always grown in the manner predicted by the equation (which they have not; see e.g., Pauly, 1998).

Following Geng et al. (2018) who recommended its use for assessments in China, the empirical formula of Pauly (1980) was used to estimate natural mortality (M), i.e.,

$$\log M = -0.0066 - 0.279 \log L_{inf} + 0.6543 \log K + 0.4634 \log T \quad (2)$$

where L_{inf} (in cm) and K are as defined for Equation (1) and T is the annual average water temperature (in °C) of the habitat for each species analyzed here (**Table 1**).

As Equation (2) requires L_{inf} values as total length (TL), conversion from standard length (SL), fork length (FL), and vent length (VT, for *T. lepturus*) were performed as required based on drawings or photos of the species in question in FishBase (www.fishbase.org).

The mean length at first capture (L_c in cm), i.e., the length at which 50% of fish will be retained in the gear, was estimated for all species from

$$L_c = S.F. \times mesh\ size \quad (3)$$

wherein *S.F.* is the selection factor of the gear, largely determined by the shape of the fish body.

S.F. estimates were derived from a simplified version of the nomogram constructed by Pauly (1983) on the basis of a large number of mesh selection experiments (**Figure 2**). Here, we applied the depth ratios from images in FishBase (www.fishbase.org).

As about 50% of all catches in the Chinese coastal fisheries are actually made by trawlers, and the rest is taken by nets also designed to retain large fish when they are caught (see China's successive *Fishery Statistical Yearbooks*, 1979–2019), it is assumed that all nets in question have trawl-like selection curves. Thus, Equation (3), Pauly's (1983) nomogram were applied here to infer mean length at first capture for the 14 species in **Table 1**.

As we could not find estimates from China, the growth parameters for red tonguesole (*Cynoglossus joyneri*) are from South Korean waters (Baech and Huh, 2004), i.e., from the same latitude as China's Yellow Sea, to which South Korean waters are adjacent. As temperature is the major factor behind differences in the growth parameters of wild fish (Pauly, 2010), and temperature varies mainly with latitude, it is considered that the effect of this substitution is negligible.

Estimation of Yield-per-Recruit (*Y′/R*)

The original equations derived by Beverton and Holt (1957) allowed the computation of absolute yield-per-recruit (*Y/R*, typically in g·year^{-1}). However, subsequent consideration by Beverton and Holt (1966) allow a for a simplified approach, based on relative yield-per-recruit (Y'/R), i.e.,

$$Y'/R = EU^{M/K}\left\{1 - \frac{3U}{(1+m)} + \frac{3U^2}{(1+2m)} - \frac{U^3}{(1+3m)}\right\} \quad (4)$$

where $E = F/Z, Z = F + M$;

$$U = 1 - (L_C/L_\infty);$$
$$m = (1-E)/(M/K) = K/Z$$

where E is the exploitation rate, F is the fishing mortality, Z is the total mortality and the other parameters are defined as same as above (Equations 2, 3).

The relationship between Y/R and Y'/R, is

$$Y/R = (Y'/R)\left(W_{inf}\ e^{-M(t_r-t_0)}\right) \quad (5)$$

where M and t_0 is the same definition with Equations (2) and (1), respectively, W_{inf} is the asymptotic fish weight (corresponding to L_{inf}), and t_r is age at recruitment to the stock in question.

TABLE 3 | Fish price for different length class in China's aquatic products market.

Species		Group 1	Group 2	Group 3	Group 4	Group 5
Yellow croaker (*Larimichthys polyactis*)	Length group	≤10	10 < L ≤ 20	>20		
	Price	25	35	45		
Largehead hairtail (*Trichiurus lepturus*)	Length group	≤15	15 < L ≤ 25	25 < L ≤ 35	35 < L ≤ 45	>45
	Price	55	160		200	
Fang's gunnel (*Pholis fangi*)	Length group	≤10	10 < L ≤ 15	>15		
	Price	40	50	80		
Whitespotted conger (*Conger myriaster*)	Length group	≤20	20 < L ≤ 40	40 < L ≤ 60	60 < L ≤ 80	>80
	Price	30	40	60	80	100
So-iuy mullet (*Planiliza haematocheila*)	Length group	≤40	40 < L ≤ 60	60 < L ≤ 80	80 < L ≤ 100	>100
	Price	40	60	80	100	120
Red tonguesole (*Cynoglossus joyneri*)	Length group	≤5	5 < L ≤ 15	15 < L ≤ 25	>25	
	Price	20	40	60	200	
Japanese Spanish mackerel (*Scomberomorus niphonius*)	Length group	≤30	30 < L ≤ 50	50 < L ≤ 70	>70	
	Price	30	40	50	80	
Bastard halibut (*Paralichthys olivaceus*)	Length group	≤20	20 < L ≤ 40	40 < L ≤ 60	>60	
	Price	40	60	80	100	
Korean rockfish (*Sebastes schlegelii*)	Length group	≤10	10 < L ≤ 20	20 < L ≤ 35	>35	
	Price	20	30	80	120	
Silver pomfret (*Pampus argenteus*)	Length group	≤10	10 < L ≤ 15	15 < L ≤ 20	>20	
	Price	30	40	80	160	
Pointhead flounder (*Cleisthenes herzensteini*)	Length group	≤15	15 < L ≤ 25	25 < L ≤ 35	>35	
	Price	60	70	100	150	
Chub mackerel (*Scomber japonicus*)	Length group	≤10	10 < L ≤ 25	25 < L ≤ 35	>35	
	Price	10	24	45	60	
Yellow goosefish (*Lophius litulon*)	Length group	≤15	15 < L ≤ 30	30 < L ≤ 45	>45	
	Price	8	10	14	24	
Blackhead seabream (*Acanthopagrus schlegelii*)	Length group	≤15	15 < L ≤ 25	25 < L ≤ 35	>35	
	Price	40	50	60	80	

Length in cm; price in Yuan/Kg, Yuan is Chinese RMB. Based on survey in Chinese market (2019).

TABLE 4 | Estimates of mortality, mean length at first capture and derived parameters in 14 species of fish exploited along Chinese coasts (M and Z in year^{-1}; L_c in cm)[a].

Common name	Scientific name	*M*	*Z*	*E*	Depth ratio	*S.F.*	L_c	L_c/L_{inf}
Yellow croaker	*Larimichthys polyactis*	0.79	1.79	0.56	3.50	2.30	2.30	0.13
Largehead hairtail	*Trichiurus lepturus*	0.48	1.48	0.68	15.67	10.00	10.00	0.20
Fang's gunnel	*Pholis fangi*	0.92	1.92	0.52	8.94	4.25	4.25	0.27
Whitespotted conger	*Conger myriaster*	0.70	1.70	0.59	20.14	10.00	10.00	0.25
So-iuy mullet	*Planiliza haematocheila*	0.19	1.19	0.84	5.33	2.80	2.80	0.08
Red tonguesole	*Cynoglossus joyneri*	0.48	1.48	0.68	3.89	2.40	2.40	0.37
Japanese Spanish mackerel	*Scomberomorus niphonius*	0.59	1.59	0.63	5.54	2.75	2.75	0.05
Bastard halibut	*Paralichthys olivaceus*	0.35	1.35	0.74	2.60	2.15	2.15	0.03
Korean rockfish	*Sebastes schlegelii*	0.48	1.48	0.68	2.89	2.25	2.25	0.13
Silver pomfret	*Pampus argenteus*	0.76	1.76	0.57	1.81	2.10	2.10	0.36
Pointhead flounder	*Cleisthenes herzensteini*	0.28	1.28	0.78	2.78	2.20	2.20	0.13
Chub mackerel	*Scomber japonicus*	0.41	1.41	0.71	4.40	2.51	2.51	0.06
Yellow goosefish	*Lophius litulon*	0.53	1.53	0.65	1.93	1.86	1.86	0.12
Blackhead seabream	*Acanthopagrus schlegelii*	0.51	1.51	0.66	2.27	2.05	2.05	0.30
Means[b]	–	0.53 ± 0.05	1.53 ± 0.05	0.66 ± 0.02	–	–	3.54 ± 0.75	0.18 ± 0.03

[a] *The depth ratios are based on drawings in FishBase (www.fishbase.org); the selection factors (S.F.) were obtained from the nomogram (**Figure 2**); the current F (1 year^{-1}) and mesh size (1 cm) are based on Liang and Pauly (2017a).*
[b] *Means with standard error.*

TABLE 5A | Current and optimum yield-per-recruit and mean first capture length of 14 species in China's coastal seas.

Common name	Scientific name	Current level		Optimum level			
		L_c (cm)	Y'/R	Opt. L_c (cm)	Opt. Y'/R	Mesh size (cm)	Increase (%)
Yellow croaker	*Larimichthys polyactis*	3.4	0.024	13.5	0.041	5.9	71
Largehead hairtail	*Trichiurus lepturus*	10.0	0.078	28.1	0.102	2.8	31
Fang's gunnel	*Pholis fangi*	5.0	0.027	9.1	0.033	2.1	22
Whitespotted conger	*Conger myriaster*	23.6	0.052	55.7	0.074	5.6	42
So-iuy mullet	*Planiliza haematocheila*	10.1	0.006	72.7	0.044	26.0	633
Red tonguesole	*Cynoglossus joyneri*	10.4	0.020	13.4	0.021	5.6	5
Japanese Spanish mackerel	*Scomberomorus niphonius*	3.9	0.033	46.5	0.079	16.9	139
Bastard halibut	*Paralichthys olivaceus*	2.2	0.009	46.2	0.046	21.5	411
Korean rockfish	*Sebastes schlegelii*	5.3	0.010	20.2	0.025	9.0	150
Silver pomfret	*Pampus argenteus*	9.6	0.035	13.9	0.039	6.6	11
Pointhead flounder	*Cleisthenes herzensteini*	6.3	0.006	23.2	0.020	10.5	233
Chub mackerel	*Scomber japonicus*	2.5	0.010	22.6	0.037	9.0	270
Yellow goosefish	*Lophius litulon*	6.7	0.015	30.6	0.035	16.5	133
Blackhead seabream	*Acanthopagrus schlegelii*	12.9	0.019	21.4	0.025	10.4	32
Means[a]	–	–	0.016 ± 0.005	–	0.037 ± 0.006	10.6 ± 1.9	128 ± 48.4

[a] *Means with standard error.*

TABLE 5B | Current and optimum utility-per-recruit and mean length at first capture of 14 species in China's coastal seas (L_c and mesh size in cm; U/R in Yuan).

Common name	Scientific name	Current level		Optimum level			Increase (%)
		L_c	U/R	Opt. L_c	Opt. U/R	Mesh size	
Yellow croaker	*Larimichthys polyactis*	3.4	260	14.0	490	6.1	89
Largehead hairtail	*Trichiurus lepturus*	10.0	13,957	34.6	35,015	3.5	151
Fang's gunnel	*Pholis fangi*	5.0	39	9.1	47	2.1	21
Whitespotted conger	*Conger myriaster*	23.6	5,549	59.4	9,862	5.9	78
So-iuy mullet	*Planiliza haematocheila*	10.1	7,451	78.8	128,582	28.1	1,626
Red tonguesole	*Cynoglossus joyneri*	10.4	107	14.8	150	6.2	40
Japanese Spanish mackerel	*Scomberomorus niphonius*	3.9	6,432	49.5	18,169	18.0	182
Bastard halibut	*Paralichthys olivaceus*	2.2	4,562	47.0	31,637	21.9	593
Korean rockfish	*Sebastes schlegelii*	5.3	763	37.1	3,757	16.5	392
Silver pomfret	*Pampus argenteus*	9.6	1,442	19.6	2,681	9.3	86
Pointhead flounder	*Cleisthenes herzensteini*	6.3	573	24.6	3,115	11.2	444
Chub mackerel	*Scomber japonicus*	2.5	281	24.7	2,023	9.8	620
Yellow goosefish	*Lophius litulon*	6.7	927	31.1	2,862	16.8	209
Blackhead seabream	*Acanthopagrus schlegelii*	12.9	2,830	24.5	4,079	11.9	44
Means[a]	–	–	3,227 ± 1,073	–	17,319 ± 9,093	12.0 ± 2.0	437 ± 113.9

[a] *Means with standard error.*

The Estimation of Utility-per-Recruit (*U/R*)

The utility of length class i for each species was computed from the Equations (6)–(11) by (Thompson and Bell, 1934):

$$V_i = Y_i\, v_i \tag{6}$$

where Y_i is the yield for class i, v_i is the unit value (or "price") for class i, and Y_i was obtained from

$$Y_i = C_i\, W_i \tag{7}$$

where the mean body weight in a class, computed by

$$\overline{W}_i = \left(\frac{1}{L_{i+1} - L_i}\right)\left(\frac{a}{b+1}\right)\left(L_{i+1}^{b+1} - L_i^{b+1}\right) \tag{8}$$

and where the parameter of a and b are the coefficients of the length-weight relationship and L_i and L_{i+1} are the lower limit and the upper limit of the length class i, respectively (Beyer, 1987).

C_i was obtained from:

$$C_i = (N_i - N_{i+1})\,(F_i/(M + F_i)) \tag{9}$$

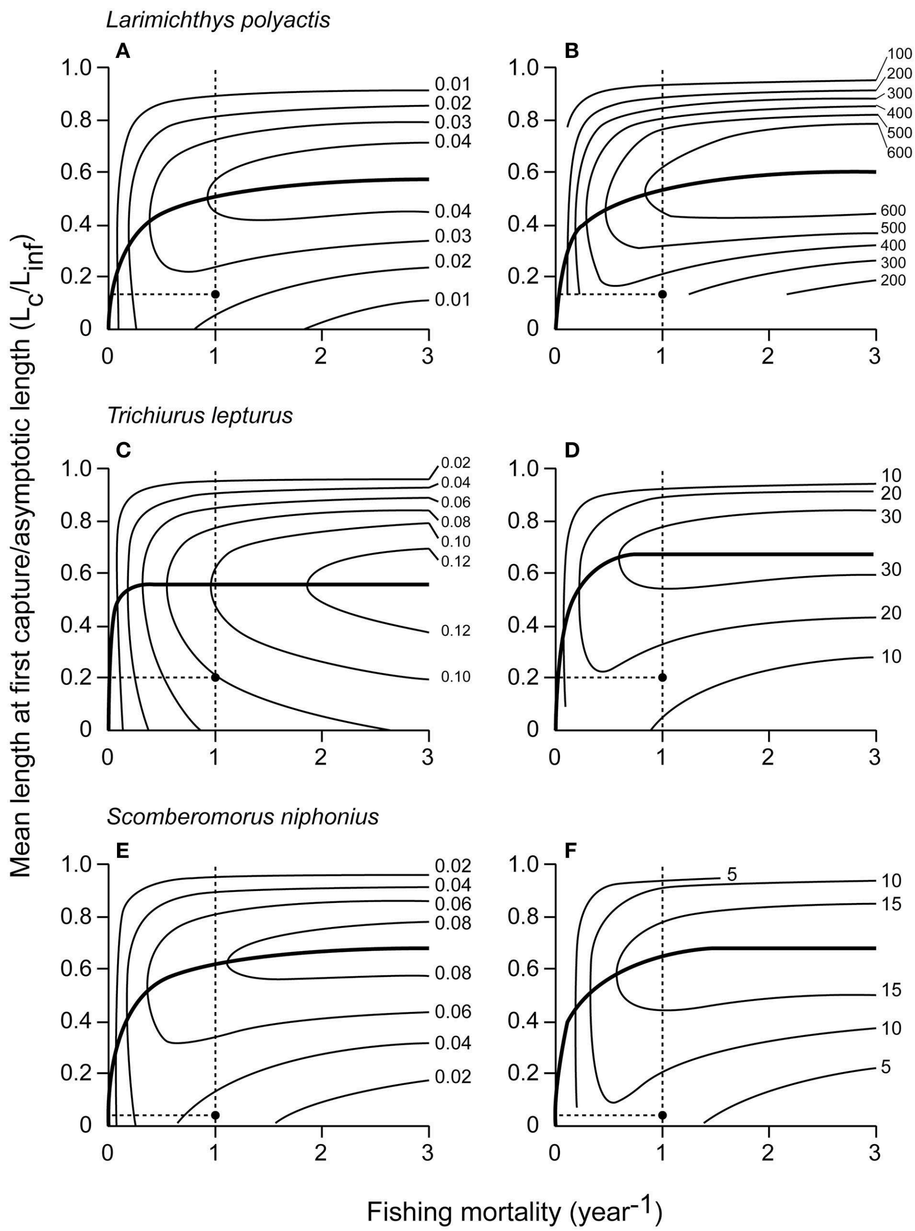


FIGURE 3 | Assessments of 3 fish species from Chinese coastal waters: *Y′/R* (left) and *U/R* (right) isopleth diagrams vs. fishing mortality and L_c/L_{inf}. The solid curves connect optimum sizes for different every level of fishing mortality and the black dots and dotted lines show the current status of the fishery status in level. U/R for *L. polyactis* is in Yuan, and in 1,000 Yuan for *T. lepturus* and *S. niphonius*. **(A)** *L. polyactis Y′/R* vs. fishing mortality and L_c/L_{inf}. **(B)** *L. polyactis* U/R vs. fishing mortality and L_c/L_{inf}. **(C)** *T. lepturus Y′/R* vs. fishing mortality and L_c/L_{inf}. **(D)** *T. lepturus* U/R vs. fishing mortality and L_c/L_{inf}. **(E)** *S. niphonius Y′/R* vs. fishing mortality and L_c/L_{inf}. **(F)** *S. niphonius* U/R vs. fishing mortality and L_c/L_{inf}.

where N_i is the cohort strength, as predicted by:

$$N_{i+1} = N_i\, e^{(-(M+F_i)\cdot\Delta t_i)} \tag{10}$$

and

$$\Delta t_i = (1/K)\ln\left(\left(L_{inf} - L_i\right)/\left(L_{inf} - L_{i+1}\right)\right) \tag{11}$$

where Δt_i is the elapsed time from L_i to L_{i+1}.

Herein, the length class are $0.01{\cdot}L_{inf}$, i.e., the computations involved 100 classes, and the market prices for the different length class of fish are given in **Table 3**.

The Estimation of Relative Biomass

Relative yield-per-recruit (Y'/R), as estimated by Equation (4), also can be expressed by (Froese et al., 2018)

$$Y'/R = \frac{F/M}{1+F/M}\left(1-\frac{L_c}{L_{inf}}\right)^{\frac{M}{K}}\left(1-\frac{3\left(1-L_c/L_{inf}\right)}{1+\frac{1}{M/K+F/K}} + \frac{3\left(1-L_c/L_{inf}\right)^2}{1+\frac{2}{M/K+F/K}} - \frac{\left(1-L_c/L_{inf}\right)^3}{1+\frac{3}{M/K+F/K}}\right) \tag{12}$$

TABLE 6 | Ratio of *U/R* vs. *Y/R* (i.e., *U/Y*, in Yuan) for 14 species in China's coastal seas, with the corresponding L_c (in cm).

Common name	Scientific name	L_{c_peak}	Current *U/Y*	Peak *U/Y*	Mean *U/Y*
Yellow croaker	*Larimichthys polyactis*	0.8	36	47	39
Largehead hairtail	*Trichiurus lepturus*	0.9	112	302	179
Fang's gunnel	*Pholis fangi*	0.2	44	44	43
Whitespotted conger	*Conger myriaster*	0.9	69	104	78
So-iuy mullet	*Planiliza haematocheila*	0.8	61	147	98
Red tonguesole	*Cynoglossus joyneri*	0.9	52	218	79
Japanese Spanish mackerel	*Scomberomorus niphonius*	0.9	44	84	52
Bastard halibut	*Paralichthys olivaceus*	0.8	67	108	85
Korean rockfish	*Sebastes schlegelii*	0.8	57	171	102
Silver pomfret	*Pampus argenteus*	0.7	76	176	109
Pointhead flounder	*Cleisthenes herzensteini*	1.0	103	275	162
Chub mackerel	*Scomber japonicus*	0.9	26	66	41
Yellow goosefish	*Lophius litulon*	0.8	15	32	20
Blackhead seabream	*Acanthopagrus schlegelii*	0.8	57	89	66

Given that CPUE can be seen as proportional to biomass, dividing Equation (12) by F/M gives

$$\frac{CPUE'}{R} = \left(\frac{Y'}{R}\right)/\left(\frac{F}{M}\right) = \left(\frac{1}{1+\frac{F}{M}}\right)\left(1-\frac{L_C}{L_{inf}}\right)^{\frac{M}{K}} \left(1-\frac{3\left(1-L_c/L_{inf}\right)}{1+\frac{1}{M/K+F/K}}+\frac{3\left(1-L_c/L_{inf}\right)^2}{1+\frac{2}{M/K+F/K}} -\frac{\left(1-L_c/L_{inf}\right)^3}{1+\frac{3}{M/K+F/K}}\right) \quad (13)$$

The relative biomass of fish with length $>L_c$ when no fishing occurs is expressed by

$$\frac{B_0 > L_c}{R} = \left(1-\frac{L_C}{L_{inf}}\right)^{\frac{M}{K}}\left(1-\frac{3\left(1-L_c/L_{inf}\right)}{1+\frac{1}{M/K}} +\frac{3\left(1-L_c/L_{inf}\right)^2}{1+\frac{2}{M/K}}-\frac{\left(1-L_c/L_{inf}\right)^3}{1+\frac{3}{M/K}}\right) \quad (14)$$

where B_0 is the unexploited biomass. From this, the relative biomass of exploited fishery can be obtained by

$$B/B_0 = \left(\frac{CPUE'}{R}\right)/\left(\frac{B_0{}' > L_C}{R}\right) \quad (15)$$

(Froese et al., 2018). The limitations of this approach lie in its assumptions, i.e., that growth follow the von Bertalanffy model, that fishing and natural mortality rates behave as expressed in the above equations, that gear selection is of the trawl type and, most importantly, that the parameters of these various relationships are not density-dependent. These assumptions are generally accepted in fisheries science and we lack the data from Chinese fisheries that would allow us to replace these assumptions by locally-derived empirical relationship.

RESULTS

Estimation of Mortality and Mean Length at First Capture

The growth parameters and hence the M values for these species, combined with $F = 1$ year^{-1} for Chinese waters (Liang and Pauly, 2017a), generates exploitation rates well over 50%, for example in *P. fangi*, *P. haematocheila*, *C. herzensteini*, *P. olivaceus*, and *S. japonicus*. The average exploitation rate of our 14 species was 66% (**Table 4**).

The estimated mean size at first capture (L_c) of 11 of 14 species were smaller than their predicted length at age zero, i.e., with the current mesh size, most of the fish are predicted to be caught as soon as they are hatched, i.e., as larvae. Therefore, considering that the von Bertalanffy equations does not represent well the growth of very young fish (Pauly, 1998), the L_c/L_{inf} were slightly increased, such that L_c matched, in these cases, length at age zero. The exceptions were *T. lepturus*, *P. olivaceous*, and *S. japonicus* (**Table 4**).

Y′/R and *U/R* Analyses

The Y'/R and U/R values for 14 species were reported (**Tables 5A,B**). *L. polyactis*, *T. lepturus*, and *S. niphonius* are provided as illustrated examples (**Figure 3**); figures for the 11 other species are provided in the **Supplementary Material**. Overall, these results suggest that the fisheries in China's coastal seas have neither optimized yield, nor utility as expressed in fish prices.

Indeed, the data suggest that Y/R would increase by over 80% on average if average L_c/L_{inf} was increased to 0.53, which would correspond to a mesh size of about 10 cm (**Table 5A**). In general, the predicted increase was bigger in species that could potentially grow to larger sizes, for example in *P. haematocheila*, *P. olivaceus*, *S. niphonius*, and *L. litulon*.

The average U/R for 14 species was predicted to increase by five times under the present fishing mortality ($F = 1$ year^{-1}) if

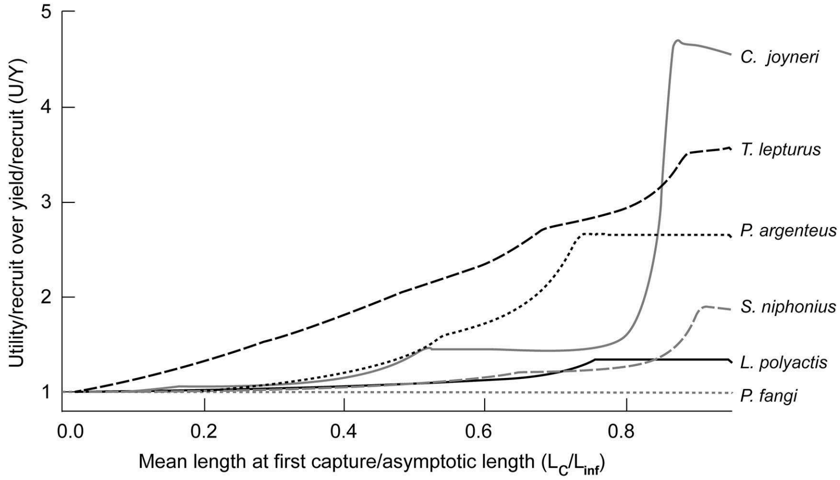


FIGURE 4 | Ratio of utility-per-recruit (*U/R*) to yield-per-recruit (*Y/R*) for different L_c/L_{inf} for 6 of the species caught in China's coastal seas. Note that this ratio is near 1 when L_c/L_{inf} is low.

TABLE 7 | Estimates of current relative biomass (B/B_0) for 21 fish species in China's coastal seas.

Common name	Scientific name	L_{c_MSY}	B/B_0	B_{MSY}/B_0
Osbeck's grenadier anchovy	*Coilia mystus*	10.2	0.32	0.35
Japanese grenadier anchovy	*Coilia nasus*	19.1	0.22	0.35
Pacific rudderfish	*Psenopsis anomala*	11.0	0.13	0.35
Yellow croaker	*Larimichthys polyactis*	14.0	0.15	0.36
Largehead hairtail	*Trichiurus lepturus*	32.8	0.09	0.38
Fang's gunnel	*Pholis fangi*	9.8	0.23	0.35
Whitespotted conger	*Conger myriaster*	57.6	0.17	0.38
So-iuy mullet	*Planiliza haematocheila*	72.8	0.01	0.36
Red tonguesole	*Cynoglossus joyneri*	13.8	0.15	0.34
Japanese scad	*Decapterus marusadsi*	13.4	0.58	0.36
Japanese Spanish mackerel	*Scomberomorus niphonius*	48.5	0.09	0.38
Bastard halibut	*Paralichthys olivaceus*	46.8	0.02	0.36
Korean rockfish	*Sebastes schlegelii*	20.9	0.06	0.34
Silver pomfret	*Pampus argenteus*	14.6	0.22	0.36
Pointhead flounder	*Cleisthenes herzensteini*	23.7	0.02	0.34
Chub mackerel	*Scomber japonicus*	22.8	0.04	0.36
Japanese anchovy	*Engraulis japonicus*	7.9	0.25	0.35
Yellow goosefish	*Lophius litulon*	31.3	0.07	0.35
Scaly hairfin anchovy	*Setipinna tenuifilis*	8.7	0.22	0.35
Blackhead seabream	*Acanthopagrus schlegelii*	21.9	0.13	0.34
Bombay-duck	*Harpadon nehereus*	16.4	0.18	0.36
Mean[a]	–	–	0.16 ± 0.03	0.36 ± 0.003

[a] *Means with standard error.*

mesh sizes were increased to 12 cm, i.e., if L_c/L_{inf} were increased from 0.18 to 0.62.

Ratio of *U/R* vs. *Y/R*

The ratios of *U/R* against *Y/R* (*U/Y*) correlate with L_c/L_{inf}, i.e., large fish are more sensitive to change of L_c than smaller species (**Table 6**). Thus, *T. lepturus*, *C. joyneri*, and *P. argenteus* increased more than *P. fangi* and *L. polyactis*. Perhaps more importantly, the values of *U/Y* appear to be sensitive to L_c only when $L_c/L_{inf} = 0.3$–0.4 (**Figure 4**), i.e., utility-per-recruit differs from yield-per-recruit substantially only if fish are allowed to grow before they are caught. Indeed, peak *U/Y* appeared at L_c/L_{inf} values of 0.79 on average. With current *U/R* at 58.5 and maximum *U/R* at 133 Yuan/kg, current practices cause an average loss of 75 Yuan/kg per recruit.

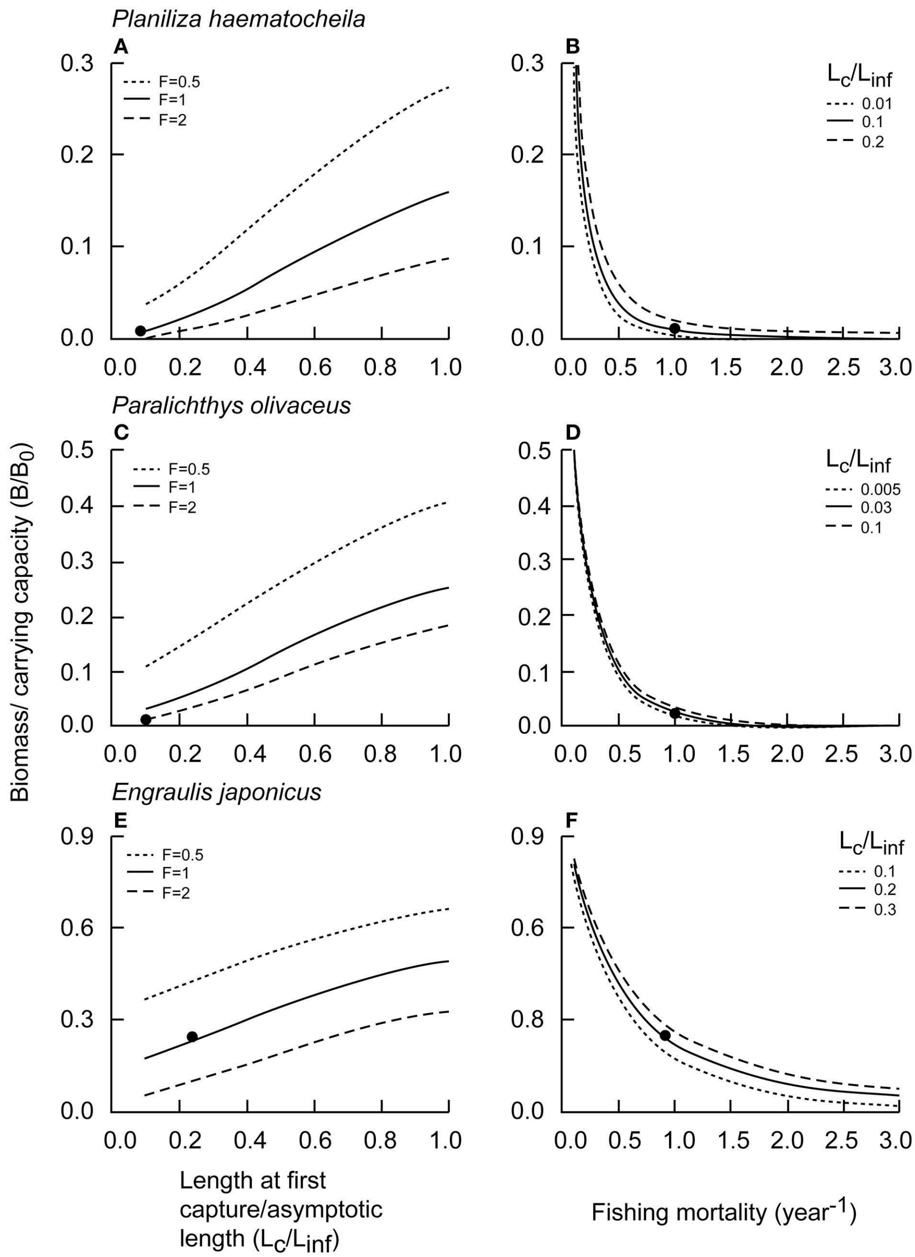


FIGURE 5 | Relative biomass (B/B_0) under different L_c and F in China's coastal seas; respectively; the black dots represent current relative biomass levels. **(A)** *P. haematocheila* B/B_0 vs. L_c/L_{inf}. **(B)** *P. haematocheila* B/B_0 vs. Fishing mortality. **(C)** *P. olivaceus* B/B_0 vs. L_c/L_{inf}. **(D)** *P. olivaceus* B/B_0 vs. Fishing mortality. **(E)** *E. japonicus* B/B_0 vs. L_c/L_{inf}. **(F)** *E. japonicus* B/B_0 vs. Fishing mortality.

Relative Biomass Analyses

If F was kept constant while L_c was increased to L_{c_MSY}, relative biomasses would increase by 77% on average (**Table 7**); the average mesh size generating B_{MSY} was about 9 cm.

Relationships between different levels of F or L_c and B/B_0 were illustrated for *P. haematocheila*, *P. olivaceus*, and *E. japonicus* (**Figure 5**). Relative biomass increased almost linearly with increasing L_c (**Figures 5A,C,E**). For large and medium species, such as *P. haematocheila* and *P. olivaceus*, relative biomasses (for $F < 0.8$ year^{-1}) was rather insensitive to increase in fishing mortality (**Figures 5B,D**). However, for small species, such as *E. japonicus*, relative biomass, i.e., B/B_0 was impacted by a wide range of fishing mortality (**Figure 5F**).

DISCUSSION

It has been often assumed that fisheries produce the maximum sustainable yield (MSY) when $E = M/Z = 0.5$, i.e., $F = M$

(Alverson and Pereyra, 1969), while other authors have suggested that $F_{opt} < M$ (Die and Caddy, 1997; Zhou et al., 2012). This issue is moot, however, as the *E* values estimated here were much higher than 0.5. Indeed, the extremely small mesh size (∼1cm) used along the coast of China leads to the bulk of the catch consisting of fish at the fingerling stage, too small for human consumption, leading to the "trash fish" and end use problems mentioned earlier.

The analyses in this contribution allowed to address these problems by considering both catch and value, since both the catch and its value were much lower than optimum levels, China's fisheries would substantially benefit from increased mesh size. Indeed, in view of difficulties in reducing fishing mortality, China's fisheries managers have attempted to increase the mesh sizes used by the commercial fisheries. Thus, mesh regulation for important species have been published (Anonymous, 2013), covering *L. polyactis*, *T. lepturus*, *P. haematocheila*, *S. niphonius*, *P. argenteus*, *C. herzensteini*, *S. japonicus*, and many other fish and invertebrates. While some of these new legal mesh sizes are still below the size shown here to be optimal, we hope that these new regulations will be respected.

The comparison of the yield- with utility-per-recruit for our species showed, unsurprisingly, that the benefit from large mesh sizes were more pronounced in the utility-per-recruit than in the yield-per-recruit analyses. Thus, Y'/R and U/R are essentially the same for *P. fangi*, because this fish remains small and its market price does not change much with size, whereas the opposite is true for species, such as *L. polyactis*, *T. lepturus*, or *C. myriaster*. As an aside, we also note that *T. lepturus*, which is most popular and high-value fish in China, is one of the few species that cannot be farmed; thus, its price remains high, especially when large, because there is no substitute to wild-caught fish. Therefore, *T. lepturus* is assumed to be the species from which most economic benefits would be derived if lengths at first capture were increased.

The relative biomass (B/B_0) for 21 species in China's coastal seas assessed here was 0.16 on average, which implied a depletion rate of 84%. The result was similar to the 80% average depletion obtained by applying the CMSY method of Froese et al. (2016) to catch time series of 15 species exploited by Chinese fisheries (Zhai et al., submitted).

Overall, this contribution provided evidence that support efforts to increase the mean length at first capture (L_c) of fish exploited along the Chinese coasts, both in terms of yield- and utility-per-recruit, because higher L_c will produce benefits even if fishing mortality is not reduced (Teh et al., 2019). However, it must be realized that the results of yield-per-recruit and utility-per-recruit analyses, as presented here, are longer-term average. In the short term, yields and catch values would decrease upon introduction of the larger mesh sizes. Therefore, supportive policies would be appropriate, which could be running parallel to existing programs to support workers transiting from fisheries to land-based occupations (Song, 2007).

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

LZ was responsible for the data collecting, formal analysis, and writing the original draft. DP was responsible for the conceptualization, methodology, and supervision.

FUNDING

LZ research was funded by China Scholarship Council (CSC). DP research was supported by the Sea Around Us, which receives funding from the Oak Foundation, the Marisla Foundation, the Paul M. Angell Family Foundation, the David and Lucile Packard Foundation, the Minderoo Foundation, and the Bloomberg Philanthropies through RARE.

ACKNOWLEDGMENTS

LZ would like to thank Mr. Y. Li from Dalian Modern Agricultural Production Development Service Center, China for contributing the fish price data used here. We also thank Ms. Evelyn Liu for drafting our figures.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2019.00724/full#supplementary-material

REFERENCES

Alverson, D. L., and Pereyra, W. T. (1969). Demersal fish explorations in the northeastern pacific ocean-an evaluation of exploratory fishing methods and analytical approaches to stock size and yield forecasts. *J. Fish. Board Can.* 26, 1985–2001. doi: 10.1139/f69-188

Anonymous (1979–2019). *China Fishery Statistical Yearbooks*. Beijing: China Agricultural Press.

Anonymous (2013). *Notice of the Ministry of Agriculture on the Implementation of the Minimum Mesh Size System for Marine Fishing and Fishing Gears*. Available online at http://jiuban.moa.gov.cn/zwllm/tzgg/tz/201312/t20131205_3699050.htm (accessed May 12, 2013).

Baech, G. W., and Huh, S. H. (2004). Age and growth of red tongue sole (*Cynoglossus joyneri*) in the Southern Sea of Korea. *Korean J. Fish. and Aquat. Sci.* 37, 307–311. doi: 10.5657/kfas.2004.37.4.307

Beverton, R. J. H., and Holt, S. J. (1957). *On the Dynamics of Exploited Fish Populations (Fishery Investigations, Series II, Vol. 19)*. London: Her Majesty's Stationery Office.

Beverton, R. J. H., and Holt, S. J. (1966). *Manual of Methods for Fish Stock Assessment. Part II. Tables of Yield Function*. FAO Fishery Biology Technical Paper, No. 38, Version 1. Rome: Food and Agriculture Organization of the United Nations.

Beyer, J. E. (1987). On length-weigh relationships: part I: computing the mean weight of the fish in a given length class. *ICLARM Fishbyte* 5, 11–13.

Cao, L., Naylor, R., Henriksson, P., Leadbitter, D., Metian, M., Troell, M., et al. (2015). China's aquaculture and the world's wild fisheries. *Science* 347, 133–135. doi: 10.1126/science.1260149

Chen, D. G., Liu, C. G., and Dou, S. Z. (1992). The biology of flatfish (Pleuronectinae) in the coastal waters of China. *Netherlands J. Sea Res.* 29, 25–33. doi: 10.1016/0077-7579(92)90005-Y

Cheung, W. W. L., Sarmiento, J. L., Dunne, J., Frölicher, T. L., Lam, V. W. L., Palomares, M. L. D., et al. (2013). Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. *Nat. Clim. Change* 3, 254–258. doi: 10.1038/nclimate1691

Chu, W. S., Wang, J. P., Hou, Y. Y., Ueng, Y. T., and Chu, P. H. (2011). Length-weight relationships for fishes off the southwestern coast of Taiwan. *Afr. J. Biotechnol.* 10, 3945–3950. doi: 10.5897/AJB10.2074

Cui, Q. M., Yuan, C. Y., Dong, J. G., and Zhang, Q. T. (2008). Age and growth of the silver pomfret *Pampus argenteus* in the Bohai Bay. *J. Tianjin Univer. Sci. Technol*. 23, 30–23.

Die, D. J., and Caddy, J. F. (1997). Sustainable yield indicators from biomass: are there appropriate reference points for use in tropical fisheries? *Fish. Res.* 32, 69–79. doi: 10.1016/S0165-7836(97)00029-5

Die, D. J., Restrepo, V. R., and Hoenig, J. M. (1988). Utility-per-recruit modeling: a neglected concept. *Trans. Am. Fish. Soc*. 117, 274–281. doi: 10.1577/1548-8659(1988)117<0274:UMANC>2.3.CO;2

Dieckmann, U., Heino, M., and Jin, X. (2005). Shrinking fish: fisheries-induced evolution in the yellow sea. *IIASA Magazine Options,* Autumn 2005:8.

Enberg, K., Jørgensen, C., Dunlop, E. S., Varpe, Ø., Boukal, D. S., Baulier, L., et al. (2012). Fishing-induced evolution of growth: concepts, mechanisms and the empirical evidence. *Mar. Ecol*. 33, 1–25. doi: 10.1111/j.1439-0485.2011.00460.x

FAO (2016). *Fishery and Aquaculture Statistics*. Rome: Food and Agriculture Organization of the United Nation.

Froese, R. (2006). Cube law, condition factor and weight–length relationships: history, meta-analysis and recommendations. *J. Appl. Ichthyol*. 22, 241–253. doi: 10.1111/j.1439-0426.2006.00805.x

Froese, R., Demirel, N., Coro, G., Kleisner, K. M., and Winker, H. (2016). Estimating fisheries reference points from catch and resilience. *Fish Fish.* 18, 506–526. doi: 10.1111/faf.12190

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A. C., Dimarchopoulou, D., et al. (2018). A new approach for estimating stock status from length frequency data. *ICES J. Mar Sci*. 75, 2004–2015. doi: 10.1093/icesjms/fsy078

Geng, P., Zhang, K., Xu, S. S., and Chen, Z. Z. (2018). Assessment of natural mortality coefficients in fish stocks: a review. *J. Fish. Sci. China* 25, 694–704. doi: 10.3724/SP.J.1118.2018.17399

Geng, X. Y., Li, X. P., Ma, W. L., Liu, M. L., Fang, E. J., Wang, Z. Q., et al. (2001). The relationship of age and growth for *Planiliza haematocheila* in Bohai Sea. *Tianjin Fish*. 4, 30–32.

Greenpeace (2017). *The Current Status of Marine Fishing for "Trash Fish" in China and its Implications for China's Sustainable Fisheries Development*. Available online at: http://www.greenpeace.org.cn/ (accessed July 31, 2017).

Hong, X. Y. (1980). A study on the age and growth of the hairtail in the Bo Hai and Huang Hai. *J. Fish. China* 4, 361–372.

Huang, X. X. (2010). *Study on the fishery biology of Enedrias fangi Wang and Wang in the inshore waters of Qingdao* (Master's thesis), Ocean University of China, Qingdao, China.

Law, C. S., and Sadovy de Mitcheson, Y. (2018). Age and growth of black seabream *Acanthopagrus schlegelii* (Sparidae) in Hong Kong and adjacent waters of the northern South China Sea. *J. Fish Biol*. 93, 382–390. doi: 10.1111/jfb.13774

Li, H. Q. (1990). Estimation of the best mesh size for many fish species in the pearl river estuary. *Fish. Sci*. 9, 4–7.

Liang, C., and Pauly, D. (2017a). Growth and mortality of exploited fishes in China's coastal seas and their uses for yield-per-recruit analyses. *J. Appl. Ichthyol*. 33, 746–756. doi: 10.1111/jai.13379

Liang, C., and Pauly, D. (2017b). Fisheries impacts on China's coastal ecosystems: unmasking a pervasive 'fishing down' effect. *PLoS ONE* 12:e0173296. doi: 10.1371/journal.pone.0173296

Lin, C. L., Su, J. L., Xu, B. R., and Tang, Q. S. (2001). Long-term variations of temperature and salinity of the Bohai Sea and their influence on its ecosystem. *Prog. Oceanogr*. 49, 7–19. doi: 10.1016/S0079-6611(01)00013-1

Lin, L. S., Cheng, J. Y., and Ling, J. Z. (2007). Analysis on recent status of the bottom trawl fishery resources in the East China sea region. *Mar. Fish*. 29, 371–374. doi: 10.13233/j.cnki.mar.fish.2007.04.016

Liu, X. Z., Guo, D., Wang, A. Y., Dong, J., Wang, X. L., Duan, Y., et al. (2018). Growth characteristics of small yellow croaker *Larimichthys polyactis* in the Liaodong Bay. *Mar. Fish.* 40, 139–146.

Pauly, D. (1980). On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. *ICES J. Mar. Sci*. 39, 175–192. doi: 10.1093/icesjms/39.2.175

Pauly, D. (1983). *Some Simple Methods for the Assessment of Tropical Fish Stocks*. Rome: Food and Agriculture Organization of the United Nation, FAO Fishery Biology Technical Paper, No. 234, 52.

Pauly, D. (1998). Beyond our original horizons: the tropicalization of Beverton and Holt. *Rev. Fish. Biol. Fish*. 8, 307–334. doi: 10.1023/A:1008863215253

Pauly, D. (2010). *Gasping Fish and Panting Squids: Oxygen, Temperature and the Growth of Water-Breathing Animals*. Preußisch Oldendorf: International Ecology Institute.

Shen, G. M., and Heino, M. (2014). An overview of marine fisheries management in China. *Mar. Policy* 44, 265–272. doi: 10.1016/j.marpol.2013.09.012

Song, L. Q. (2007). *Study on Dual-Transform of Marine Fishermen in China*. Qingdao: China Ocean University Press.

Teh, L. S. L., Cashion, T., Alava Saltos, J. J., Cheung, W. W. L., and Sumaila, U. R. (2019). *Status, Trends, and the Future of Fisheries in the East and South China Seas*. Vancouver: Institute for the Oceans and Fisheries, The University of British Columbia, Fisheries Centre Research Reports 27, 101.

Thompson, W. F., and Bell, F. H. (1934). Effect of changes in intensity upon total yield and yield per unit of gear. *Rep. Int. Fish. Comm.* 8, 7–49.

von Bertalanffy, L. (1934). Investigations on the rules of growth. Part I. General principles of the theory; mathematical and physiological laws of growth in aquatic animals. *Wilhelm Roux Archiv. Entwicklungsmech. Organ.* 131, 613–652. doi: 10.1007/BF00650112

von Bertalanffy, L. (1938). A quantitative theory of organic growth (inquiries on growth laws. II). *Hum. Biol*. 10, 181–213.

Wang, X. H., Qiu, Y. S., Du, F. Y., Lin, Z. J., Sun, D. R., and Huang, S. L. (2011). Spatio-temporal variability of fish diversity and dominant species in the Beibu Gulf. *J. Fish. Sci. China* 18, 427–436. doi: 10.3724/SP.J.1118.2011.00427

Ye, C. C., Tang, Q. S., and Qin, Y. J. (1980). The Huanghai herring and their fisheries. *J. Fish. China* 4, 339–352.

Yin, Z. Q., Lu, W. Q., Chen, Y., Liu, Y. H., Zhou, S. L., Meng, W. D., et al. (2016). Growth characteristics and resource evaluation of *Sebastes schlegelii* in Zhangzidao artificial reef area. *Anim. Husbandry Feed Sci*. 8, 186–188.

Yin, Z. Q., Xu, C. C., and Chen, Y. (2015). Growth and rational utilization of *Lophius litulon* in Dalian Sea. *J. Anhui Agri. Sci.* 43, 125–127. doi: 10.13989/j.cnki.0517-6611.2015.28.049

Zhai, L., Xu, B. D., Ji, Y. P., and Ren, Y. P. (2015). Spatial pattern of fish assemblage and the relationship with environmental factors in yellow river estuary and its adjacent waters in summer. *Chin. J. Appl. Ecol*. 26, 2852–2858. doi: 10.13287/j.1001-9332.20150630.030

Zhang, X. W., and Liu, X. S. (1959). Investigation and study on four main economic fish ecology in China in the past ten years. *Oceanol. Limnol. Sinica* 11, 233–240.

Zhang, Y. Q. (2018). *The analysis on the current situation of the main fishery resources in the coastal waters of Shandong during 2015–2016* (Master's thesis), Yantai University, Yantai, China.

Zhou, S. J., Y, S.W., Thorson, J. T., Smith, A. D. M., and Fuller, M. (2012). Linking fishing mortality reference points to life history traits: an empirical study. *Can. J. Fish. Aquat. Sci*. 69, 1292–1301. doi: 10.1139/f2012-060

Zhu, X. H., Wu, H. Z., Cheng, G. S., and Wang, X. C. (1991). Study on age and growth of the bastard halibut, *Paralichthys olivaceus* of the Northern China Sea. *Oceanol. Limnol. Sinica* 22, 402–411.

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Marine Science

ORIGINAL RESEARCH
published: 18 February 2021
doi: 10.3389/fmars.2021.567240

Accounting for Seasonal Growth in Per-Recruit Analyses: A Case Study of Four Commercial Fish in Coastal China Seas

Yiwen Liu[1,3], *Chongliang Zhang*[1,3], *Binduo Xu*[1,3], *Ying Xue*[1,3], *Yiping Ren*[1,2,3]* and *Yong Chen*[4]

[1] College of Fisheries, Ocean University of China, Qingdao, China, [2] Laboratory for Marine Fisheries Science and Food Production Processes, Pilot National Laboratory for Marine Science and Technology, Qingdao, China, [3] Field Observation and Research Station of Haizhou Bay Fishery Ecosystem, Ministry of Education, Qingdao, China, [4] School of Marine Sciences, University of Maine, Orono, ME, United States

OPEN ACCESS

Edited by:
Daniel Pauly,
Sea Around Us, Canada

Reviewed by:
Hui Zhang,
Institute of Oceanology (CAS), China
Maite Pons,
University of Washington, United States
Qi Lee,
University of Washington, United States

***Correspondence:**
Yiping Ren
renyip@ouc.edu.cn

Specialty section:
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

Received: *29 May 2020*
Accepted: *28 January 2021*
Published: *18 February 2021*

Citation:
Liu Y, Zhang C, Xu B, Xue Y, Ren Y and Chen Y (2021) Accounting for Seasonal Growth in Per-Recruit Analyses: A Case Study of Four Commercial Fish in Coastal China Seas. Front. Mar. Sci. 8:567240. doi: 10.3389/fmars.2021.567240

Biological reference points (BRPs) derived from per-recruit analyses are commonly used in inferring stock status and serve as the target or threshold in fisheries management. However, the estimation of BRPs may be impacted by the variability in life history processes, and particularly, individual growth rates often display substantial seasonal oscillations but are seldomly considered in per-recruit analyses. Using four commercial fish species *Lophius litulon*, *Saurida elongata*, *Hexagrammos otakii*, and *Larimichthys polyactis* in coastal China Seas as examples, this study examined the effects of seasonal growth variability on per-recruit analyses and on the estimation of BRPs. We developed an individual-based modeling framework to simulate growth patterns with and without variations at the seasonal and the individual levels and adopted two common assessment methods, age-based analysis and length-frequency analysis, to estimate growth parameters regarding data availability in data-rich or data-poor fisheries, respectively. We found that ignoring seasonality could lead to substantial errors in the estimation of BRPs for the small-size species *H. otakii* and *L. polyactis* in our evaluation; when seasonal growth was considered, the estimation could be largely improved. Length-frequency analysis might yield considerably less reliable estimations than age-based method. The time of year when fast growth occurs determines positive or negative bias in estimation, and the amplitude of seasonal growth determines the degree of biases. In general, ignoring the seasonality of growth when there is can lead to underestimated growth parameter *K* and trigger biases that propagate in stock assessment and management, whereas incorporating seasonality falsely in assessment when there is no seasonal variation will have little influences on the estimation of BRPs. This study contributes to demonstrate the risk of ignoring seasonality in stock assessment and the approaches accounting for seasonal variability in fishery management.

Keywords: seasonality, per-recruit analyses, biological reference points, data availability, model improvement, growth parameters

INTRODUCTION

Successful management of global fish and invertebrate species relies on quantitative stock assessment, which aims to maintain stocks at sustainable levels while yielding optimal catch (Brooks, 2013; Punt et al., 2016). Even in data-limited situations that lack sufficient data supporting a comprehensive stock assessment, numerous data-limited methods are developed to meet management objectives. However, these models are commonly developed on specific assumptions or simplification of biological processes, some of which may be violated in realistic fisheries. For instance, heterogeneity of fish life-history and fishing activities is prevalent in fisheries (Truesdell et al., 2016), but it is not usually considered in assessment models. Management advices obtained from these models, consequently, may be misleading if the risks of violating assumptions are not sufficiently understood. To achieve valid management decision, uncertainty in stock assessment models needs to be widely tested in terms of robustness (Patterson et al., 2001; Magnusson et al., 2013).

Uncertainties in stock assessments may come from multiple sources, including methods, biological processes, and observation error. Regarding process uncertainty, there has been increasing studies to investigate the effect of seasonal variability in life-history processes on stock assessment and ecological models (Hufnagl et al., 2013; Datta and Blanchard, 2016). In particularly, numerous species in temperate seas display seasonal oscillations in growth on account of fluctuations of temperature, light, and food supply (Adolph and Porter, 1996; Coma et al., 2000; Carmona-Catot et al., 2014). Even at tropic latitudes, strong seasonal growth oscillations exist resulting from estivation or minor temperature changes (Pauly et al., 1992). Growth is one of the basis life-history processes that is often required in data-limited methods, understanding of which is fundamental to the knowledge of life histories, demography, and productivity (Pardo et al., 2013). Thus, seasonal growth variability has been a concern in stock assessments for a long time. Sparre (1990) indicated that length-converted catch curves (LCCC) could overestimate total mortality (Z) when growth was seasonal. Accordingly, Pauly (1990) proposed an approach to seasonal length converted catch curves (sLCCC). Recently, Hufnagl et al. (2013) evaluated the performance of length-based total mortality estimators and showed that the tested methods were sensitive to seasonal growth and recruitment. In spite of the established methods to account for seasonal growth, the common applications appear to be resistant to changing. For instance, Von Bertalanffy growth function (VBGF) (Beverton and Holt, 1957) doesn't routinely incorporate this feature but instead assume a constant growth coefficient K, which impose crucial problems for assessment methods. However, there is still limited understanding about the effect of seasonality on stock assessments, i.e., estimation of biological reference points (BRPs).

In addition to the process errors, there are substantial observation errors in stock assessments from sampling, especially in data-poor situations. For example, estimation of growth parameters is commonly dependent on age determination, by counting annual increments of otolith rings or other hard tissue, which is assumed to be relatively accurate but not invulnerable to measurement errors. Besides, species with accurate age estimates are limited by high costs and technical difficulties. In this circumstance, length-based methods, such as electronic length frequency analysis (ELEFAN), are useful in estimating growth parameters, as length composition data are more easily obtained than age data. However, the effectiveness of length frequency data may be affected by diverse issues, i.e., sample size, selectivity, and uncovered distribution area (Schwamborn et al., 2019). In addition, both methods can be impacted by the variations in growth at the individual level, which largely contributes to uncertainty in the studies of growth. In practice, the different aspects of errors are likely to influence stock assessments altogether, whereas their interactions and overall effects remain unknown. Therefore, explicitly accounting for seasonality and individual variability is desired in the considerations of stock assessment.

This study examines the effect of seasonal growth when using classic per-recruit analyses. We consider two models, yield-per-recruit (YPR) and spawning-stock-biomass-per-recruit (SSBPR) analyses, which reflect the trade-off between fisheries yields and stock status, emphasizing growth-overfishing (King, 2013) and recruit-overfishing (Katsukawa, 2005), respectively. Combined with BRPs, per-recruit analyses are widely used in guiding fisheries management, especially in data-limited situations (Gabriel and Mace, 1999; Moreau and Matthias, 2018; Zhai and Pauly, 2019), due to its light data requirement (Chrysafi and Kuparinen, 2016) and partially the widespread application of FiSAT II (FAO-ICLARM Fish Stock Assessment Tools; FAO, 2006). In a recent evaluation for data-limited length-based methods (Chong et al., 2019), TB method (length-structure per-recruit analyses) could provide the most accurate assessment. However, it should be noted that per-recruit analyses are based on several strong assumptions such as equilibrium, including constant vital rates (i.e., growth, natural mortality, spawning, and recruitment) (King, 2013). In these types of models, seasonal variability in growth is not incorporated in most cases. As YPR analyses has been proved to be sensitive to the choice of growth function (Spence and Turtle, 2017), such unawareness of seasonal conditions may result in misleading management guidelines.

In this study, we selected four species in coastal China Sea to investigate how seasonal variability in growth affected per-recruit analyses. We developed an individual-based modeling framework to simulate seasonality and individual variations in the process of growth. Additionally, regarding the possible sources of information in data-rich and data-poor stocks, we evaluated how two types of data, length-at-age data and length-frequency data, contribute to estimating growth functions and subsequent per-recruit analyses. With a range of simulation scenarios about process and observation errors, we aim to evaluate the risk of ignoring seasonality when using per-recruit analyses in guiding management and to demonstrate the uncertainty of BRPs. This study may contribute to understanding uncertainties of BPRs in fisheries management under the circumstance of seasonal variability and data-poor stocks.

MATERIALS AND METHODS

Data Sources

We considered four species in China's coastal area, including anglerfish (*Lophius litulon*), slender lizardfish (*Saurida elongata*), greenling (*Hexagrammos otakii*), and small yellow croaker (*Larimichthys polyactis*). They were all commercially important and dominant species in ecosystem. These species had different life-history traits, ranging from slow-growing and long lifetime to short-lived fast-growing species. *H. otakii* represented a cold-temperate species differing from other three warm-temperate species.

A suit of biological data was collected from a trawl-based fishery-independent survey in coastal waters of Shandong Peninsula, China (See **Supplementary Material** for more details), from which life-history parameters of those species were derived with different methods. Length at recruitment (Lr) was set according to the range of minimum length caught in fisheries landings. Length-weight relationship was used to convert length into weight, and parameters a and b were calculated from size data using linear regression. Growth and maturation parameters were gathered from literature (**Table 1**). Total mortality (Z), as well as length-specific selectivity, was estimated by LCCC (Pauly, 1983). Natural mortality (M) was calculated by Pauly's empirical equation (Pauly, 1980). The parameters were listed in **Table 1** and in **Supplementary Material** for detailed formula.

A General Framework of Simulation

We designed an individual-based modeling framework to investigate how seasonal and individual growth variability affected the per-recruit analyses and accounted for different amplitude of seasonality and data availability for different scenarios (**Figure 1**). In the following sections, we described each component of our simulation study.

Operating Model

The operating model is developed to account for the variability of growth rate at the seasonal and individual levels. The model is developed on the basis of "fishdynr" package (version 0.4.1, Taylor, 2016) in R (version 3.5.3, R Core Team, 2018) with modifications on sub-models of the sampling process and types of available data.

Our model describes the primary life history processes, i.e., growth, mortality, and reproduction of fish species. With a time step of 1 month, individual grows following a given growth function and has probabilities to be caught in fishery or die of natural mortality. At specific time of year, reproduction occurs and new cohort is generated. Individuals caught by fishery are sampled as survey data for subsequent assessments. Detailed life-history processes are described as follows:

Seasonal growth

Seasonal growth models are generally based on the modifications of the basic VBGF. Extensions that incorporate a seasonality component into the model are used to describe seasonal oscillation of growth, and many of them use sine functions. This study adopts the model proposed by Hoenig and Hanumara (1982) and described by Somers (1988), so-called seasonal oscillation growth function (soVBGF):

$$L_t = L_\infty(1 - e^{-K(t-t_0)-(\frac{CK}{2\pi})(sin2\pi(t-t_s)-sin2\pi(t_0-t_s))})$$

where L_t is the average length at age t, L_∞ is the asymptotic length (cm), K is the growth coefficient (year^{-1}), t_0 is the theoretical age at length of zero, C modulates the amplitude of the seasonal oscillation, and ts is the so-called summer point, indicating the start of the convex portion of the first sinusoidal growth oscillation. In this study, t_0 is set to zero, assuming that fish has zero length at birth. The "summer point" ts could be calculated by: $t_s = T_{fast} - T_{spawn}$, where T_{fast} is the fastest-growing time of the year and T_{spawn} is the peak spawning time. Here, T_{fast} is assumed to be 7/12 for warm-temperate species, and 1/12 for cold-temperate species (*H. otakii*), according to their life-history characteristics. T_{spawn} is set based on known life-history information (**Table 1**).

Individual variability

The growth function describes the average growth parameters of the whole population, whereas individual growth trajectory may be considerably different from the mean growth curve, which may substantially bias the estimation of growth parameters (Pilling et al., 2002). Here, individual growth variation is introduced into growth parameters K and L_∞ of each simulated individual i, by multiplying the average growth parameters with the coefficient of variation (CV): $L_{\infty\, i} = \bar{L}_\infty * \varepsilon_i$, where ε_i is a random number generated for individual i following a log normal distribution with mean = 0 and standard deviation = CV on the log scale. The same procedure is used to generate the growth parameter K_i for each individual i. CV of both K and L_∞ is set to 0.1 in this study (Taylor and Mildenberger, 2017). The remaining growth parameters, variables t_0, C, and ts are set constantly for all individuals.

Mortality and recruitment

Individual survival rate $S = e^{-(M+F)\Delta t}$, where M and F indicate annual natural and fishing mortality coefficient, respectively. Δt is the time step on a yearly basis. For each time step, individual stochastically dies from fishing or natural cause, with a probability consistent with their relative proportions ($\frac{M}{(M+F)}$ versus $\frac{F}{(M+F)}$).

The model coupled a Beverton–Holt stock–recruitment relationship, combining spawning stock biomass with parameters for maximum recruitment, *rmax*, and a steepness coefficient, *beta*. In order to focus on the effects of growth variability, *beta* was set to 1 to imply constant recruitment at *rmax* level, as the assumption is not concerned for per-recruit analyses. In addition, recruitment was assumed to occur in single month, T_{spawn}, instantaneously. When recruitment occurred, individual had a length of zero. More detailed information about model description can be found in Taylor and Mildenberger (2017).

Simulation Process

We set six gradients of seasonal growth oscillation, C = 0, 0.2, 0.4, 0.6, 0.8, and 1, to simulate different magnitudes of seasonal variability. According to whether individual variation

TABLE 1 | Input parameters used in per-recruit analyses and simulation.

	Parameters	Meanings (unit)	*Lophius litulon*	*Saurida elongata*	*Hexagrammos otakii*	*Larimichthys polyactis*
	Lr	Length at first recruitment (cm)	8.00	4.00	5.00	4.00
Growth	a	Length-weight relationship constant	0.007	0.003	0.004	0.006
	b	Length-weight relationship power	3.21	3.24	3.35	3.13
	L_∞	Asymptotic length (cm)	154.70	56.70	38.00	27.00
	K	Growth coefficient (year^{-1})	0.06	0.19	0.36	0.56
	ts	"Summer point" (year^{-1})	0.25	0.08	0.17	0.25
	T_{fast}	Fastest-growing time of the year (year^{-1})	7/12	7/12	1/12	7/12
Mortality	M	Natural mortality coefficient (year^{-1})	0.14	0.38	0.64	0.94
	Z	Total mortality coefficient (year^{-1})	1.52	1.00	1.97	2.43
Selectivity	S_{50}	Length at 50% fishery selectivity (cm)	25.43	12.92	7.04	12.14
	rs	Constant in selectivity function	0.41	0.44	2.20	0.79
Maturation	M_{50}	Length at 50% sexual maturity (cm)	56.7	21.18	20.67	14.16
	rm	Constant in maturity function	0.24	0.13	0.46	0.68
	T_{spawn}	Peak spawning time of the year (year^{-1})	3/12	6/12	11/12	4/12
References			Yoneda et al., 1997; Yoneda et al., 2001	Sakai et al., 2009; Du et al., 2011	Shan et al., 2017	Sun et al., 2018

Length-specific variable were used in per-recruit analyses.

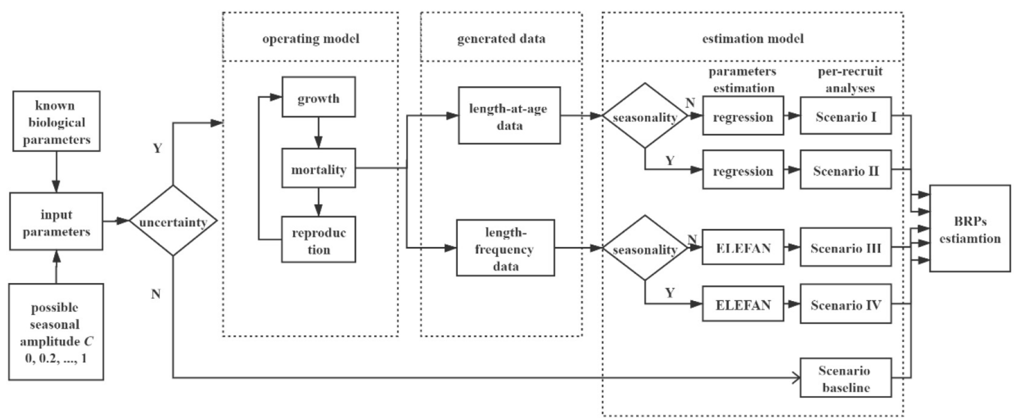


FIGURE 1 | Flowchart of the simulation in the present study. Six gradients of variable C (amplitude of the seasonal oscillation, 0, 0.2, 0.4, ..., 1) are set in this study. Deterministic section (scenario baseline) runs 1 time for each gradient of C, as the output is a deterministic value without uncertainty. Stochastic simulation runs 1000 times for each gradient of variable C, incorporating with individual growth variations (variability of K and L_∞).

was incorporated, simulation process was divided into two parts for each gradient (**Figure 1**).

Deterministic scenario

Before the simulation, the performance of estimation method was evaluated without incorporating individual variations. The result proved the validation of the estimation model (**Supplementary Figure 2**). In this scenario, growth parameters were set unbiased. The biological parameters and pre-designed variable C (using soVBGF) in simulation were used directly as input of per-recruit analyses. Therefore, the parameters represented the "true" vital rates of biological processes, and this scenario thus served as a baseline to examine BRPs. Parameters other than growth were assumed to be constant (this and the stochastic scenarios in this study).

Stochastic section

With the same biological parameters as deterministic section, we conducted the individual-based model ("operating model") to account for individual growth variations and errors in sampling. In each simulation run, we generated two types of data, length-at-age data and length-frequency data, from which growth parameters were estimated and used for per-recruit analyses (**Figure 1**). The former represented the cases of data-rich stocks where ages were determined from otoliths, scales, or dorsal fin spines, and the latter represented a data-poor situation, where age data were unavailable but length data were collected.

To evaluate the bias resulting from growth seasonality and sampling errors, we developed four simulation scenarios (**Table 2**) that were based on length-at-age data (scenario I, II) versus length-frequency data (scenario III, IV) and that considered seasonality (using soVBGF as growth functions, scenario II, IV) versus ignoring seasonal growth (using VBGF as growth functions, scenario I, III), respectively. It should be noted that no additional observation error or other source of uncertainty was incorporated into simulation process, except the stochasticity in mortality. The simulations were run 1000 times for each gradient of variable *C*.

Assessment

Parameter estimation

In the simulation, the size and age of caught individuals were recorded to generate length-at-age data and length-frequency data (**Figure 1**). For length-at-age data, age was assumed to be accurately estimated to the unit of seasons to estimate seasonal growth. The growth parameters were estimated by non-linear regression, using the "port" algorithm in R function "nls," in which the values of *C* and *ts* were constrained between 0 and 1 (Ogle, 2017). For length-frequency data, ELEFAN was used to estimate growth parameters (Pauly and David, 1981), using "ELEFAN_GA" in R package "TropFishR" (Mildenberger et al., 2017). Regarding the common practices of seasonal surveys, simulation data were selected from 4 months, January, April, July, and October. Regarding the typical cost of aging, 400 individuals per species were age-determined to generate length-at-age data, and all length measurement of catch was used as length-frequency data.

Length-structure per-recruit analyses

Traditional per-recruit analyses are generally age-structured, requiring age-dependent parameters, including age at recruitment to the fishery and age-specific selectivity. However, processes such as recruitment and selectivity are more closely associated with individual size, rather than age-dependent for many species (Hilborn and Walters, 1992). Thus, length-structure per-recruit analyses is considered as better reflecting biological and fishery-related processes (Kvamme and Bogstad, 2007), and this study re-parameterizes age-structure per-recruit analyses to length-structure model to better reflect length-dependent fishing and seasonality.

The length-structure per-recruit model uses length cohort instead of age cohort in analyses. Interval between length at recruitment (Lr) and asymptotic mean length (L_∞) can be divided into n segments (L_1, L_2, ..., L_n), and L_1 and L_{n+1} represent Lr and L_∞, respectively. Let d represent the width of each class, and thus, $d_j = L_{j+1} - L_j$. d is set to equal in this study for convenience while it should be noted that width d does not necessarily to be equal. Combining above, length-structure per-recruit analyses can be calculated as:

$$\frac{Y}{R} = \sum_{j=1}^{n} \left[\frac{W_j S_j F}{S_j F + M} (1 - e^{-(S_j F + M)\Delta T_j}) e^{-\sum_{k=1}^{j-1} (S_k F + M)\Delta T_k} \right]$$

$$\frac{SSB}{R} = \sum_{j=1}^{n} \left[W_j m_j e^{-\sum_{k=1}^{j-1} (S_k F + M)\Delta T_k} \right]$$

where j (k) represents the length class, W_j indicates the average weight of length class j, S_j is the selectivity coefficient for length class j, and m_j is the maturation proportion for length class j. The average time that species takes to grow from L_j to L_{j+1}, ΔT_j, can be estimated from growth function. When growth is modeled by VBGF, ΔT_j can be estimated as $\Delta T_j = \frac{1}{K} ln \frac{L_\infty - L_j}{L_\infty - L_{j+1}}$. When growth is modeled by soVBGF, ΔT_j cannot be estimated directly, because of the complication resulting from sine function. The R function "fzero" is used to convert length into age, and ΔT_j can be obtained for SOGF through a similar approach presented by de Graaf and Dekker (2006). The full description of per-recruit analyses can be found in **Supplementary Material**.

Biological reference points

Four typical BRPs were calculated by per-recruit analyses: $F_{\max}$, the fishing mortality rate which produces the maximum YPR; $F_{0.1}$, the fishing mortality coefficient corresponding to 10% of the slope of the YPR curve at the origin; $F_{20\%}$ and $F_{40\%}$, the fishing mortality coefficient at which SSBPR is 20% and 40% of the SSBPR when fishing mortality coefficient is zero. The estimated BRPs were compared to the corresponding true values to evaluate the effects of diverse factors considered.

RESULTS

Risk of Ignoring Seasonality

We simulated four species under six gradients of seasonal growth and four scenarios of data analyses (**Figure 1**) and herein showed the results of $F_{0.1}$ and $F_{40\%}$ as example (**Figure 2**). Ignoring seasonality (scenario I) could lead to underestimation of BRPs when seasonality existed, and this bias trended to increase dramatically with amplitudes of seasonal oscillation, which implied that the species was less productive than expected. The pattern was consistent for all four BRPs considered. Incorporating seasonality (scenario II) could largely reduce the bias, whereas certain level of bias remained compared to the "true" values (deterministic scenario). The bias could be attributed to the errors in the estimation of growth parameters, i.e., overrating L_∞ and

TABLE 2 | Simulation scenarios for testing the impact of seasonality on estimation of biological reference points.

	Scenario	Data for growth estimation	Estimation methods	Seasonality	Levels of seasonality
Deterministic section	Baseline	"True" values	None	Yes	0, 0.2, . . ., 1
Stochastic section	I	Length-at-age data	Non-linear regression	No	0, 0.2, . . ., 1
	II	Length-at-age data	Non-linear regression	Yes	0, 0.2, . . ., 1
	III	Length-frequency data	ELEFAN	No	0, 0.2, . . ., 1
	IV	Length-frequency data	ELEFAN	Yes	0, 0.2, . . ., 1

Growth parameters are calculated by two methods: non-linear regression for length-at-age data and electronic length frequency analysis (ELEFAN) for length-frequency data.

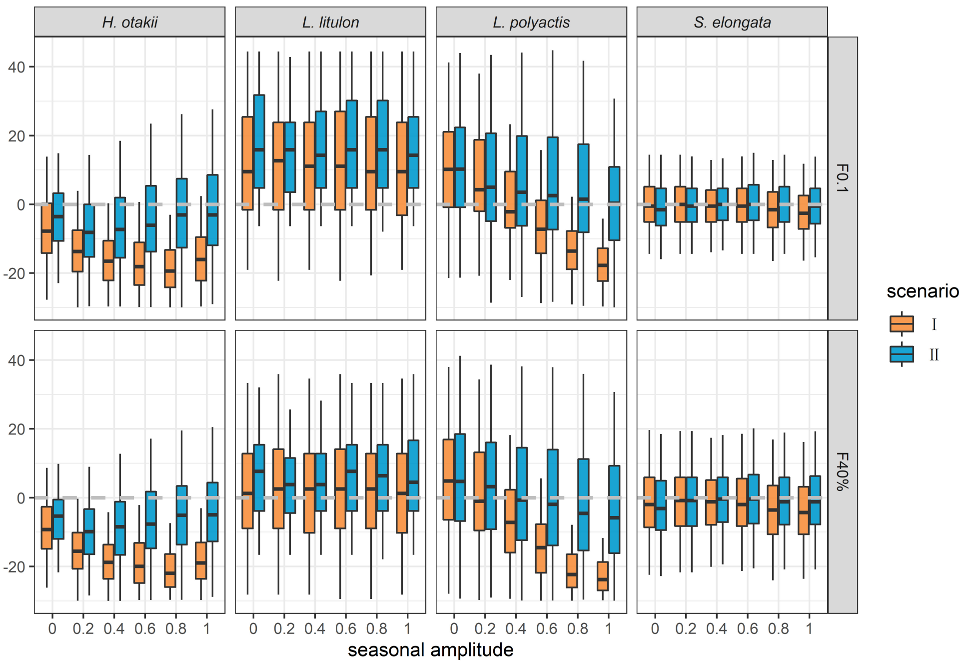


FIGURE 2 | Relative bias of estimated BRPs $F_{0.1}$ and $F_{40\%}$ for four case species in the case of ignoring seasonality (scenario I) and considering seasonality (scenario II) under different gradients of seasonal growth amplitude.

underrating K (**Supplementary Figure 5**). In addition, the results revealed that seasonal growth could cause systematic deviation in per-recruit analyses (**Supplementary Figures 3, 4**). Besides, the extent of bias caused by seasonality varied substantially among different species. Ignoring seasonality had minor influence on the estimation of BRPs for the large-size species (*L. litulon* and *S. elongata*), while it could lead to serious under-estimation for small-sized species (*H. otakii* and *L. polyactis*).

Risk of Falsely Incorporating Seasonality

Not all species display seasonal growth oscillation, and the consequences of incorporating seasonality falsely were showed in the case where seasonal amplitude C was zero but soVBGF was adopted (scenario II when $C = 0$). Our results showed that the inappropriate procedure would not substantially bias the estimation, although leading to little overestimation in *H. otakii* (**Figure 3**). The overestimation was similar or less for other species. However, when seasonality was absent, fitting soVBGF was likely to fail (**Supplementary Table 1**) because the length-at-age data did not support fitting additional seasonal growth parameters, which also reduced the risk of misdiagnose.

Effects of Data Types

To investigate the effect of seasonal growth in data insufficient situation, we designed scenarios III and IV, in which only length-frequency data were used for analyses. The estimations of BRPs were generally biased in these two scenarios regardless of the amplitude of seasonal oscillation (**Figure 4**). Incorporating seasonality in ELEFAN might have little improvement for the estimation of BRPs. Furthermore, ELEFAN cannot track the changing of seasonal amplitude C properly (**Supplementary Figure 6**), and its estimation for *ts* was highly volatile, indicating its sensitivity to sample data.

How Seasonality Works

Our "baseline" scenario indicated that seasonality could result in biased BRPs estimate even if the growth parameters were

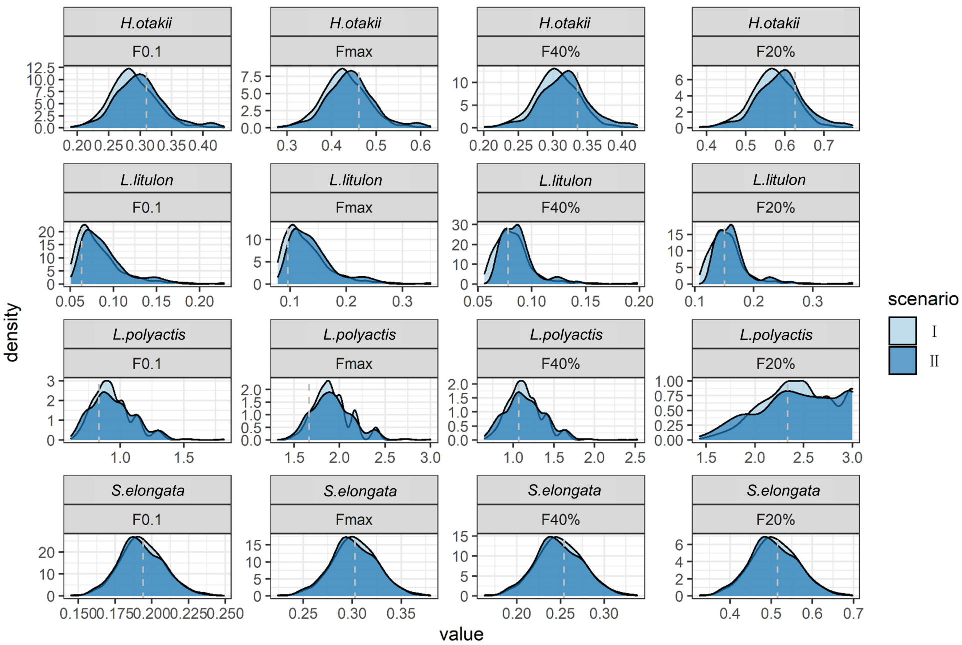


FIGURE 3 | Comparison of estimated BRPs between ignoring seasonality (scenario I) and considering seasonality falsely (scenario II) when seasonality was absent, shown as density plot. *X*-axis denotes the value of BRPs, *Y*-axis denotes the density of each value. The dashed gray lines indicate the "true" values in deterministic scenarios.

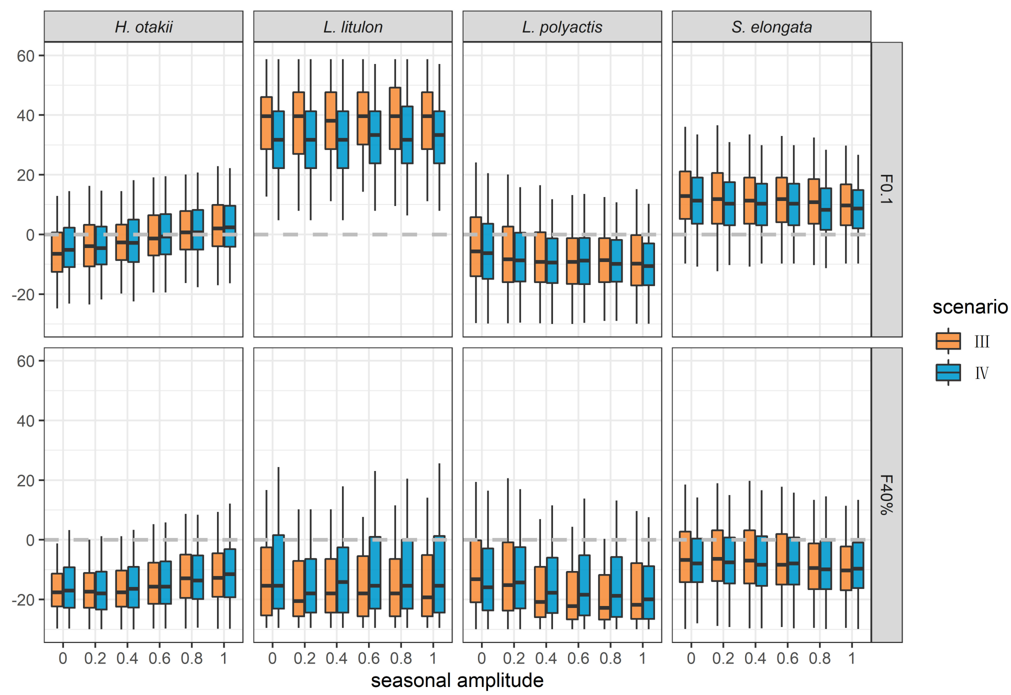


FIGURE 4 | Relative bias of the estimation of BRPs $F_{0.1}$ and $F_{40\%}$ in data insufficient situation. Scenario III and IV indicated ignoring and considering seasonality, respectively.

accurately obtained, and the extent was affected by seasonal oscillation amplitude (**Supplementary Figure 3**). We therefore explored two additional sub-scenarios to investigate how seasonality affected the estimation of BRPs (see **Supplementary Material** for details), and *H. otakii* were used as an example. Fitting VBGF with data of seasonal growth oscillation could lead

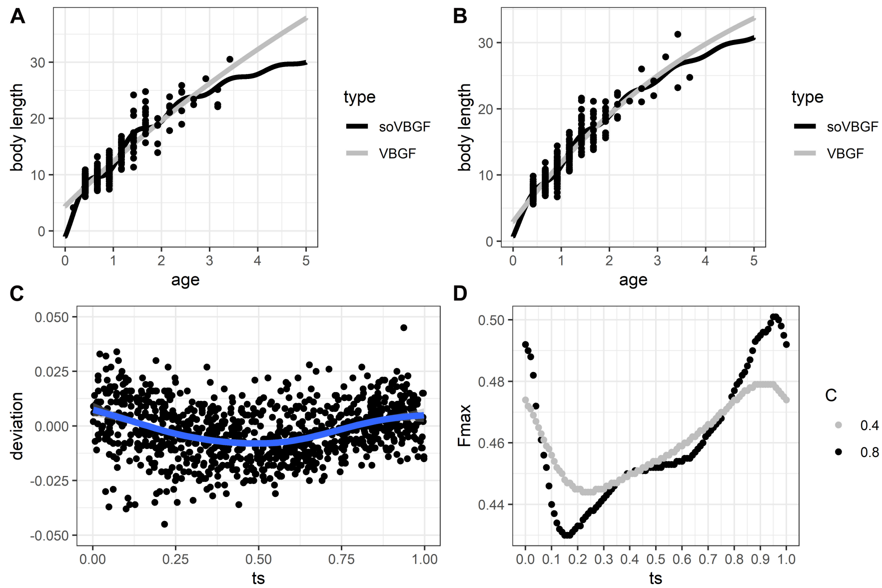


FIGURE 5 | (A) Fitting growth function by VBGF and soVBGF within dataset that display seasonal growth oscillation, the amplitude of seasonality is 0.8. **(B)** Similar plot with panel **(A)** except that the amplitude of seasonality is 0.4. **(C)** Scatterplot of the deviation caused by ignoring seasonality. Full line indicates trend line generated by generalized additive models (GAMs). **(D)** Deterministic estimation of reference point $F_{\max}$ for *H. otakii* under different *ts*. Black points and gray points indicate that *C* is 0.8 and 0.4, respectively.

to higher L_∞ and lower K, because algorithm could not handle the deceleration phase of growth (**Figures 5A,B**, illustrating an amplitude of seasonality of 0.8 and 0.4, respectively). In addition, a remarkable correlation was observed between the range of deviation in reference points and the value of parameter *ts* (**Figure 5C**), and reference points also showed obvious patterns with the change parameter *ts* and parameter *C* according to numerical computation (**Figure 5D**). The results suggested *ts* might be associated with the direction of bias and *C* determined the magnitude of errors.

DISCUSSION

Seasonality in growth has been widely observed in aquatic organisms, including marine and freshwater fish and invertebrate (e.g., crustacean), as responses to variations of environment conditions (e.g., fluctuations of temperature, light, and food supply) and individual life history process (e.g., molting). However, seasonality is seldomly incorporated into routine practices of stock assessment for many reasons, including that additional parameters used for incorporating seasonality may increase the difficulty of model fitting. Nevertheless, given the demand for accuracy of stock assessment and success of management strategy, our results suggest the influence of seasonality cannot be ignored in deriving management references.

Our finding demonstrates that ignoring seasonality in growth when it exists may result in misleading estimation of BRPs, which may lead to further errors in management, such as the under-estimation results in the loss of potential yield. Meanwhile, the risk of misleading was different among the four species. Seasonality showed negligible impact on the large-size species *L. litulon* and *S. elongata*, but for medium or small-size species *H. otakii* and *L. polyactis*, the mis-estimation could reach up to 20% and thus was hard to be overlooked. The conclusion was consistent with a previous study (Sparre, 1991), although that focused on fisheries yield. This situation suggests that management of some species (especially small-size one) may be exposed to high risk when fishing-mortality based reference points are used as proxies for MSY due to data insufficient. As seasonality in growth is quite common for small-size short-lived species (Veale et al., 2015; Yard et al., 2015; Tremont et al., 2016), we recommend a prior test of seasonality for stock assessment on those species to avoid possible bias.

This study explores how seasonal variability affects the estimation of reference points and demonstrated that the effect is associated with seasonal parameters *C* and *ts*. When seasonal variability is considered in per-recruit analyses, the time span of each length cohort ΔT is distorted, suggesting that slow-growing phase will be exposed to longer periods of fishing pressure before moving into next cohort, which can be reflected in the tumbling decrease within length composition (**Figure 6**). The position of distortion can influence the population length composition, for instance, population with a value of 0.95 for *ts* (shown in **Figure 6B**) has earlier gone through the first "slippery slope" than population of which *ts* is 0.15 (shown in **Figure 6A**) before reaching length at first capture, which is why the former has higher overall survival. The position is in control of variable *ts*, as thus, position parameter *ts* regulates the direction of misleading (if theoretical age at zero length is not equal to 0, position should be controlled by both *ts* and t_0). This perspective could explain

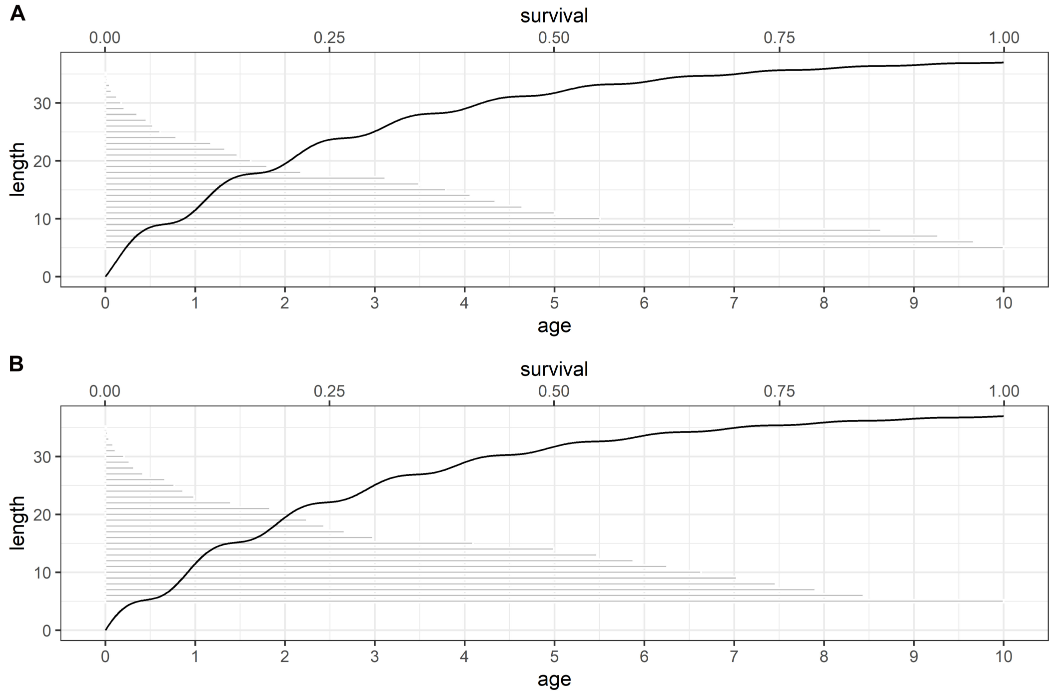


FIGURE 6 | Growth curve and survival rates of each length group for *H. otakii*. **(A)** The population has a constant fishing mortality coefficient $F = 0.4$. C and ts are set to 0.8 and 0.15, respectively. **(B)** ts is set to 0.95, and other parameters are same as former.

the interspecific difference on response to seasonality. Short-lived species have shorter length group and higher mortality than long-lived species, which made the distortion of growth rate and ΔT in per-recruit analyses more influential.

Our results reveal a potential risk of serious mis-estimation of growth parameters L_∞ and K if seasonality is ignored. These parameters have been proved as the key parameters that affect accuracy of estimated BRPs (Lin et al., 2015), implying that management plans for those species may need to be re-considered. Specifically, the misleading may cause the loss of securable yield, as the estimates of growth rate tend to be biased to lower values when ignoring seasonality. Furthermore, the growth rate K is considered to correlate with natural mortality, and in data-limited stocks, natural mortality coefficient is often derived from empirical estimators on the basis of K (Kenchington, 2014), e.g., Pauly's estimator (Pauly, 1980). The combination of two effects above may lead to serious under-estimation of BRPs and undermine the demand of maximum sustainable catches (United Nations, 2002). On the contrary, we illustrated that incorporating seasonality falsely might not bias the estimation of growth parameter as well as the BRPs, although fitting soVBGF with two additional seasonal parameters requires data with higher accuracy. We emphasize that seasonality should be considered to ensure the validity of fishery management, especially for stock management based on fishing mortality-based BRPs.

Reliable stock assessment requires accurate input parameters, which depends on the quality of data collected from monitoring programs (Li et al., 2019) and effective methods for parameter estimation (Schwamborn et al., 2019). In the present study, parameter estimations were conducted according to a regular seasonal sampling, and age-based methods was superior to length-based methods. The results suggested that the estimation based on age-structure data could track the change of seasonal growth parameters, whereas ELEFAN were less effective (**Supplementary Figure 6**). Compared with Taylor and Mildenberger (2017) which conducted a similar ELEFAN simulation process with monthly observation and showed accurate estimation of seasonal parameters, we assume the monitoring programs matter, that is, quarter sampling may be insufficient to calculate seasonal parameters using ELEFAN. Sampling design need to be adjusted to satisfies the requirements of such research objective, which need further examination.

The individual-based modeling framework proposed in this study aims to reflect realistic population dynamic and improve understanding the effect of uncertainty from multiple sources on per-recruit analyses. Meanwhile, there are many issues that worth further consideration. For example, incorporating seasonality in growth requires selecting suitable growth function. Several functions have been proposed to account for seasonal growth, wherein the models from Hoenig and Hanumara (1982) and Somers (1988) were most popular. Despite that, proper growth functions may be species-specific, for example, the seasonal growth function proposed by Pauly et al. (1992) allows individuals to stop growing over a particular period of time (which is called as "no-growth time," *NGT*), which can be useful to describe growth cessation of some species. In addition, the models modified from VBGF were criticized for inappropriate choice of the exponent relating the allometric relationship between anabolism and size of the organism (Chowdhury et al., 2013). Some novel models might be considered, e.g., Powell et al. (2019) conducted two new model to account for seasonality in a rate:state form, and Spence and Turtle (2017) used a flexible equation to represent the proportion of growth already occurred to describe growth function. Further comparison study for above models should benefit to the model selection. In addition, some assumptions and simplifications in our simulation should be noted for improvement. Input parameters except for growth parameters were assumed to be constant, and some parameters such as natural mortality coefficient and stock-recruitment relationship were considered to vary substantially due to environment changes. The effects of varying parameters may interact with that of seasonal growth, thus the integrative effects need to be further examined. To this end, the energy budget theory may be crucial to avoid the burden of examining numerous patterns of interactions and correlations among life-history parameters. Seasonality and correlations of vital rates may be better reflected with respect to body condition such as food shortage and starvation and ambient environment such as temperature (Brown et al., 2004). A mechanistic individual-based model may further improve our understanding of seasonal growth variability and its influence on fisheries assessment and management.

CONCLUSION

This study demonstrated that unawareness of seasonal growth could lead to biased BRPs estimation when it existed. Incorporating seasonality into consideration could largely improve the model estimation. The bias could occur at two processes: the biased estimation of growth parameters and the systematic error in per-recruit analyses caused by seasonality. Thus, the knowledge for life history traits should be better introduced in stock assessment to reduce the possible bias, as seasonal growth has been observed in many marine organisms.

The mechanism of effect of seasonal growth on population dynamic was discussed. The distortion caused by seasonal growth impacted the overall length compositions of fish stock. This inference could explain the observed situation: seasonal parameters *ts* were associated with the direction of bias and *C* determined the magnitude of errors. Under this condition, other length-based methods, that is, using length frequency data as model input, should be tested to identify the sensitivity to seasonal variability. In addition, this study observed interspecific difference on response to seasonal growth. Further research was required to investigate the biological mechanisms behind it.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

YL performed the data analyses and wrote the manuscript. CZ contributed significantly to analysis and manuscript preparation. BX and YX helped to perform the analysis with constructive discussions. YR and YC contributed to the conception of the study. All authors contributed to the article and approved the submitted version.

FUNDING

The research was supported by the National Key R&D Program of China (2018YFD0900904 and 2018YFD0900906).

ACKNOWLEDGMENTS

We thank the editor and three reviewers for their review and comments on the manuscript. We also thank the members of the Fisheries Ecosystem Monitoring and Assessment Laboratory of Ocean University of China for data collection and their perspectives.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.567240/full#supplementary-material

REFERENCES

Adolph, S. C., and Porter, W. P. (1996). Growth, seasonality, and lizard life histories: age and size at maturity. *Oikos* 77, 267–278. doi: 10.2307/3546065

Beverton, R. J. H., and Holt, S. J. (1957). *On the Dynamics of Exploited Fish Populations. Fisheries Investigations (Series 2)*, vol 19. London: United Kingdom Ministry of Agriculture and Fisheries.

Brooks, E. N. (2013). Effects of variable reproductive potential on reference points for fisheries management. *Fish. Res.* 138, 152–158. doi: 10.1016/j.fishres.2012.06.003

Brown, J. H., Gillooly, J. F., Allen, A. P., Savage, V. M., and West, G. B. (2004). Toward a metabolic theory of ecology. *Ecology* 85, 1771–1789. doi: 10.1890/03-9000

Carmona-Catot, G., Santos, A. F. G. N., Tedesco, P. A., and Emili García-Berthou. (2014). Quantifying seasonality along a latitudinal gradient: from stream temperature to growth of invasive mosquitofish. *Ecosphere* 5, 1–23.

Chong, L., Mildenberger, T. K., Rudd, M. B., Taylor, M. H., Cope, J. M., Branch, T. A., et al. (2019). Performance evaluation of data-limited, length-based stock assessment methods. *ICES J. Mar. Sci.* 77, 97–108. doi: 10.1093/icesjms/fsz212

Chowdhury, M. A. K., Siddiqui, S., Hua, K., and Bureau, D. P. (2013). Bioenergetics-based factorial model to determine feed requirement and waste output of tilapia produced under commercial conditions. *Aquaculture* 410, 138–147. doi: 10.1016/j.aquaculture.2013.06.030

Chrysafi, A., and Kuparinen, A. (2016). Assessing abundance of populations with limited data: lessons learned from data-poor fisheries stock assessment. *Environ. Rev.* 24, 25–38. doi: 10.1139/er-2015-0044

Coma, R., Ribes, M., Gili, J. M., and Zabala, M. (2000). Seasonality in coastal benthic ecosystems. *Trends. Ecol. Evol.* 15, 448–453. doi: 10.1016/s0169-5347(00)01970-4

Datta, S., and Blanchard, J. L. (2016). The effects of seasonal processes on size spectrum dynamics. *Can. J. Fish. Aquat. Sci.* 73, 598–610. doi: 10.1139/cjfas-2015-0468

de Graaf, G. J., and Dekker, P. (2006). A simple spreadsheet model to incorporate seasonal growth into length-based stock assessment methods. *NAGA* 29, 46–54.

Du, J., Lu, Z., Yang, S., and Chen, M. (2011). Studies on ecological characteristics variation and population dynamics of four lizardfishes in the southern Taiwan straits. *Acta. Oceanol. Sin.* 30, 72–81. doi: 10.1007/s13131-011-0163-y

FAO (2006). *Fisat II - Fao-Iclarm Stock Assessment Tool (Version 1.2.2)*. Rome: Food and Agriculture Organization of the United Nations.

Gabriel, W. L., and Mace, P. M. (1999). "A review of biological reference points in the context of the precautionary approach," in *Proceedings of the Fifth National NMFS Stock Assessment Workshop: Providing Scientific Advice to Implement the Precautionary Approach Under the Magnuson-Stevens Fishery Conservation and Management Act*, (Washington, DC: NOAA Tech Memo NMFS-F/SPO-40), 34–45.

Hilborn, R., and Walters, C. J. (1992). *Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty*. New York: Chapman and Hall.

Hoenig, J. M., and Hanumara, R. C. (1982). *A Statistical Study of a Seasonal Growth Model for Fishes. in Technical Report of the Department of Computer Science and Statistics*.: Kingston, RI: University of Rhode Island, 91.

Hufnagl, M., Huebert, K. B., and Temming, A. (2013). How does seasonal variability in growth, recruitment, and mortality affect the performance of length-based mortality and asymptotic length estimates in aquatic resources? *ICES J. Mar. Sci.* 70, 329–341. doi: 10.1093/icesjms/fss163

Katsukawa, T. (2005). Evaluation of current and alternative fisheries management scenarios based on spawning-per-recruit (SPR), revenue-per-recruit (RPR), and yield-per-recruit (YPR) diagrams. *ICES J. Mar. Sci.* 62, 841–846. doi: 10.1016/j.icesjms.2005.04.002

Kenchington, T. J. (2014). Natural mortality estimators for information-limited fisheries. *Fish Fish.* 15, 533–562. doi: 10.1111/faf.12027

King, M. (2013). *Fisheries Biology, Assessment and Management*. Hoboken, NJ: John Wiley & Sons.

Kvamme, C., and Bogstad, B. (2007). The effect of including length structure in yield-per-recruit estimates for northeast arctic cod. *ICES. J. Mar. Sci.* 64, 357–368. doi: 10.1093/icesjms/fsl027

Li, B., Chen, Y., Reardon, K., and Wilson, C. (2019). A simulation-based evaluation of sea sampling design for American lobster in the Gulf of Maine. *Fish. Res.* 216, 145–154. doi: 10.1016/j.fishres.2019.04.012

Lin, Y. J., Sun, C. L., Chang, Y. J., and Tzeng, W. N. (2015). Sensitivity of yield-per-recruit and spawning-biomass-per-recruit models to bias and imprecision in life history parameters: an example based on life history parameters of Japanese eel (*Anguilla japonica*). *Fish. Bull. NOAA* 113, 302–312. doi: 10.7755/fb.113.3.6

Magnusson, A., Punt, A. E., and Hilborn, R. (2013). Measuring uncertainty in fisheries stock assessment: the delta method, bootstrap, and MCMC. *Fish Fish.* 14, 325–342. doi: 10.1111/j.1467-2979.2012.00473.x

Mildenberger, T. K., Taylor, M. H., and Wolff, M. (2017). TropFishR: an R package for fisheries analysis with length-frequency data. *Methods Ecol. Evol.* 8, 1520–1527. doi: 10.1111/2041-210x.12791

Moreau, C. M., and Matthias, B. G. (2018). Using limited data to identify optimal bag and size limits to prevent overfishing. *N. Am. J. Fish Manag.* 38, 747–758. doi: 10.1002/nafm.10073

Ogle, D. H. (2017). An algorithm for the von Bertalanffy seasonal cessation in growth function of Pauly et al. (1992). *Fish. Res.* 185, 1–5. doi: 10.1016/j.fishres.2016.09.020

Pardo, S. A., Cooper, A. B., and Dulvy, N. K. (2013). Avoiding fishy growth curves. *Methods Ecol. Evol.* 4, 353–360. doi: 10.1111/2041-210x.12020

Patterson, K., Cook, R., Darby, C., Gavaris, S., and Gunnar Stefánsson. (2001). Estimating uncertainty in fish stock assessment and forecasting. *Fish Fish.* 2, 125–157. doi: 10.1046/j.1467-2960.2001.00042.x

Pauly, D. (1980). On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. *ICES J. Mar. Sci.* 39, 175–192. doi: 10.1093/icesjms/39.2.175

Pauly, D. (1983). Length-converted catch curves: a powerful tool for fisheries research in the tropics (part 1). *Fishbyte* 1, 9–13.

Pauly, D. (1990). Length-converted catch curves and the seasonal growth of fishes. *Fishbyte* 8, 33–38.

Pauly, D., and David, N. (1981). ELEFAN I, a BASIC program for the objective extraction of growth parameters from length-frequency data. *Meeresforschung* 28, 205–211.

Pauly, D., Soriano-Bartz, M., Moreau, J., and Jarre-Teichmann, A. (1992). A new model accounting for seasonal cessation of growth in fishes. *Mar. Freshw. Res.* 43, 1151–1156. doi: 10.1071/mf9921151

Pilling, G. M., Kirkwood, G. P., and Walker, S. G. (2002). An improved method for estimating individual growth variability in fish, and the correlation between von Bertalanffy growth parameters. *Can. J. Fish. Aquat. Sci.* 59, 424–432. doi: 10.1139/f02-022

Powell, C. D., López, S., and France, J. (2019). Elementary functions modified for seasonal effects to describe growth in freshwater fish. *J. Theor. Biol.* 461, 133–144. doi: 10.1016/j.jtbi.2018.10.036

Punt, A. E., Haddon, M., and McGarvey, R. (2016). Estimating growth within size-structured fishery stock assessments: what is the state of the art and what does the future look like? *Fish. Res.* 180, 147–160. doi: 10.1016/j.fishres.2014.11.007

R Core Team (2018). *R: A Language and Environment for Statistical Computing.* Vienna: R Foundation for Statistical Computing. Available online at: https://www.R-project.org/.

Sakai, T., Yoneda, M., Shiraishi, T., Tokimura, M., Horikawa, H., and Matsuyama, M. (2009). Age and growth of the lizardfish saurida elongata from the Tsushima/Korea Strait. *Fish. Sci.* 75, 895–902.

Schwamborn, R., Mildenberger, T. K., and Taylor, M. H. (2019). Assessing sources of uncertainty in length-based estimates of body growth in populations of fishes and macroinvertebrates with bootstrapped ELEFAN. *Ecol. Model.* 393, 37–51. doi: 10.1016/j.ecolmodel.2018.12.001

Shan, X., Li, X., Yang, T., Sharifuzzaman, S. M., Zhang, G., Jin, X., et al. (2017). Biological responses of small yellow croaker (*Larimichthys polyactis*) to multiple stressors: a case study in the yellow sea, China. *Acta Oceanol. Sin.* 36, 39–47. doi: 10.1007/s13131-017-1091-2

Somers, I. F. (1988). On a seasonally oscillating growth function. *Fishbyte* 6, 8–11.

Sparre, P. (1990). Can we use traditional length-based fish stock assessment when growth is seasonal? *Fishbyte* 8, 29–32.

Sparre, P. (1991). Estimation of yield per recruit when growth and fishing mortality oscillate seasonally. *Fishbyte* 9, 40–44.

Spence, M. A., and Turtle, A. J. (2017). Making the most of survey data: incorporating age uncertainty when fitting growth parameters. *Methods Ecol. Evol.* 7, 7058–7068. doi: 10.1002/ece3.3280

Sun, M., Zhang, C., Li, Y., Xu, B., Xue, Y., and Ren, Y. (2018). Management strategy evaluation of fishery stocks in Haizhou bay based on data-limited methods. *J. Fish. Chin.* 42, 1661–1669.

Taylor, M. H. (2016). *Fishdynr: Fisheries Science Related Population Dynamics Models (version 0.4.1)*.

Taylor, M. H., and Mildenberger, T. K. (2017). Extending electronic length frequency analysis in R. *Fish. Manag. Ecol.* 24, 330–338. doi: 10.1111/fme.12232

Tremont, R. M., Harding, J. M., and Allen, D. M. (2016). Effects of within-season temperature variations on the early life history of two estuarine demersal fishes. *Environ. Biol. Fish.* 99, 79–94. doi: 10.1007/s10641-015-0455-8

Truesdell, S. B., Hart, D. R., and Chen, Y. (2016). Effects of spatial heterogeneity in growth and fishing effort on yield-per-recruit models: an application to the US Atlantic sea scallop fishery. *ICES J. Mar. Sci.* 73, 1062–1073. doi: 10.1093/icesjms/fsv238

United Nations (2002). *Report of the World Summit on Sustainable Development*. Johannesburg: United Nations.

Veale, L., Coulson, P., Hall, N., Hesp, A., and Potter, I. C. (2015). Age and size compositions, habitats, growth and reproductive characteristics of a terapontid (Pelates octolineatus) in coastal waters. *Mar. Freshw. Res.* 66, 535–548. doi: 10.1071/mf14079

Yard, M. D., Korman, J., Walters, C. J., and Kennedy, T. A. (2015). Seasonal and spatial patterns of growth of rainbow trout in the Colorado river in grand Canyon, Arizona. *Can. J. Fish. Aquat. Sci.* 73, 125–139. doi: 10.1139/cjfas-2015-0102

Yoneda, M., Tokimura, M., Fujita, H., Takeshita, N., Takeshita, K., Matsuyama, M., et al. (1997). Age and growth of anglerfish lophius litulon in the east china sea and the yellow sea. *Fish. Sci.* 63, 887–892. doi: 10.2331/fishsci.63.887

Yoneda, M., Tokimura, M., Fujita, H., Takeshita, N., Takeshita, K., Matsuyama, M., et al. (2001). Reproductive cycle, fecundity, and seasonal distribution of the anglerfish Lophius litulon in the East China and Yellow seas. *Fish. Bull. NOAA* 99, 356–370.

Zhai, L., and Pauly, D. (2019). Yield-per-recruit, utility-per-recruit, and relative biomass of 21 exploited fish species in China's coastal seas. *Front. Mar. Sci.* 6:724.

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Marine Science

BRIEF RESEARCH REPORT
published: 07 April 2020
doi: 10.3389/fmars.2020.00164

Check for updates

Stock Assessment Using LBB Method for Eight Fish Species From the Bohai and Yellow Seas

Yibang Wang[1,2], Yuanchao Wang[1,3], Shude Liu[4], Cui Liang[1,5], Hui Zhang[1,5,6]* and Weiwei Xian[1,5,6]*

[1] CAS Key Laboratory of Marine Ecology and Environmental Sciences, Institute of Oceanology, Chinese Academy of Sciences, Qingdao, China, [2] Qingdao University of Science and Technology, Qingdao, China, [3] University of Chinese Academy of Sciences, Beijing, China, [4] Shandong Hydrobios Resources Conservation and Management Center, Yantai, China, [5] Laboratory for Marine Ecology and Environmental Science, Qingdao National Laboratory for Marine Science and Technology, Qingdao, China, [6] Center for Ocean Mega-Science, Chinese Academy of Sciences, Qingdao, China

OPEN ACCESS

Edited by:
Athanassios C. Tsikliras, Aristotle University of Thessaloniki, Greece

Reviewed by:
Gianpaolo Coro, Istituto di Scienza e Tecnologie dell'Informazione "Alessandro Faedo" (ISTI), Italy
Nazli Demirel, Istanbul University, Turkey

***Correspondence:**
Hui Zhang
zhanghui@qdio.ac.cn
Weiwei Xian
wwxian@qdio.ac.cn

Specialty section:
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

Received: *23 December 2019*
Accepted: *02 March 2020*
Published: *07 April 2020*

Citation:
Wang Y, Wang Y, Liu S, Liang C, Zhang H and Xian W (2020) Stock Assessment Using LBB Method for Eight Fish Species From the Bohai and Yellow Seas. Front. Mar. Sci. 7:164. doi: 10.3389/fmars.2020.00164

Eight common and commercially important marine fishes from coastal and offshore areas of Shandong Province, China, were assessed using the "Length-based Bayesian Biomass" estimator (LBB) method. These species were *Scomber japonicus* (chub mackerel), *Sebastiscus marmoratus* (false kelpfish), *Hexagrammos otakii* (fat greenling), *Thryssa kammalensis* (kammal thryssa), *Gadus macrocephalus* (Pacific cod), *Setipinna taty* (scaly hairfin anchovy), *Sillago sihama* (silver sillago), and *Lophius litulon* (yellow goosefish). LBB is a new and powerful, yet simple, approach to evaluate a fisheries' status using length and frequency data. Shandong Province's coastal areas, adjacent to the Yellow and Bohai Seas, are an important fishing ground of China, where the 2018 catch of three of these species, yellow goosefish, chub mackerel, and Pacific cod, yielded up to 57,200, 21,100, and 1330 tons, respectively. The ratios of current relative to unexploited biomass (B/B_0) is smaller than the relative biomass that can produce MSY (B_{MSY}/B_0) in eight stocks save for silver sillago, indicating overfishing. Also, the sizes at first capture were well below the optimal, suggesting that larger mesh sizes would be beneficial. Our study provides evidence that LBB is an efficient method to evaluate the fishery resources in the Yellow and Bohai Seas, especially when length frequencies are the only available data. Also, LBB provided evidence useful for the management of the costal fishery resources of Shandong Province.

Keywords: Bohai and Yellow Seas, LBB method, overfishing, stock assessment, fishery resources

INTRODUCTION

For capture fisheries, China ranked first among the world's fishing countries in terms of quantity, and their capture production was up to 15,373,196 tons (FAO, 2019). With the increasing impact of human activities on the Marine ecosystem, the fish community has undergone considerable changes, and the resources of dominant economic species have been declining continuously. It was apparent that fishing individuals were younger, of lower quality, and smaller (Li et al., 2012). Shandong Province is adjacent to the Yellow Sea and the Bohai Sea, and it has economically important coastal fishing grounds (Tang and Ye, 1990) that are among the oldest in China (Lü et al., 2012). The increasing impact of human activities on the marine ecosystem of Shandong's waters, especially overfishing, has caused a noticeable decline in fishery resources, including once-abundant species (Fu et al., 2007).

Scomber japonicus (chub mackerel), *Gadus macrocephalus* (Pacific cod), *Setipinna taty* (scaly hairfin anchovy), and *Sillago sihama* (silver sillago) have been the most important economic species in China, but their resources have presented a downward trend because of excessive fishing pressure (Huang et al., 2013; Cai et al., 2014; Xu et al., 2017; Yi and Chen, 2019). Since the 1970s, fishing intensity on chub mackerel has steadily increased, but the total catch of chub mackerel in East China and Yellow Seas has been on the decline; however, strong inter-year fluctuations have been documented (Yi and Chen, 2019). Pacific cod is one of the most important marine resources in northern China, where it is mainly caught in the Yellow Sea, with an annual catch that reached as high as 26,000 tons (Tang and Ye, 1990); the trend has, however, been gradually decreasing (Xu et al., 2017). For over a decade, starting in the early 1970s, the catch of scaly hairfin anchovy has steadily increased, partly compensating for the declining catches of more valuable species (Gu, 1990). However, since the 1980s, it has been on the decline because of excessive fishing pressure (Cai et al., 2014). Silver sillago is an economically important fish in China, but its yield is gradually declining (Zhang et al., 2018), and the species' biomass appears to be depleted (Du et al., 2009). As a local species, the *Hexagrammos otakii* (fat greenling) resources were destroyed (Feng and Han, 1998). In these waters, there has been a decline in fat greenling in both species diversity and the number and size of fish caught (Feng and Han, 1998). Similarly, *Sebastiscus marmoratus* (false kelpfish) experienced a sharp decline in natural resources due to long-term fishing (Yan et al., 2018). However, as an offshore small pelagic fish, the production and economic status of *Thryssa kammalensis* (kammal thryssa) were relatively improved (Yao et al., 2003). Kammal thryssa is a pelagic fish that is a vital fishery resource both economically and ecologically (Park et al., 2015). *Lophius litulon* (yellow goosefish) became one of the main aquatic products exported by China (Lin and Zheng, 2004). Therefore, it is necessary to carry out effective resource assessments and concerns need to be devoted to the sustainable use of fishery resources.

LBB is a length-based Bayesian biomass (LBB) estimation method for analyzing length frequency data from exploited fish or invertebrate populations in which all relevant parameters are estimated synchronously using Bayesian Monte Carlo Markov Chain (MCMC) approach (Froese et al., 2018). In this contribution, we have presented the LBB method as applied to eight common commercial fishes from the coastal waters of Shandong Province. The goal here is to provide an evidential basis for the protection and management of fishery resources in this area.

MATERIALS AND METHODS

Data Sources

Samples were collected in the coastal waters of Shandong between 35°–38° 30′ N and 118°–124° E, and a total of 177 resource survey stations were set up, with trawling time of 1 h per station and towing speed of 3 kn. Fish samples were obtained using single bottom trawlers (30.6 × 8 m) with a cod end (mesh size: 30 mm) from October 2016 to August 2017. Samples were taken to a laboratory for further analysis, including species identification and a standard-length measurement. All collected fish were identified to species level, and scientific and common names were verified using FishBase[1], as summarized in **Table 1**. The LF data are presented in the **Supplementary Material**.

In this study, all analyses were performed using the R-code (LBB_20.R), which can be downloaded from http://oceanrep.geomar.de/44832/, including a New User Guide, whose various recommendations were followed.

General Description of the LBB Method

The LBB estimator is a new approach to estimate stock status using length-frequency data (Froese et al., 2018). The LBB method is applicable to species that grow throughout their lives, as do most commercially exploited fish and invertebrates. These species required no input apart from length-frequency (LF) data. The LBB estimates several parameters for one or several LF samples representing the population in question, including asymptotic length (L_{inf}), mean length at first capture (L_c), relative natural mortality (M/K), and relative fishing mortality (F/M) (Froese et al., 2018, 2019).

Here, we have only given the basic and final formulas, and we have referred to Froese et al. (2018) for details.

In LBB, it is assumed that the growth in length follows von Bertalanffy (1938) growth equation in the form given to it by Beverton and Holt (1957), i.e.,

$$L_t = L_{inf}\left[1 - e^{-K(t-t_0)}\right] \tag{1}$$

where L_t is the length at age t, L_{inf} is the asymptotic length, K is the rate at which L_{inf} is approached, and t_0 is the theoretical age at zero length (Froese et al., 2018).

When the fish are fully selected by the gear, the curvature of the right side of catch samples is a function of total mortality ($Z = M + F$) relative to K. This curve is expressed by the equation

$$N_L = N_{L_{start}}\left(\frac{L_{inf} - L}{L_{inf} - L_{start}}\right)^{Z/K} \tag{2}$$

where N_L is the number of survivors to length L, N_{Lstart} is the number at length L_{start} with full selection, i.e., from which all individuals entering the gear are retained by the gear, and Z/K is the ratio of the total mortality rate Z to somatic growth rate.

The lengths affected by partial selection are, for each species, a function of the fishing gear (here assumed to be a trawl or another gear with a trawl-like selection curve), as given by the ogive described by Eq. 3:

$$S_L = \frac{1}{1 + e^{-a(L-L_c)}} \tag{3}$$

where S_L is the fraction of individuals that are retained by the gear at length L, and α describes the steepness of the ogive (Froese et al., 2018).

[1] www.fishbase.org

TABLE 1 | Basic information and priors of eight species used in the present study.

Scientist name	Common name	Min (mm)	Max (mm)	Class interval	Numbers	L_{inf} prior (cm)	*Z/K* prior	*M/K* prior	*F/K* prior	L_c prior	*Alpha* prior
Scomber japonicus	Chub mackerel	55	303	10	764	34.5	10	1.5	8.74	11.2	55.9
Sebastiscus marmoratus	False kelpfish	35	114	10	96	15.3	5.5	1.5	3.95	7.14	39.3
Hexagrammos otakii	Fat greenling	40	255	15	1115	27.1	5.3	1.5	3.8	10.7	25.7
Thryssa kammalensis	Kammal thryssa	50	115	5	266	13.9	5	1.5	3.51	6.12	83.7
Gadus macrocephalus	Pacific cod	10	445	20	975	45	5.4	1.5	3.89	9.18	24.6
Setipinna taty	Scaly hairfin anchovy	12	222	10	1402	26.5	4.3	1.5	2.82	8.67	20.2
Sillago sihama	Silver sillago	51	147	5	115	14.8	1.6	1.5	0.0994	8.42	46.3
Lophius litulon	Yellow goosefish	11	494	10	1248	52.9	5.7	1.5	4.25	18.4	16.2

The parameters of the selection ogive are estimated at the same time as L_{inf}, L_c, α, *M/K*, and *F/K* by fitting

$$N_{L_i} = N_{L_{i-1}} \cdot \left(\frac{L_{inf} - L_i}{L_{inf} - L_{i-1}} \right)^{\frac{M}{K} + \frac{F}{K} S_{L_i}} \tag{4}$$

and

$$C_{L_i} = N_{L_i} S_{L_i} \tag{5}$$

where L_i is the number of individuals at length *i*, L_{i-1} is the number at the previous length, *C* refers to the number of individuals vulnerable to the gear, and all other parameters are as described above (Froese et al., 2018).

Finally, the following equation describes the framework for approximating stock status from L_{inf}, *M/K*, *F/K*, and L_c (Froese et al., 2016). First, given the estimates of L_{inf} and *M/K*, L_{opt}, i.e., the size at which cohort biomass is at maximum, can be obtained from equation (6):

$$L_{opt} = L_{inf}\left(\frac{3}{3 + \frac{M}{K}}\right) \tag{6}$$

Based on Eq. (6) and a given fishing pressure (*F/M*), the mean length at first capture, which maximizes catch and biomass (L_{c_opt}), can be obtained from

$$L_{c\_opt} = \frac{L_{inf}\left(2 + 3\frac{F}{M}\right)}{\left(1 + \frac{F}{M}\right)\ \left(3 + \frac{M}{K}\right)} \tag{7}$$

Estimates of L_{c_opt} are used below to calculate a proxy for the relative biomass that can produce MSY (Froese et al., 2018).

The estimate of $F/M > 1$ confirms that the stock is overfished, while the estimate of $B/B_0 < 0.5$ indicates that the current biomass is extremely low. The ratios L_{mean}/L_{opt} and L_c/L_{c_opt} were below unity, suggesting truncated length structure and fishing of too small individuals. The ratio of the 95th percentile length to asymptotic length L_{95th}/L_{inf} was close to unity (>0.9), suggesting that at least some large fish were still present.

The relative biomass and the length at first capture estimated by LBB can then be used directly for management of data-poor stocks:

If relative stock size B/B_0 is smaller than B_{MSY}/B_0, catches should be reduced.

If the mean length at first capture L_c is smaller than L_{c_opt}, fishing should start at larger sizes.

RESULTS

The results of our application of the LBB methods to eight fish species in the waters of Shandong Province are presented below, first by species and then in general terms.

Chub Mackerel (*S. japonicus*)

Chub mackerel is distributed in the Indian and Pacific oceans as well as the East China and Yellow Seas. This species reaches a maximum length of 64 cm (see text footnote 1) and is a valued commercial fish in the coastal waters of China. The estimate of $F/M = 5.4$ confirms that chub mackerel is greatly overfished, while the estimate of $B/B_0 = 0.033$ indicates that the current biomass of chub mackerel is extremely low, i.e., that it has declined by 97% from its original level (**Figure 1A**). The estimate of $L_{95}/L_{inf} = 0.88$ implies that large individual should be very rare to non-existent, which is supported by the ratios L_{mean}/L_{opt} (=0.59) and L_c/L_{c_opt} (=0.49); these ratios are both below unity, implying a truncated length structure and fishing of individuals that are too small.

False Kelpfish (*S. marmoratus*)

False kelpfish is a species distributed in the Western Pacific, and these fish reach a maximum length of 36.2 cm (see text footnote 1). The parameters *F/M* (= 1.8) and B/B_0 (= 0.18) indicate that the low biomass for false kelpfish is primarily due to fishing pressure (**Figure 1B**).

Fat Greenling (*H. otakii*)

Fat greenling, which reaches a maximum length of 57 cm (see text footnote 1), is distributed in the Northwest Pacific, including Japan and from the southern Korean Peninsula to the Yellow Sea. There has been a decline in both species diversity and in the number and size of fish caught, confirmed in this study, by the ratios *F/M* (= 2.6) and B/B_0 (= 0.12) and by our estimates of L_{mean}/L_{opt} (=0.77) and L_c/L_{c_opt} (=0.66) (**Figure 1C**).

Kammal Thryssa (*T. kammalensis*)

Kammal thryssa is a widespread species in the Indo-West Pacific. It reaches a maximum length of 15.0 cm (see text footnote 1). In this study, the *F/M* (=2.9) indicates that this fish is under increasing fishing pressure. The ratio B/B_0 (=0.1) is very low, suggesting that its standing biomass is undergoing a sharp decline. Similarly, the parameters L_{mean}/L_{opt}

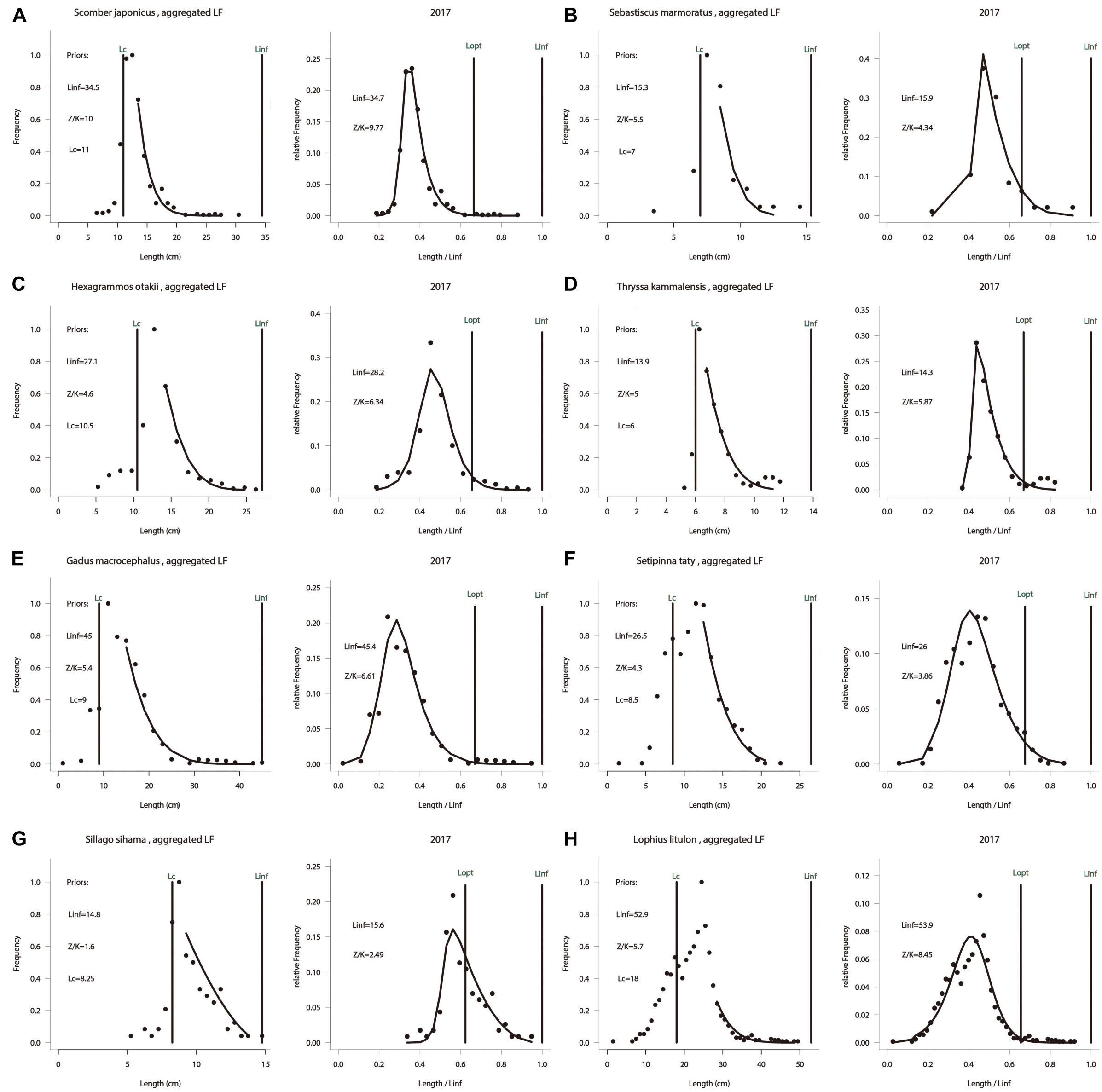


FIGURE 1 | Length-based Bayesian biomass analyses of eight fish species in the coastal of Shandong province. The left curve shows the fit of the model to the length data; the right curve is the prediction of the LBB method, L_c is the length of 50% individuals captured, L_{inf} is the limit body length of this species, and L_{opt} is the length at which the maximum catch is obtained. All right curves were on the left of L_{opt} line except for *Sillago sihama*, indicating seven stocks were overfished if to a variable extent. The labels **(A–H)** represent the result of LBB method for each species.

(= 0.77) and L_c/L_{c_opt} (= 0.66) are below unity, suggesting a truncated length structure and fishing of individuals that are too small (**Figure 1D**).

Pacific Cod (*G. macrocephalus*)

Pacific cod, which reaches 120 cm (see text footnote 1), is widely distributed in the North Pacific Ocean, including the area from the western Pacific to the Yellow Sea. The parameters F/M (= 3.5), B/B_0 (= 0.043), L_{mean}/L_{opt} (= 0.51), and L_c/L_{c_opt} (= 0.37) indicate that overfishing has depleted the species (**Figure 1E**).

Scaly Hairfin Anchovy (*S. taty*)

Scaly hairfin anchovy, which reaches a maximum length of 15.3 cm (see text footnote 1), is widely distributed in the Indo-West Pacific and along most of China's coastline, notably in the Bohai Sea. In this study, the ratios F/M (=1.7) and B/B_0 (=0.16) suggest that this species is suffering from overfishing pressure (**Figure 1F**) and a low biomass.

Silver Sillago (*S. sihama*)

Silver sillago, which reaches a maximum length of 31 cm (see text footnote 1), is widely distributed in the Indo-West Pacific, including China's coasts, from the Bohai Sea in the North to the South China Sea. This study estimated ratios F/M (=0.37) and B/B_0 (= 0.62). This suggests that fishing pressure may not be the major cause for the decrease in biomass of silver sillago. The parameters L_{c95}/L_{inf} (=0.95), L_{mean}/L_{opt} (=1), and L_c/L_{c_opt} (=1.1) are close to 1 (>0.9), suggesting that large fish are still present (**Figure 1G**).

Yellow Goosefish (*L. litulon*)

Yellow goosefish, reaching a maximum length of 150 cm (see text footnote 1), is distributed in the Northwest Pacific, including Japan, Korea, and the Yellow and East China Seas. The ratios F/M (= 4.4) and B/B_0 (= 0.06) indicate that yellow goosefish are suffering from overfishing pressure, and the biomass for this species is very low (**Figure 1H**).

Eight fish stocks in the coastal areas of Shandong Province, for which abundant data were available, were analyzed by the LBB method. The priors for the eight fish stocks, including asymptotic length, L_{inf}, Z/K, M/K, F/K, L_c, and α, are given in **Table 1**.

The results for the eight fish stocks obtained by the LBB method are presented in **Figure 1**. All eight stocks showed a similar trend; the top of the curve of relative frequency to L/L_{inf} was situated the left of L_{opt} and stayed away from the limit body length.

Three parameters (Z/K, L_{95th}/L_{inf}, and B/B_0) of eight stocks were all below unity, and three ratios (L_{mean}/L_{opt}, L_c/L_{c_opt}, and B/B_{MSY}) were also < 1, except for silver sillago. Both F/M and F/K were > 1. Detailed information for each parameter is given in **Table 2**.

DISCUSSION

The ratios L_{mean}/L_{opt} and L_c/L_{c_opt} were below unity in seven of the eight stocks, suggesting truncated length structure and fishing of too small individuals. The ratio of the 95th percentile length to asymptotic length L_{95th}/L_{inf} was close to unity (>0.9) in five of eight stocks, suggesting that at least some large fish were still present. The ratio B/B_0 was smaller than B_{MSY}/B_0 in all eight stocks, except for *S. sihama*, suggesting the fish species included in this study are being overfished. Furthermore, the relative biomass (B/B_0) for the eight species in Shandong's coastal seas evaluated here was 0.16 on average, which indicated a depletion rate of 84%. The result was consistent with the 84% average depletion reported by Zhai and Pauly, 2019.

The results given by the LBB method were compared with other research (**Table 3**). It was found that there were few studies on fishery resource assessments in coastal waters of Shandong. The assessments of *S. marmoratus* and *G. macrocephalus* were not reported in recently years. The studies on the other species, except for *S. sihama*, were consistent with our results that fishery resources of these species in this area were overfished.

For *S. japonicus*, our result was confirmed by the results of Yi and Chen (2019), who believed that the species was overfished in 2015 (**Table 3**). Thus, we strongly recommend that the intensity of fishing for *S. japonicus* in this area can be reduced, especially for larvae. For *H. otakii*, our result corresponded to other published research (Wang et al., 2018), where Beverton-Holt Y/R analysis was used to assess the resource of *H. otakii* in Shandong, with the result showing overfishing (**Table 3**). Reducing fishing pressure on this species would allow it to recover. Our result is also consistent with the study published by Li et al. (2015) in

TABLE 2 | Estimates of eight fish species for 2017 given by LBB.

Scientist name	L_{mean}/L_{opt}	L_c/L_{c_opt}	L_{95th}/L_{inf}	B/B_0	B/B_{MSY}	F/M	F/K	Z/K	Assessment
Scomber japonicus	0.59	0.49	0.88	0.033	0.091	5.4	8.3	9.77	Collapsed
Sebastiscus marmoratus	0.8	0.61	0.91	0.18	0.49	1.8	2.8	4.31	Grossly overfished
Hexagrammos otakii	0.82	0.73	0.93	0.12	0.35	2.6	4.6	6.34	Grossly overfished
Thryssa kammalensis	0.77	0.66	0.82	0.1	0.28	2.9	4.4	5.86	Grossly overfished
Gadus macrocephalus	0.51	0.37	0.95	0.043	0.12	3.5	5.1	6.61	Grossly overfished
Setipinna taty	0.72	0.57	0.87	0.16	0.44	1.7	2.4	3.87	Grossly overfished
Sillago sihama	1	1.1	0.95	0.62	1.7	0.37	0.67	2.48	Healthy
Lophius litulon	0.74	0.67	0.92	0.06	0.17	4.4	6.9	8.46	Grossly overfished

TABLE 3 | Comparison of fishery resource assessment studies for eight fish species.

Scientific name	Assessment method	Assessment result	Comparison with this study	References
Scomber japonicus	Pella-Tomlinson Model	Overfished	Consistent	Yi and Chen, 2019
Sebastiscus marmoratus	None	None	None	None
Hexagrammos otakii	Beverton-Holt Y/R analysis	Overfished	Consistent	Wang et al., 2018
Thryssa kammalensis	Fisheries resource survey	Overfished	Consistent	Ren et al., 2002
Gadus macrocephalus	None	None	None	None
Setipinna taty	Fisheries resource survey	Overfished	Consistent	Zhang et al., 2004
Sillago sihama	Beverton-Holt Y/R analysis	Overfished	Inconsistent	Liu et al., 2010
Lophius litulon	Fisheries resource survey	Overfished	Consistent	Li et al., 2015

which they found that *L. litulon* was suffering from overfishing, especially in the Yellow Sea (**Table 3**). In this study, our results suggested that *S. taty* is suffering from overfishing pressure and a low biomass, thus confirming the results of Zhang et al. (2004); they believed that it has been grossly overfished, and its juveniles have been severely damaged (**Table 3**). Thus, local governments should take measures to ease the decline of the species, such as reducing the intensity of fishing in the area and limiting the size of the nets. Similarly, Ren et al. (2002) suggested that *T. kammalensis* have been overfished, which is consistent with our results (**Table 3**). However, no models have been used to evaluate the resources of *T. kammalensis* in coastal areas of Shandong. Here, the taxonomic status of the species is unclear, and the name used here is tentative (Munroe and Nizinski, 1999). For *S. marmoratus*, this result is similar to other published studies, e.g., Yan et al. (2018), where the authors just mentioned that false kelpfish was overfished. Unfortunately, there is no research on resource assessment of *S. marmoratus* in coastal areas of Shandong. Similar issues face *G. macrocephalus*, and measures should be taken to limit the fishing of it, as this would allow its population to recover. While *S. sihama* was different, our result suggests that large fish are still present. However, Liu et al. (2010) used Beverton-Holt Y/R analysis to evaluate the resources of *S. sihama* in the waters of Beibu gulf in China, resulting in overfishing (**Table 3**), but the assessment in Shandong has not been reported.

CONCLUSION

Seven of the eight stocks examined in this study are overfished species in the Yellow and Bohai Seas and are trending toward miniaturization. As a result of long-term overfishing, the structure of fisheries resources in coastal areas of Shandong has been changed, i.e., scaly hairfin anchovy and kammal thryssa are no longer the dominant stock in this area; instead, the dominant stock are Pacific cod, fat greenling, and yellow goosefish. More seriously, chub mackerel of Shandong is on the verge of collapse due to chronic overfishing.

Fishery managers should provide species-specific size limits and enforce specific mesh sizes for fishing nets to help rebuild the fish populations. However, increasing mesh size would be difficult to implement (Liang and Pauly, 2017). Thus, we also suggest that the fishing intensity should be reduced by limiting the number, type, and time of fishing boats in Shandong's waters.

The LBB method needs no data other than body length and frequency to evaluate the fish resources in a certain area, which solves the problem that the resources cannot be evaluated due to the lack of available data in some areas. In contrast, the LBB method is not accurate enough in resource assessment because it just inputs length and frequency data. If the LBB method is used in combination with other models, the results may be more reliable.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

ETHICS STATEMENT

Our manuscript was based on survey cruise data, and no live vertebrates or higher invertebrates were involved, thus we believe an ethical review process was not required for our study.

AUTHOR CONTRIBUTIONS

YW analyzed the LF data and completed the first draft. YW provided guidance on data analysis and structure of the manuscript. SL provided the original length data. WX and HZ modified the manuscript. CL offered suggestions on the analysis and revised the manuscript again. All authors contributed to the revision of the manuscript.

FUNDING

The present work was supported by the National Key Research and Development Project of China (2019YFD0902101), the National Natural Science Foundation of China (Nos. 41976094 and 31872568), the Natural Science Foundation of China–Shandong Joint Fund for Marine Ecology and Environmental Sciences (U1606404), and the Key Deployment Project of Center for Ocean Mega-Science, Chinese Academy of Sciences (COMS2019Q14).

ACKNOWLEDGMENTS

The authors are grateful for advice from Rainer Froese on the use of the LBB method and to Daniel Pauly for his editing of the draft of this contribution.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00164/full#supplementary-material

REFERENCES

Beverton, R. J. H., and Holt, S. J. (1957). *On the dynamics of exploited fish populations. Ministry of Agriculture, Fisheries and Food*, Series II, XIX. London: Fishery Investigations, 533.

Cai, S., Xu, S., Song, N., Gao, T., and Zhang, Z. (2014). Mitochondrial DNA control region structure and length polymorphism analysis of *Setipinna tenuifilis*. *Acta Hydrobiol. Sin.* 38, 980–986. doi: 10.7541/2014.145

Du, T., Huang, Y., and Cao, J. (2009). A preliminary study on the temporary cultivation of *Sillago sihama*. *Anim. Breed. Feed* 10, 15–17.

FAO (2019). *FAO Yearbook*. Rome: Fishery and Aquaculture Statistics 2017.

Feng, Z., and Han, H. (1998). Rational utilization of *Hexagrammos otakii* resources. *J. Dalian Fish. Univ.* 13, 24–28.

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A. C., Dimarchopoulou, D., et al. (2018). A new approach for estimating stock status from length frequency data. *ICES J. Mar. Sci.* 75, 2004–2015. doi: 10.1093/icesjms/fsy078

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A. C., Dimarchopoulou, D., et al. (2019). On the pile-up effect and priors for Linf and M/K: response to a comment by hordyk et al. on "A new approach for estimating stock status from length-frequency data. *ICES J. Mar. Sci.* 76, 461–465. doi: 10.1093/icesjms/fsy199

Froese, R., Winker, H., Gascuel, D., Sumaila, U. R., and Pauly, D. (2016). Minimizing the impact of fishing. *Fish Fish.* 17, 785–802. doi: 10.1111/faf.12146

Fu, X., Song, T., Dai, G., Wang, Y., Lu, S., Guan, H., et al. (2007). Status and issues of marine fishery resources in Shandong province and the strategies for its sustainable exploitation. *Trans. Oceanol. Limnol.* 2, 164–170. doi: 10.13984/j.cnki.cn37-1141.2007.02.024

Gu, H. (1990). Feeding habits and food composition of scaly half-fin anchovy. Setipinna taty (C et V) in the Bohai Sea. *Chin. J. Oceanol. Limnol.* 8, 280–289. doi: 10.1007/BF02849668

Huang, Y., Du, T., and Huang, H. L. (2013). A study on artificial breeding of *Sillago sihama* Forskál. *J. Guangdong Ocean Univ.* 33, 15–21.

Li, F., Xu, B., and Wang, B. (2012). Fish community diversity during spring and autumn in the Yellow Sea off the coast of Shandong. *Biodiv Sci.* 20, 207–214. doi: 10.3724/sp.j.1003.2012.08239

Li, Z., Shan, X., Jin, X., Dai, F., and Lu, H. (2015). Interannual variations in the biological characteristics, distribution and stock density of anglerfish *Lophius litulon* in the central and southern Yellow Sea. *Acta Hydrobiol. Sin.* 26, 4007–4015. doi: 10.5846/stxb201310262585

Liang, C., and Pauly, D. (2017). Growth and mortality of exploited fishes in China's coastal seas and their uses for yield-per-recruit analyses. *J. Appl. Ichthyol.* 33, 746–756. doi: 10.1111/jai.13379

Lin, L., and Zheng, Y. (2004). Preliminary research on stock of *Lophius litulon* in the East China Sea region. *Mar. Fish* 26, 179–183.

Liu, J. D., Zhu, L. X., and Lu, H. S. (2010). Estimation of growth and mortality parameters of the silver sillago (*Sillago sihama*) in Beibu Gulf. *J. Zhejiang Ocean Uni.* 29, 64–69.

Lü, Z., Li, F., Xu, B., and Wang, B. (2012). Fish community diversity during spring and autumn in the Yellow Sea off the coast of Shandong. *Biodiversity Sci.* 20, 207–214. doi: 10.3724/SP.J.1003.2012.08239

Munroe, T. A., and Nizinski, M. (1999). "Engraulidae. Anchovies," in *FAO Species Identif. Guide Fish. Purp*, eds K. E. Carpenter, and V. H. Niem, (Rome: FAO), 1698–1706.

Park, J. M., Huh, S.-H., and Baeck, G. W. (2015). Feeding habits of kammal thryssa *Thryssa kammalensis* (Bleeker, 1849) in the coastal waters of Gadeok-do. *Korea. Anim. Cells Syst.* 19, 350–358. doi: 10.1080/19768354.2014.907206

Ren, Y., Liu, Q., Li, Q., and Chen, Y. (2002). Biological characteristics of some small species in *Engraulidae* and *Clupeidae*. *JOL* 1, 69–74. doi: 10.13984/j.cnki.cn37-1141.2002.01.010

Tang, Q., and Ye, M. Z. (1990). *Exploitation and Conservation of Offshore Fishery Resources in Shandong Province*. Beijing: China Agriculture Press.

von Bertalanffy, L. (1938). A quantitative theory of organic growth (inquiries on growth laws. ii). *Hum. Biol.* 10, 181–213. doi: 10.2307/41447359

Wang, J. Q., Liu, S. D., Tang, Y. L., Yang, W. Z., and Fang, G. J. (2018). Growth, mortality and resource evaluation of *Hexagrammos otakii* inhabiting the artificial reef area of Lidao. Shandong Province. *Periodical. Ocean Univ. China* 48, 51–59.

Xu, Y., Liu, X., Shi, B., and Wang, B. (2017). Domestication of wild broodstock and early development of Pacific cod (*Gadus macrocephalus*) *J. Prog.Fish. Sci.* 38, 159–167.

Yan, Y., Liu, Y., Shi, Y., Xie, Y., Deng, P., and Yuan, X. (2018). Preliminary study on indoor artificial breeding technology of *Sebastes marmoratus*. *Fish. Sci. Technol. Inform.* 45, 322–326.

Yao, S., Yong, L., Bo, Z., and Qisheng, T. (2003). Food consumption, growth and ecological conversion efficiency of *Thryssa kammalensis*, determined by eggers model in laboratory. *Acta Hydrobiol. Sin.* 23:1216.

Yi, W., and Chen, X. (2019). Establishment of Pella-tomlinson model for east china and yellow sea *Scomber japonicus* based on environmental factors. *J. Guangdong Ocean Univ.* 39, 49–55.

Zhai, L., and Pauly, D. (2019). Yield-per-recruit, utility-per-recruit and relative biomass of 21 exploited fish species in China's coastal seas. *Front. Mar. Sci.* 6:724. doi: 10.3389/fmars.2019.00724

Zhang, M. H., Wang, Y., and Zhang, J. (2004). Studies on the growth and death character of *Setipinna taty* in the South of Bohai Sea. *J. Zhejiang Ocean Univ.* 23, 31–36.

Zhang, N., Du, W., Wang, Z., Huang, Y., Du, T., and Dong, Z. (2018). Screening of reference genes for Real-time PCR in different tissues from *Sillago sihama*. *J. Guangdong Ocean Univ.* 38, 8–14. doi: 10.3969/j.issn.1673-9159.2018.05.002

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Marine Science

BRIEF RESEARCH REPORT
published: 14 May 2020
doi: 10.3389/fmars.2020.00314

Assessments of 14 Exploited Fish and Invertebrate Stocks in Chinese Waters Using the LBB Method

Cui Liang[1,2,3], Weiwei Xian[1,2,3]*, Shude Liu[4] and Daniel Pauly[5]*

[1] CAS Key Laboratory of Marine Ecology and Environmental Sciences, Institute of Oceanology, Chinese Academy of Sciences, Qingdao, China, [2] Laboratory for Marine Ecology and Environmental Science, Qingdao National Laboratory for Marine Science and Technology, Qingdao, China, [3] Center for Ocean Mega-Science, Chinese Academy of Sciences, Qingdao, China, [4] Shandong Hydrobios Resources Conservation and Management Center, Yantai, China, [5] Sea Around Us, Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, BC, Canada

Due to limited data availability, only a small subset of the exploited fish and invertebrate populations have been assessed along Chinese coasts, which precludes comprehensive management of the fisheries. Here, we applied a length-based Bayesian biomass estimator (LBB) to 14 fish and invertebrate stocks in China's coastal waters to estimate their growth, length at first capture and current relative biomass (B/B_0, B/B_{MSY}) from length-frequency (LF) data. Of the 14 populations assessed, one have collapsed, nine are grossly over-exploited, and three are overfished. Moreover, 13 populations have smaller mean lengths at first capture (L_c) than the optimal length at first capture (L_{c_opt}), indicating that they are suffering from growth overfishing. Thus, larger mesh sizes in commercial fishery would increase both the catch and biomass for these species, given current levels of fishing mortality. Our results confirm that fishery resources in China's coastal waters are strongly depleted, and that stricter management measures are needed to restore the abundance of China's marine fisheries resources.

Keywords: stock assessment, data-poor stocks, length-frequency data, biomass estimation, LBB method

OPEN ACCESS

Edited by:
JInghui Fang,
Yellow Sea Fisheries Research Institute (CAFS), China

Reviewed by:
Hiroshi Okamura,
Japan Fisheries Research and Education Agency, Japan
Claudio Vasapollo,
National Research Council (CNR), Italy

****Correspondence:***
Cui Liang
liangc@qdio.ac.cn;
cui-liang@hotmail.com
Weiwei Xian
wwxian@qdio.ac.cn

Specialty section:
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

Received: *21 January 2020*
Accepted: *16 April 2020*
Published: *14 May 2020*

Citation:
Liang C, Xian W, Liu S and Pauly D (2020) Assessments of 14 Exploited Fish and Invertebrate Stocks in Chinese Waters Using the LBB Method. Front. Mar. Sci. 7:314. doi: 10.3389/fmars.2020.00314

INTRODUCTION

As a result of decades of rapid development, China has become the country with the world's largest fishery (FAO, 2018). Currently, China's marine catch is around 10 million metric tons, with the bottom trawl fishery accounting for five million metric tons. However, this high reported catch is associated with very low catch per unit of effort, and the "fishing down" phenomenon was also shown to occur. Thus, to effectively rebuild fishery resources in China, robust management systems are needed, based on reliable stock assessment.

Most stock assessment models are designed to estimate fisheries and population-related reference points using fisheries-independent data sets, such as catch-at-age data and biomass estimates from scientific surveys (Methot and Wetzel, 2013). However, in China, due to limited data and expertise, only a small subset of the commercially exploited stocks, such as largehead hairtail *Trichiurus lepturus* and yellow croaker *Larimichthys polyactis*, have been assessed by dedicated stock assessment (Liu et al., 2013; Zhang and Chen, 2015). This situation is similar to that of many countries in the global South, where fishery research has been languishing.

In response to this issue, two basic approaches of methods were developed to perform stock assessments in data-sparse environments. One approach was to use catch time series and ancillary data to estimate Maximum Sustainable Yield (MSY) and related statistics (Schaefer, 1954; Froese et al., 2017). The other approach uses length-frequency (LF) data for inferences on the growth, mortality and hence populations' response to fishing; see contributions in Pauly and Morgan (1987) and Pauly (1998), and Liang and Pauly (2017b) for a recent application to China's coastal fisheries. The latter approach has the advantage that LF data is generally easier and cheaper to acquire, which makes LF-based methods the preferred approach in many situations.

LBB is a newly developed length-based Bayesian biomass estimation method (Froese et al., 2018) requiring LF data that are representative of the fishery under study. It then uses a Bayesian Monte Carlo Markov Chain (MCMC) to estimate growth and mortality parameters and relative stock size. Thus, even in data-poor situations, LBB assessment can be used directly by fishery managers. Also, LBB results can be used as priors for stock assessment methods requiring an independent estimate of biomass relative to unfished biomass as input.

In this contribution, we applied LBB method to 14 fish and invertebrate populations in Chinese coastal waters to explore the extent of biomass depletion caused by fisheries, and to provide evidence for potential alternative harvest policies.

MATERIALS AND METHODS

Data Source

The data source and basic information of the 14 fish and invertebrate populations covered here are given in **Supplementary Tables S1**, **S2** (see **Supplementary Materials**). Most LF data were read off from scientific papers.

However, the LF data for spiny red gurnard *Chelidonichthys spinosus*, hakodate sand shrimp *Crangon affinis*, red tonguesole *Cynoglossus joyneri*, slender lizardfish *Saurida elongata*, southern rough shrimp *Trachysalambria curvirostris* were obtained from cruises performed in 2016 to 2017 on board of hired private fishing vessels operating in the Bohai Sea and North Yellow Sea, and which used the same gear as when fishing commercially.

General Description of LBB Method

The core of the LBB method is the von Bertalanffy growth function (VBGF; von Bertalanffy, 1938; Pauly, 1998), used to depict the growth in body length.

$$L_t = L_{\text{inf}} \left[1 - e^{-K(t-t_0)}\right] \quad (1)$$

where L_t is the length at age t, L_{inf} is the asymptotic length, i.e., the mean length that the individuals of the species and stock in question would reach if they were to grow indefinitely, K is the rate by which L_{inf} is approached (year^{-1}), and t_0 is the age the fish would have at zero length if they always grew according to the VBGF.

Most species exploited by commercial fishery grow throughout their lives, and thus would approach L_{inf} if it were not for mortality, which is expressed by:

$$N_{t2} = N_{t1} \cdot exp - (Z\ (t_2 - t_1)) \quad (2)$$

where N_{t1} and N_{t2} are the numbers of a given cohort or a population at time 1 and 2, and Z is the instantaneous rate of total mortality, consisting of natural and fishing mortality, i.e., $Z = M + F$ (Beverton and Holt, 1957; Pauly, 1998; Sparre and Venema, 1998).

Fishing gears have characteristic selection curves; the selection assumed in LBB is of the trawl type, i.e., very small individuals ($<L_x$) are not caught, all individuals past a certain size ($>L_{start}$) are caught, while the faction caught between L_x and L_{start} is an increasing function of the sizes. Such gear selectivity can be represented by

$$S_L = \frac{1}{1 + e^{-\alpha\,(L-L_c)}} \quad (3)$$

where S_L is the fraction of individuals that are retained by the gear at length L. In other words, S_L equals 0 when the length of individuals is less than L_x, and is 1 when individuals exceed the length where full selection occurs. When individuals are subject to partial selection, S_L ranges from 0 to 1. In Eq. 3, α is the steepness of the ogive describing the length-dependent selectivity of the gear (Sparre and Venema, 1998). Thus, one can calculate the mean size at first capture (L_c), i.e., the length at which 50% of the individuals encounter the gear will be retained by it.

Combining Eqs. (1–3) and rearranging lead to:

$$N_{L_i} = N_{L_{i-1}} \left(\frac{L_{\text{inf}} - L_i}{L_{\text{inf}} - L_{i-1}}\right)^{\frac{M}{K} + \frac{F}{K} S_{L_i}} \quad (4)$$

and

$$C_{L_i} = N_{L_i}\, S_{L_i} \quad (5)$$

where N_{L_i} is the number of individuals at length L_i,$N_{L_{i-1}}$ refers to the number at the previous length L_{i-1}, C is the number of individuals vulnerable to the gear, and all other parameters are as defined above. To minimize the parameter requirements of this approach method, the ratios *M/K* and *F/M* are output, instead of the absolute values of *F*, *M*, and *K*; note that *F/M = (F/K)/(M/K)*.

Also note that LBB, although it refers to "mean length at first capture" (L_c) in fact accounts for gradual selection as described by Eq. 3, including accounting for the fish that are caught at very small sizes (larger than L_x, but below L_c) which are not compensated for by the larger fish that are not caught above L_c, but below L_{start} (Silvestre et al., 1991).

When a species has more than one year LF data, the catch in numbers are made comparable between years by dividing both sides of Eq. 5 by their respective sums:

$$\frac{C_{L_i}}{\sum C_{L_i}} = \frac{N_{L_i} S_{L_i}}{\sum N_{L_i} S_{L_i}} \tag{6}$$

Then M/K and F/K can be deduced by fitting Eq. 4 to LF data.

Relative yield-per-recruit (Y'/R), as defined by Beverton and Holt (1966) can be computed, as presented by Froese et al. (2018) from:

$$\frac{Y'}{R} = \frac{F/M}{1+F/M}\left(1-\frac{L_c}{L_{\text{inf}}}\right)^{\frac{M}{K}}\left(1-\frac{3\,(1-L_c/L_{\text{inf}})}{1+\frac{1}{M/K+F/K}} + \frac{3\,(1-L_c/L_{\text{inf}})^2}{1+\frac{2}{M/K+F/K}} - \frac{(1-L_c/L_{\text{inf}})^3}{1+\frac{3}{M/K+F/K}}\right) \tag{7}$$

Assuming CPUE proportional to biomass, dividing Eq. 7 by F/M gives:

$$\frac{CPUE'}{R} = \left(\frac{Y'}{R}\right) \Big/ \left(\frac{F}{M}\right) = \left(\frac{1}{1+\frac{F}{M}}\right)\left(1-\frac{L_c}{L_{\text{inf}}}\right)^{\frac{M}{K}} \left(1-\frac{3\,(1-L_c/L_{\text{inf}})}{1+\frac{1}{M/K+F/K}} + \frac{3\,(1-L_c/L_{\text{inf}})^2}{1+\frac{2}{M/K+F/K}} - \frac{(1-L_c/L_{\text{inf}})^3}{1+\frac{3}{M/K+F/K}}\right) \tag{8}$$

Relative biomass of fish ($>L_c$) when $F = 0$ is then given by

$$\frac{B_0 > L_c}{R} = \left(1-\frac{L_c}{L_{\text{inf}}}\right)^{\frac{M}{K}}\left(1-\frac{3\,(1-L_c/L_{\text{inf}})}{1+\frac{1}{M/K}} + \frac{3\,(1-L_c/L_{\text{inf}})^2}{1+\frac{2}{M/K}} - \frac{(1-L_c/L_{\text{inf}})^3}{1+\frac{3}{M/K}}\right) \tag{9}$$

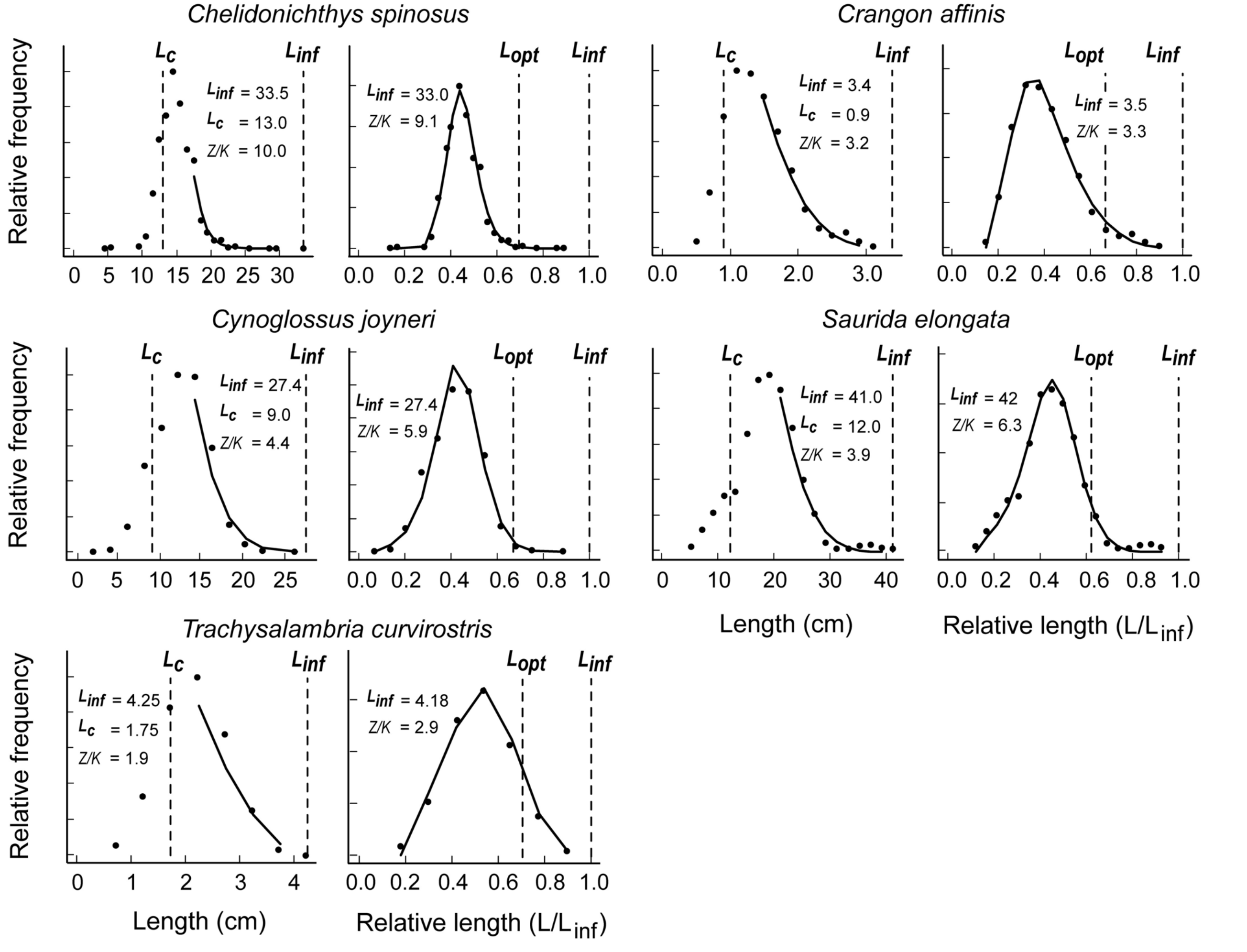


FIGURE 1 | Application of the LBB method to five species of commercially exploited fish for which length-frequency sample were obtained from cruises (see also **Table 1** and **Supplementary Tables S1, S2**).

TABLE 1 | Summary of LBB results for 14 populations.

Scientific name (common name)	L_{inf} (mm)*	L_c/L_{c_opt}	Z/K*	B/B_0*	B/B_{MSY}*	Status†
Chelidonichthys spinosus (spiny red gurnard)	330 (326–336)	0.62	9.10 (8.52–9.74)	0.042 (0.029–0.059)	0.11 (0.078–0.16)	Collapsed
Crangon affinis (hakodate sand shrimp)	34.5 (34.0–35.1)	0.46	3.28 (3.11–3.47)	0.21 (0.16–0.29)	0.58 (0.44–0.80)	Overfished
Cynoglossus joyneri (red tonguesole)	274 (270–280)	0.69	5.87 (5.52–6.3)	0.10 (0.071–0.14)	0.28 (0.19–0.39)	Grossly overfished
Saurida elongata (slender lizardfish)	420 (411–426)	0.78	6.32 (5.82–6.69)	0.13 (0.099–0.17)	0.37 (0.28–0.47)	Grossly overfished
Trachysalambria curvirostris (southern rough shrimp)	41.8 (41.1–42.5)	0.78	2.92 (2.68–3.26)	0.26 (0.15–0.39)	0.70 (0.41–1.00)	Overfished
Hexagrammos agrammus (spotty-bellied greenling)	284 (279–290)	0.64	5.48 (5.09–5.93)	0.076 (0.046–0.12)	0.21 (0.12–0.30)	Grossly overfished
Muraenesox cinereus (daggertooth pike conger)	534 (525–541)	0.67	4.91 (4.52–5.27)	0.13 (0.085–0.19)	0.35 (0.23–0.52)	Grossly overfished
Pennahia pawak (pawak croaker)	242 (239–245)	1.10	2.09 (1.93–2.30)	0.70 (0.034–1.80)	1.90 (0.094–4.90)	Healthy
Setipinna taty (scaly hairfin anchovy)	200 (196–204)	0.60	3.48 (3.27–3.70)	0.19 (0.11–0.29)	0.51 (0.30–0.79)	Overfished
Decapterus maruadsi (Japanese scad)	279 (276–282)	0.90	2.72 (2.49–2.95)	0.30 (0.14–0.50)	0.78 (0.36–1.30)	Overfished (1998)
	278 (274–282)	0.81	5.14 (4.81–5.52)	0.17 (0.11–0.24)	0.46 (0.30–0.68)	Grossly overfished (2009)
Evynnis cardinalis (threadfin porgy)	219 (215–221)	0.72	3.39 (3.19–3.72)	0.17 (0.096–0.26)	0.46 (0.25–0.69)	Grossly overfished (1962)
	215 (212–218)	0.62	5.59 (5.23–5.92)	0.082 (0.053–0.12)	0.22 (0.14–0.32)	Grossly overfished (2006)
Liparis tanakae (Tanaka's snailfish)	545 (538–555)	1.00	4.11 (3.80–4.49)	0.29 (0.20–0.41)	0.80 (0.55–1.10)	Slightly overfished (2005)
	531 (525–539)	0.88	5.53 (5.13–6.03)	0.11 (0.077–0.15)	0.28 (0.20–0.40)	Grossly overfished (2010)
Nemipterus bathybius (yellowbelly threadfin bream)	244 (240–248)	0.82	3.97 (3.77–4.32)	0.24 (0.17–0.32)	0.66 (0.46–0.88)	Overfished (2005)
	239 (235–242)	0.65	5.06 (4.86–5.33)	0.10 (0.073–0.15)	0.28 (0.19–0.40)	Grossly overfished (2009)
Priacanthus macracanthus (red bigeye)	307 (302–312)	0.53	3.08 (2.91–3.32)	0.33 (0.20–0.52)	0.91 (0.55–1.40)	Slightly overfished (1999)
	303 (297–308)	0.56	3.70 (3.46–3.96)	0.18 (0.12–0.25)	0.48 (0.32–0.67)	Grossly overfished (2015)

**The number between brackets stand for 95% confidence intervals for the parameter estimates in provides; †The number between brackets represent different years when the LF data were sampled.*

where B_0 is the unfished biomass. Thus, the ratio of fished to unfished biomass is

$$B\Big/B_0 = \left(\frac{CPUE'}{R}\right)\Big/\left(\frac{B_0' > L_c}{R}\right) \tag{10}$$

(Froese et al., 2018).

Also, we have

$$L_{opt} = L_{inf} \cdot 3/(3 + \ M/K) \tag{11}$$

where L_{opt} is the length when a cohort of fish has its maximum biomass (Holt, 1958). This allows defining:

$$L_{c\_opt} \ = \ \frac{L_{\text{inf}}\left(2 + 3\frac{F}{M}\right)}{\left(1 + \frac{F}{M}\right)\left(3 + \frac{M}{K}\right)} \tag{12}$$

i.e., the mean length at first capture which maximizes the catch and the biomass for a given pair of F/M and M/K ratios.

A proxy for the relative biomass that can produce MSY (B_{MSY}/B_0) was obtained by re-running Eqs. 7–10 with $F/M = 1$ and $L_c = L_{c\_opt}$. With these parameters, current relative stock size (B/B_{MSY}) can be deduced; the nomenclature in Palomares et al. (2018) was used to convert estimates of B/B_{MSY} into qualifiers of fisheries status.

If reliable estimates of L_{inf} from independent sources are available, they can be used as priors in LBB analyses to decrease their uncertainty. In this contribution, we use L_{inf} information from FishBase for fishes[1] or SeaLifeBase for invertebrates[2] as priors.

We used the 32.0 version of the LBB software (a package in R), which automatically generate priors for L_c using the mean of L_{10} and L_{90}, where L_{10} and L_{90} are lengths at 10 and 90% of the range of the LF data, respectively. M/K is set as a default value 1.5; Z/K prior is estimated according to Beverton and Holt [1957; $Z/K = (L_{inf} - L_{mean})/(L_{mean} - L_c)$]; F/K prior equals to Z/K-M/K.

RESULTS

Figure 1 presents the LBB analyses for the five species with original LF data obtained from field surveys conducted in the Bohai Sea and North Yellow Sea 2016–2017 (see **Supplementary Tables S1, S2**). As might be seen, the LBB model fit to all five species, yielding estimates of B/B_{MSY} ranging from 0.70 to 0.11 (**Table 1**). Among these five stocks, that of spiny red

[1] www.fishbase.org
[2] www.sealifebase.org

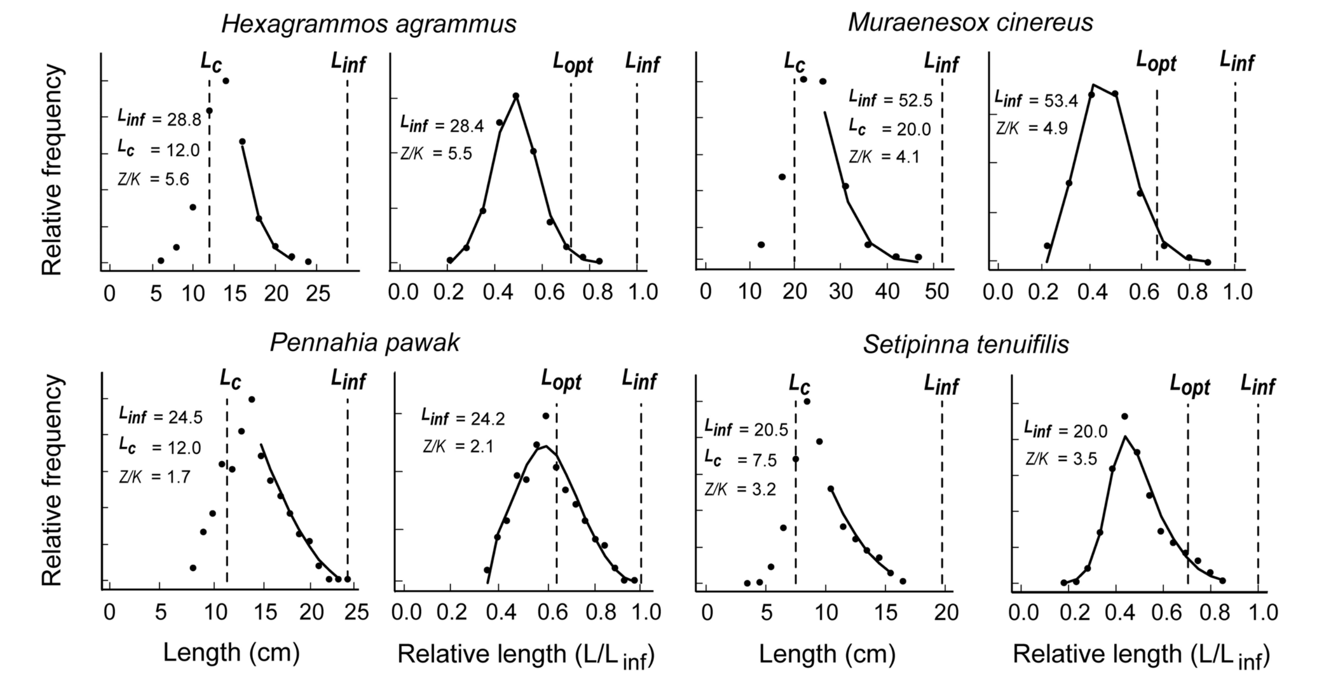


FIGURE 2 | Application of the LBB method to 4 species of commercially exploited fish along the coast of China and for with length-frequency data were obtained from Zhou and Xu (2007), Xiong et al. (2009), Yan et al. (2011), and Ji (2014); see also **Table 1** and **Supplementary Tables S1, S2**.

gurnard (*C. spinosus*) has collapsed, and the other four stocks are overfished or grossly overfished given the definitions of stock status in Palomares et al. (2018).

Figure 2 presents similar results for four species with previously published LF data (see **Supplementary Tables S1**, **S2**). Here again, the LBB gives a good fit, and estimates of B/B_{MSY} ranging from 1.90 to 0.21 (**Table 1**). Except for pawak croaker (*Pennahia pawak*), which appeared to be in a healthy state based on our estimates, the other stocks appear to be over-exploited.

Figure 3 presents LBB applications to five species each, and for which LF data were available for two distinct periods (see also **Supplementary Tables S1, S2**). As might be seen, for all five species, the estimates of L_{inf}, L_c/L_{c_opt} and Z/K increased (**Figure 3** and **Table 1**), while B/B_{MSY} decreased (**Table 1**), as would occur if fishing effort increased over time.

Besides pawak croaker, 13 stocks have L_c/L_{c_opt} less than one, implying that they are suffering from growth overfishing; thus increasing the mesh size of the gears exploiting them would lead to increases of their biomass and catch.

DISCUSSION

Full stock assessment generally requires fisheries-independent data sets, thus constrains its application in data-poor circumstances, which is the case for most China's coastal stocks (Geng et al., 2018). New computer-based methods came to the rescue with the advent of personal computers. One of the methods which the availability of computers made possible is the CMSY method (Froese et al., 2017), which uses a time series of catch and - if available - proxies of stock abundance (such as CPUE data) to infer MSY and fisheries reference points. However, in China, due to the fisheries catch misreporting, reliable catch data cannot be easily accessed (Jacquet et al., 2010).

The size composition (LF data) of exploited stocks has long been used to estimate exploitation rate and stock status (Beverton and Holt, 1957; Pauly and Morgan, 1987). Methods based on LF data can be either used directly in data-sparse fisheries management, or for providing prior of current relative biomass in other assessment models (Froese et al., 2017). LBB is a new Bayesian MCMC approach for the analysis of LF data from commercial catch.

The LBB method assumes constant recruitment, growth and mortality; thus it should not be used if these assumptions are strongly violated. The LBB method will also generate biased estimates if LF data are not representative, such as data sampled by gears that have a different selectivity or catchability than commercial gears, or in areas where only juveniles or adults occur. However, when reliable LF data are available, the LBB method can offer a window into the dynamics of the stocks, especially in data-poor situations.

In this contribution, we applied the LBB method to LF data of 14 fish and invertebrate populations from China's coastal waters. Among these, and given the nomenclature in Palomares et al. (2018), one population has collapsed and nine are grossly overfished. Our results are generally consistent with what is known of China's coastal resources, that is, the biomass of most populations are severely depleted, especially for main commercial species. The decline of fishery resources

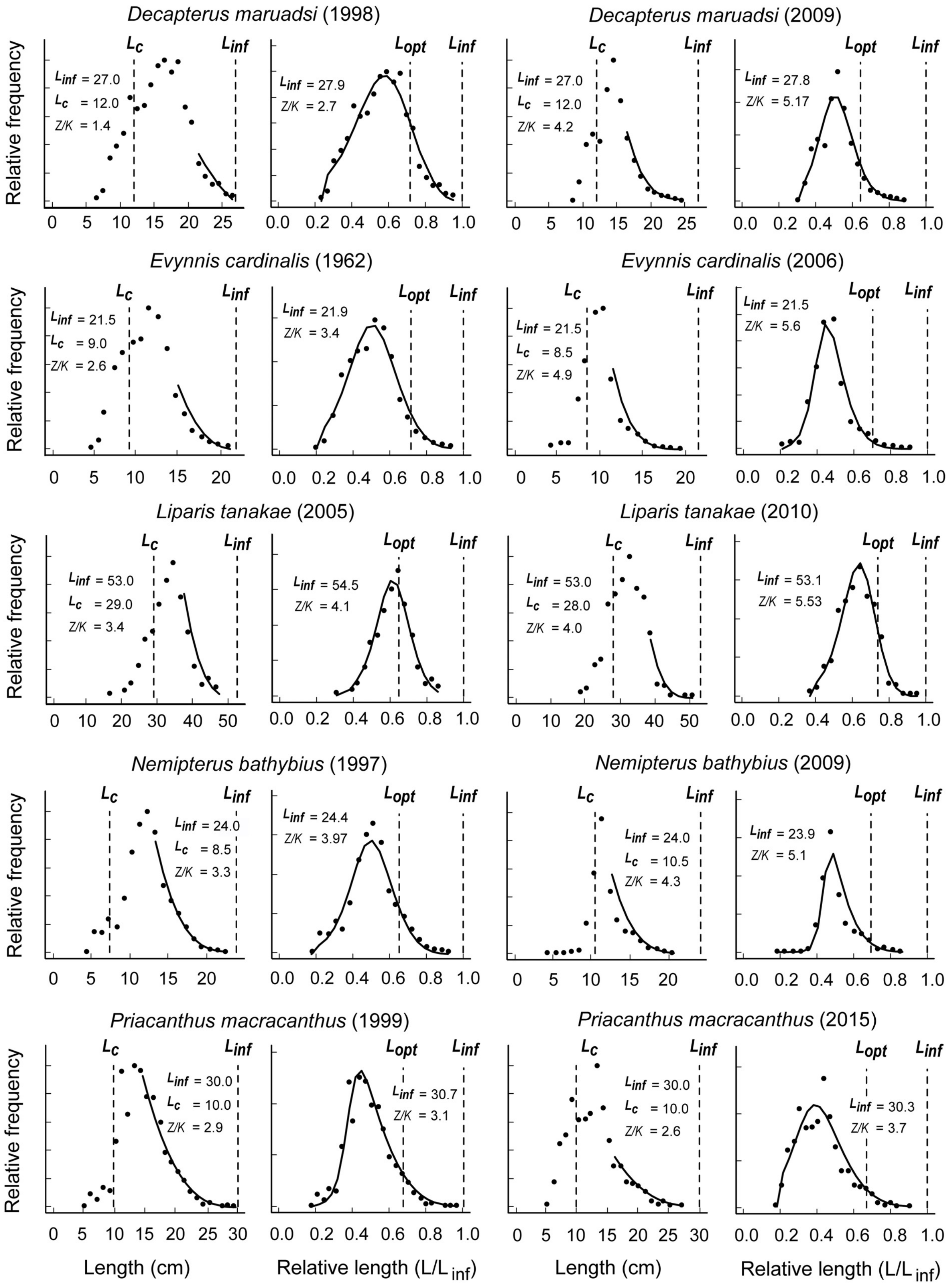


FIGURE 3 | Application of the LBB method to 5 species of commercially exploited fish along the coast of China (Japanese scad *Decapterus maruadsi*, threadfin porgy *Evynnis cardinalis*, Tanaka's snailfish *Liparis tanakae*, yellowbelly threadfin bream *Nemipterus bathybius*, and red bigeye *Priacanthus macracanthus*) and for with length-frequency data were obtained from two different time periods from Geng et al. (2018), Chen et al. (2012, 2013), and Zhang et al. (2016a,b); see **Table 1** and **Supplementary Tables S1, S2**.

is confirmed by the decreased CPUE along Chinese coastal waters (Kang et al., 2018), the increased proportion of "trash fish" (Greenpeace, 2017; Zhang et al., 2020), and the occurrence of the "fishing down" effect in China's coastal waters (Liang and Pauly, 2017a).

Despite the depletion of its coastal resources, China's reported marine catch remains at a high level, which might be attributed to the illegal use of very small mesh size (∼10 mm) in commercial bottom trawl fisheries along Chinese coastal waters. Based on our results, we concluded that among 14 populations in question, 13 stocks had smaller mean sizes at first capture than L_{c_opt}, indicating that an increase in mesh size would increase both the catch from, and the biomass of these populations. This is in accordance with the finding of Liang and Pauly (2017b) and of Zhai and Pauly (2019).

Greenpeace (2017) released a report on China's "trash fish" (fish that are too small for direct human consumption) fisheries, and pointed out that fishes in the larval or fingerling stages accounted for a large proportion of the catch of China's coastal fisheries. To promote the restoration and sustainable use of marine fishery resources, China issued an announcement to regulate minimum catchable standards and juvenile fish proportion for 14 important commercial fish species, including *Trichiurus japonicus*, *L. polyactis* and *Pampus argenteus* (Ministry of Agriculture and Rural Affairs of the People's Republic of China, 2018). This shows that China has taken this issue into account; how this regulation will be implemented will be crucial.

Our results show that reducing fishing mortality and increasing mesh size would benefit catch and biomass. This was backed up by Costello et al. (2016), who demonstrated that applying sound management reforms to Chinese fisheries could generate considerable increases in catch, biomass and profit relative to business as usual. In China, seafood is regarded as an excellent source of high-quality protein. The domestic consumption for seafood in China has significantly increased, from 7 kg per person in 1985 to around 25 kg per person in the early 2000s (Gao and Gao, 2005). The large demand for seafood has imposed enormous pressure on China's coastal fisheries. However, it is obvious that the current management measures are not sufficient, and more stringent measures are needed to restore thriving coastal fisheries.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because our manuscript was based on survey cruise data or published data, and no live vertebrates or higher invertebrates were involved.

AUTHOR CONTRIBUTIONS

CL, WX, and SL were responsible for data collecting, formal analysis and writing original manuscript. DP contributed to the methodology, reviewing and editing the draft.

FUNDING

CL and WX acknowledge financial support from National Natural Science Foundation of China (No. 31872568), NSFC-Shandong Joint Fund for Marine Ecology and Environmental Sciences (U1606404), and Qingdao Postdoctoral Applied Research Project; DP is supported by the *Sea Around Us*, a research initiative at UBC funded by a number of philanthropic foundations, notably the Oak, Marisla and Minderoo Foundationd.

ACKNOWLEDGMENTS

We are grateful to Evelyn Liu for redrawing the Figures.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00314/full#supplementary-material

REFERENCES

Beverton, R. J. H., and Holt, S. J. (1957). *On the Dynamics of Exploited Fish Populations*. London: Ministry of Agriculture, Fisheries and Food.

Beverton, R. J. H., and Holt, S. J. (1966). "Manual of methods for fish stock assessment, Part II – tables of yield functions," in *FAO Fisheries Technical Paper No. 38*, (Rome: FAO), 10.

Chen, Y., Shan, X., Zhou, Z., Dai, F., Li, Z., and Jin, X. (2013). Interannual variation in the population dynamics of snailfish *Liparis tanakae* in the Yellow Sea. *Acta Ecol. Sin.* 33, 6227–6235.

Chen, Z., Kong, X., Xu, S., Qiu, Y., and Huang, Z. (2012). Dynamic changes of population parameters of *Nemipterus bathybius* in the Beibu Gulf. *J. Fish. China* 36, 584–591.

Costello, C., Ovando, D., Clavelle, T., Strauss, C. K., Hilborn, R., Melnychuk, M. C., et al. (2016). Global fishery prospects under contrasting management regimes. *Proc. Natl. Acad. Sci.* 113, 5125–5129. doi: 10.1073/pnas.1520420113

FAO (2018). *The State of World Fisheries and Aquaculture 2018-Meeting the Sustainable Development Goals*. Rome: FAO.

Froese, R., Demirel, N., Coro, G., Kleisner, K. M., and Winker, H. (2017). Estimating fisheries reference points from catch and resilience. *Fish Fish.* 18, 506–526.

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A. C., Dimarchopoulou, D., et al. (2018). A new approach for estimating stock status from length frequency data. *ICES J. Mar. Sci.* 75, 2004–2015.

Gao, J., and Gao, X. (2005). "The import and export of China's seafood," in *The Chinese seafood Industry: Structural Changes and Opportunities for Norwegians*, eds K. B. Lindkvist, Z. Wang, G. H. Hansen, and H. Haarstad (Bergen: Samfunns- og næringslivsforskning AS), 155–164.

Geng, P., Zhang, K., Chen, Z., Xu, Y., and Sun, M. (2018). Interannual change in biological traits and exploitation rate of *Decapterus maruadsi* in Beibu Gulf. *South China Fish. Sci.* 14, 1–9.

Greenpeace (2017). The Current Status of Marine Fishing for "Trash Fish" in China and its Implications for China's Sustainable Fisheries Development. Available online at: https://www.greenpeace.org.cn/nearly-4-million-tons-of-trash-fish-in-china-inshore-fishery-catch/

Holt, S. J. (1958). "The evaluation of fisheries resources by the dynamic analysis of stocks, and notes on the time factors involved," in *International Commission for the Northwest Atlantic Fisheries*, (Vancouver: ICNAF Special Publication), 77–95.

Jacquet, J., Zeller, D., and Pauly, D. (2010). Counting fish: a typology for fisheries catch data. *J. Integr. Environ. Sci.* 7, 135–144.

Ji, D. (2014). *Study on the Fishery Biology of Hexagrammos Agrammus and Hexagrammos Otakii in Lidao Rongcheng*. Doctor dissertation, Ocean University of China, Qingdao.

Kang, B., Liu, M., Huang, X. X., Li, J., Yan, Y. R., Han, C. C., et al. (2018). Fisheries in Chinese seas: what can we learn from controversial official fisheries statistics? *Rev. Fish Biol. Fish.* 28, 503–519.

Liang, C., and Pauly, D. (2017a). Fisheries impacts on China's coastal ecosystems: unmasking a pervasive 'fishing down'effect. *PloS One* 12:e0173296. doi: 10.1371/journal.pone.0173296

Liang, C., and Pauly, D. (2017b). Growth and mortality of exploited fishes in China's coastal seas and their uses for yield-per-recruit analyses. *J. Appl. Ichthyol.* 33, 746–756.

Liu, Z., Xie, H., Yan, L., Yuan, X., Yang, L., Li, Y., et al. (2013). Comparative population dynamics of small yellow croaker *Larimichthys polyactis* in Southern Yellow Sea and East China Sea. *J. Dalian Ocean Univ.* 28, 627–632.

Methot, R. D., and Wetzel, C. R. (2013). Stock synthesis: a biological and statistical framework for fish stock assessment and fishery management. *Fish. Res.* 142, 86–99.

Palomares, M. L. D., Froese, R., Derrick, B., Nöel, S.-L., Tsui, G., Woroniak, J., et al. (2018). "A preliminary global assessment of the status of exploited marine fish and invertebrate populations," in *A Report Prepared by the Sea Around Us for OCEANA*, (Washington, DC: OCEANA), 64.

Pauly, D. (1998). Beyond our original horizons: the tropicalization of Beverton and Holt. *Rev. Fish Biol. Fish.* 8, 307–334.

Pauly, D., and Morgan, G. R. (1987). *Length-Based Methods in Fisheries Research*. Penang: WorldFish.

Schaefer, M. B. (1954). Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Inter Am. Trop. Tuna Comm. Bull.* 1, 23–56. doi: 10.1016/S0065-2881(09)56003-8

Silvestre, G., Soriano, M., and Pauly, D. (1991). Sigmoid selection and the beverton and holt equation. *Asian Fish. Sci.* 4, 85–98.

Sparre, P., and Venema, S. C. (1998). *Introduction to Tropical Fish Stock Assessment. Part 1. Manual. FAO Fisheries Technical Paper No. 306.1, Rev. 2*. Rome: FAO.

von Bertalanffy, L. (1938). A quantitative theory of organic growth (inquiries on growth laws. II.). *Hum. Biol.* 10, 181–213.

Xiong, Y., Tang, J., Liu, P., Zhong, X., Yan, L., Gao, Y., et al. (2009). Resource estimate on *Setipinna taty* in the Southern Yellow Sea. *Oceanol. Limnol. Sin.* 40, 500–505.

Yan, Y., Hou, G., Lu, H., and Yin, Q. (2011). Age and growth of pawak croaker *Pennahia pawak* in Beibu Gulf. *J. Fish. Sci. China* 18, 145–155.

Zhai, L., and Pauly, D. (2019). Yield-per-recruit, utility-per-recruit and relative biomass of 21 exploited fish species in China's coastal seas. *Front. Mar. Sci.* 6:724. doi: 10.3389/fmars.2019.00724

Zhang, K., and Chen, Z. (2015). Using bayesian state-space modelling to assess *Trichiurus lepturus* stock in the East China Sea. *J. Fish. Sci. China* 22, 1015–1026.

Zhang, K., Chen, Z., and Qiu, Y. (2016a). Decadal changes in growth, mortality and maturity parameters of *Evynnis cardinalis* in Beibu Gulf. *South China Fish. Sci.* 12, 9–16.

Zhang, K., Chen, Z., Wang, Y., Sun, D., and Qiu, Y. (2016b). Population structure of *Priacanthus macracanthus* in the Beibu Gulf, and parameters for its growth, mortality and maturity. *J. Trop. Oceanogr.* 35, 20–28.

Zhang, W., Liu, M., Mitcheson, Y., Cao, L., Leadbitter, D., Newton, R., et al. (2020). Fishing for feed in China: Facts, impacts and implications. *Fish Fish.* 21, 47–62. doi: 10.1111/faf.12414

Zhou, Y., and Xu, H. (2007). Biomass estimates of Muraenesox cinereus are calculated by LCA in the East China Sea. *J. Z. Ocean Univ.* 26, 399–403.

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Marine Science

BRIEF RESEARCH REPORT
published: 24 July 2020
doi: 10.3389/fmars.2020.00507

Check for updates

Fishery Stock Assessments in the Min River Estuary and Its Adjacent Waters in Southern China Using the Length-Based Bayesian Estimation (LBB) Method

Lan-lan Zhang[1†], Qing-qiang Ren[1†], Min Liu[1*], Qing Xu[1], Bin Kang[2] and Xiao-bin Jiang[3]

[1] State Key Laboratory of Marine Environmental Science and College of Ocean and Earth Sciences, Xiamen University, Xiamen, China, [2] Fisheries College, Ocean University of China, Qingdao, China, [3] Fuzhou Marine and Fisheries Technology Center, Fuzhou, China

OPEN ACCESS

Edited by:
Maria Lourdes D. Palomares,
The University of British Columbia,
Canada

Reviewed by:
Hui Zhang,
Institute of Oceanology (CAS), China
Siquan Tian,
Shanghai Ocean University, China

***Correspondence:**
Min Liu
minliuxm@xmu.edu.cn

†These authors have contributed equally to this work

Specialty section:
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

Received: 31 December 2019
Accepted: 03 June 2020
Published: 24 July 2020

Citation:
Zhang L, Ren Q, Liu M, Xu Q, Kang B and Jiang X (2020) Fishery Stock Assessments in the Min River Estuary and Its Adjacent Waters in Southern China Using the Length-Based Bayesian Estimation (LBB) Method. Front. Mar. Sci. 7:507. doi: 10.3389/fmars.2020.00507

The Min River Estuary and its adjacent waters, connecting to the East China Sea, is one of the most important fishing grounds in Fujian Province, southern China; however, stock assessments have not yet been conducted. In the present study, the length-based Bayesian estimation method was applied for the first time to assess 20 single-species fishery stocks in the region. Catches of eight fish species from the Class Actinopterygii and 12 shrimp species from the Class Malacostraca were obtained from two commercial demersal trawlers, operated in the Min River Estuary and its adjacent waters, in February, May, August, and November of 2017 and 2018, covering all four seasons. The results showed that eight species were overexploited with an estimated B/B_{MSY} (i.e., the current exploited biomass relative to the biomass producing the maximum sustainable yield) < 0.8 (range from 0.26 to 0.71). Three overexploited fish species (Gray's grenadier anchovy *Coilia grayii*, the big head croaker *Collichthys lucidus*, and the Trevavas croaker *Johnius trewavasae*) are commercially important food species in the region. All four overexploited shrimp species (the shrimp *Parapenaeopsis cultrirostris*, the Japanese snapping shrimp *Alpehus japonicus*, and the Caridean shrimps *Palaemon annandalei* and *Palaemon carinicouda*) are small-sized and have low commercial value. The three-lined tongue sole *Cynoglossus abbreviates*, a commercially important species, was classified as fully exploited ($0.8 \leq B/B_{MSY} \leq 1.2$). Osbeck's grenadier anchovy *Coilia mystus* and the Japanese mantis shrimp *Oratosquilla oratoria*, both commercially important food species in the region, had non-fully exploited statuses ($B/B_{MSY} > 1.2$). The results revealed that some commercially important food fishes are overexploited in the region and that small-sized, non-commercial food species can also be overexploited. There is an urgent need for local and national fisheries authorities to focus on coastal fishery management.

Keywords: commercial trawl fishery, estuarine waters, fishes, shrimps, length-based Bayesian estimation

INTRODUCTION

Stock assessments are essential for managing the fishery resources exploited. The age composition of fisheries catches provide, for many fisheries in, e.g., Europe and North America, the key parameters for stock assessments and evaluations (Fournier et al., 1998; Sparre and Venema, 1998; Mesnil, 2003; Benjamin and Kurup, 2012; Mäntyniemi et al., 2013; Francis et al., 2016; Zhu et al., 2016). However, age studies are time-consuming in fishes and are not feasible in crustaceans such as crabs and shrimps. Thus, length-frequency data, which can be collected easily from catches, have been widely used in stock assessments in both fishes (e.g., Munro, 1983; Fournier et al., 1990; Dennis, 1991; Pauly, 1998; Al-Qishawe et al., 2014; Nadon et al., 2015; Rudd and Thorson, 2018) and crustaceans (e.g., Pauly et al., 1984; Dineshbabu et al., 2007; Haist et al., 2009; Afzaal et al., 2016).

Notably, length-frequency data can be used to estimate L_∞ and K, the parameters of the von Bertalanffy growth function (VBGF), which has the form:

$$L_t = L_{\text{inf}}\left(1 - e^{-K(t-t_0)}\right)$$

where L_t is the mean size (here in diameter) at age t of the animals in question, L_{inf} their asymptotic length, i.e., the mean length attained after an infinitely long time, and K a growth coefficient (here in year^{-1}). Finally, t_0, which cannot be estimated from length-frequency data alone, is the (usually negative) age they would have had at a size of zero if they had always grown in the manner predicted by the equation (which they have not; see, e.g., Pauly, 1998). However, the parameter t_0, which allows the computation of mean length at *absolute* ages, is not required in most stock assessment models (Pauly, 1998). Other important parameters are mean length at the first capture (L_c, i.e., the length at which 50% of the fish are retained by the gear), the instantaneous rates of natural (M) and fishing (F) mortalities, which can be combined into a rate of total mortality ($Z = M + F$) and an exploitation rate ($E = F/Z$), as well as catch and effort time series for some methods.

Recently, a length-based Bayesian estimation (LBB) method was proposed to estimate stock status from length-frequency data, representative of commercial catches (Froese et al., 2018). To minimize the data requirements, the LBB method is not based on the absolute rates of growth and mortality but rather on the ratios of the rates of natural mortality to somatic growth (M/K) and of fishing mortality to somatic growth (F/K). Given representative length-frequency data, the LBB method, after estimating the above ratios, uses them to estimate the ratio of the current exploited biomass relative to unexploited biomass (B/B_0) and relative to the biomass producing maximum sustainable yield (B/B_{MSY}). The relative biomass estimated using the LBB method has been shown to have good validity for species that grow throughout their life span, such as most fish species (Froese et al., 2019)[1].

[1] www.fishbase.org

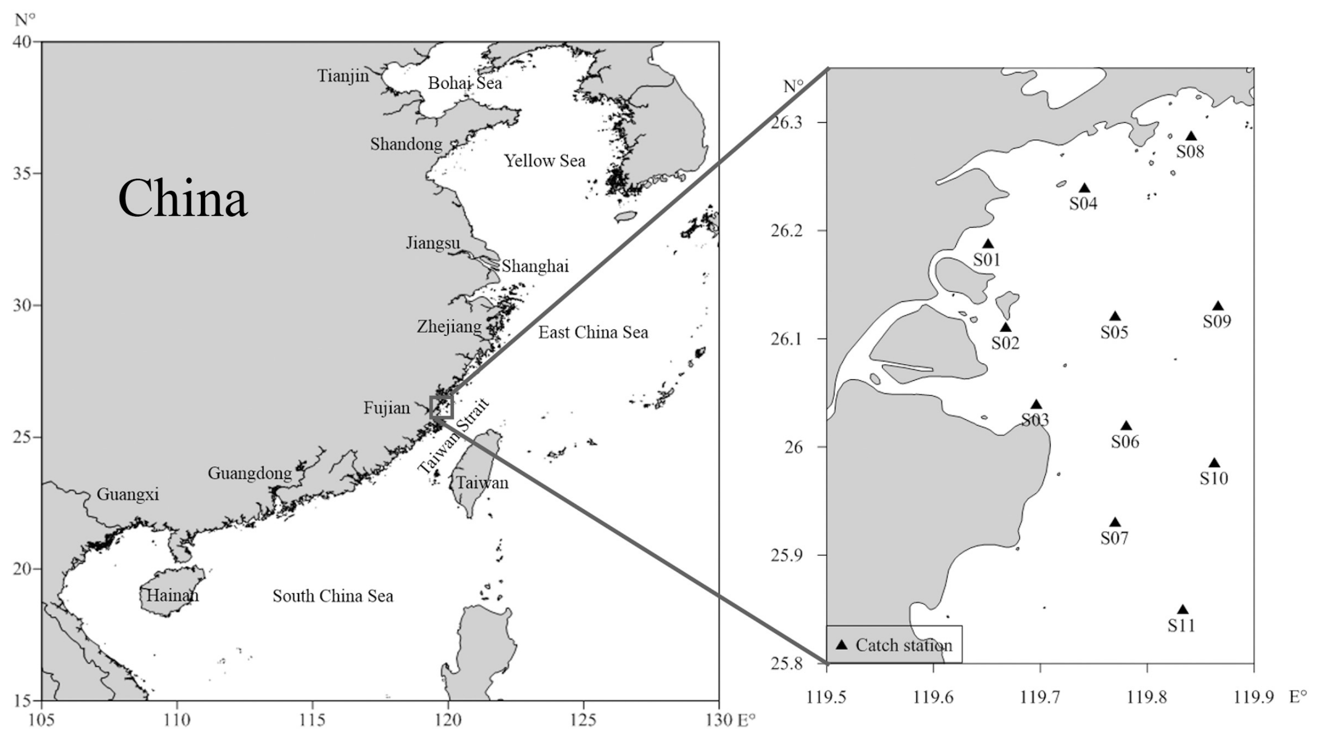


FIGURE 1 | Location of the Min River Estuary and its adjacent waters (left: small square), Fujian Province, China, with the commercial trawl catches from 11 stations (right: S01–S11).

China is the largest contributor to the global catch of marine fisheries (FAO, 2018). However, China's marine fisheries resources have tended to be over-exploited since the 1970s, and dramatic declines in catches have occurred in some traditionally important commercial species and stocks (Jin et al., 2015; Kang et al., 2018a). As some of these declines or collapses may be attributed to the absence of strict management measures, fishery stock assessment is required.

Size measurement is the most fundamental and essential requirement in marine fishery resource surveys in China (Jin et al., 2012). This provides a great opportunity to assess commercial fishery stocks in Chinese waters using the LBB method when other parameters are little known. The Min River is the largest river in Fujian Province, and the estuary and its adjacent waters, connecting to the East China Sea, is one of the most important fishing grounds in Fujian Province (Fujian Province Atlas, 2001; **Figure 1**). Fisheries resources in the region have been shown to be declining; however, stock assessment has not yet been conducted, and the biology of most species has not yet been studied (Huang et al., 2010; Kang et al., 2018b). The objectives of the present study are to assess 20 fishery single-species stocks (henceforth, "species") exploited by commercial demersal trawlers in the Min River Estuary and its adjacent waters using the LBB method. The samplings were conducted in all four seasons in 2017 and 2018, and a rapid understanding of the current status of the commercial fisheries was developed based thereon.

MATERIALS AND METHODS

In the Min River Estuary and its adjacent waters (25.80°–26.30°N, 119.60°–119.90°E), two commercial demersal trawlers operated in 11 stations, covering all four seasons (February for Winter, May for Spring, August for Summer, and November for Autumn) in 2017 and 2018 (**Figure 1**). The power and size are 16.2 kW and 4 t for the small trawler, and 202 kW and 122 t for the large one. Both trawlers had mesh sizes of 4.5 cm at the net opening and 2.5 cm at the cod-end. The operating time of each station was around 30 min, and the speed was 3.7–7.8 km/h. The fishing areas have a depth range of 8–13 m and salinity range of 10–13 at Stations 01–03 (near the mouth of the river) and a depth range of 10–26 m and salinity range of 25–31 at Stations 04–11 (off the mouth of the river).

Catches of 20 species, including 8 fishes from the Class Actinopterygii and 1 mantis shrimp and 11 shrimps from the Class Malacostraca (henceforth all called "shrimps"), were collected. Standard length (SL, to 1 mm) and total length (TL, to 1 mm) were subsequently measured for fish species and carapace length (CL, to 1 mm) and standard length (SL, to 1 mm) for shrimp species. For each species, all individuals were measured if there were < 50 at a given station and season; 50 individuals were randomly selected if the sample size > 50 individuals. Eventually, the number of individuals measured ranged from 244 to 2508 for fish species, and from 129 to 1995 for shrimp species; all 20 species included small-sized juveniles and large adults, i.e., there was a wide size range (**Table 1**).

TABLE 1 | Summary of the size range and the number of individuals measured of the 20 fish and shrimp species collected in 2017 and 2018 for stock assessment in the Min River Estuary and its adjacent waters, Fujian Province, southern China.

Species (common and scientific names)	Length (SL or CL) range (cm)	Number of individuals measured
Class Actinopterygii		
Osbeck's grenadier anchovy *Coilia mystus*	4.0–21.0	2508
Gray's grenadier anchovy *Coilia grayii*	4.7–30.4	290
Big head croaker *Collichthys lucidus*	1.9–15.6	928
Trewavas croaker *Johnius trewavasae*	2.4–18.5	405
Goby *Chaeturichthys hexanema*	2.0–12.4	765
Goby *Odontamblyopus lacepedii*	2.8–22.8	275
Three-lined tongue sole *Cynoglossus abbreviatus*	7.2–32.0	256
Tongue sole *Cynoglossus sibogae*	7.7–22.0	244
Class Malacostraca		
Japanese mantis shrimp *Oratosquilla oratoria*	0.5–4.4	1995
Coastal mud shrimp *Solenocera carssicornis*	0.6–3.4	386
Shiba shrimp *Metapenaeus joyneri*	0.9–4.8	628
Periscope shrimp *Atypopenaeus stenodactylus*	0.4–2.1	317
Southern rough shrimp *Trachypenaeus curvirostris*	0.2–3.6	452
Shrimp *Parapenaeopsis cultrirostris*	0.5–5.3	332
Spear shrimp *Parapenaeopsis hardwickii*	0.6–6.4	803
Smoothshell shrimp *Parapenaeopsis tenella*	0.4–3.3	320
Whiskered velvet shrimp *Metapenaeopsis barbata*	0.6–3.8	299
Japanese snapping shrimp *Alpehus japonicus*	0.4–2.0	129
Caridean shrimp *Palaemon annandalei*	0.3–2.0	167
Caridean shrimp *Palaemon carinicouda*	0.5–4.0	248

SL, standard length for Class Actinopterygii; CL, carapace length for Class Malacostraca.

Length-frequency data (SL for fish species, CL for shrimp species) of each species accumulating from four seasons of two years were input into LBB version 28.0 in R version 3.5.0 software. The M/K prior was generated as 1.5 and the L_{inf} as the maximum length obtained from the present study if the maximum length is unknown (for shrimp species) or the recorded maximum length (fish species from www.fishbase.org) is smaller than that of the present study. The Z/K prior was generated based on the equation (Beverton and Holt, 1957; Quinn and Deriso, 1999):

$$Z = K\frac{L_{\text{inf}} - \bar{L}}{\bar{L} - L_c}$$

where $\bar{L}$ is the average length of all individuals of the species measured above. The F/K prior is determined by (Z/K - M/K).

According to the obtained parameters (i.e., L_c, L_{inf}, M/K, and F/K), the estimated B/B_0 and B/B_{MSY} values were generated (Froese et al., 2018). Stocks were classified to different categories

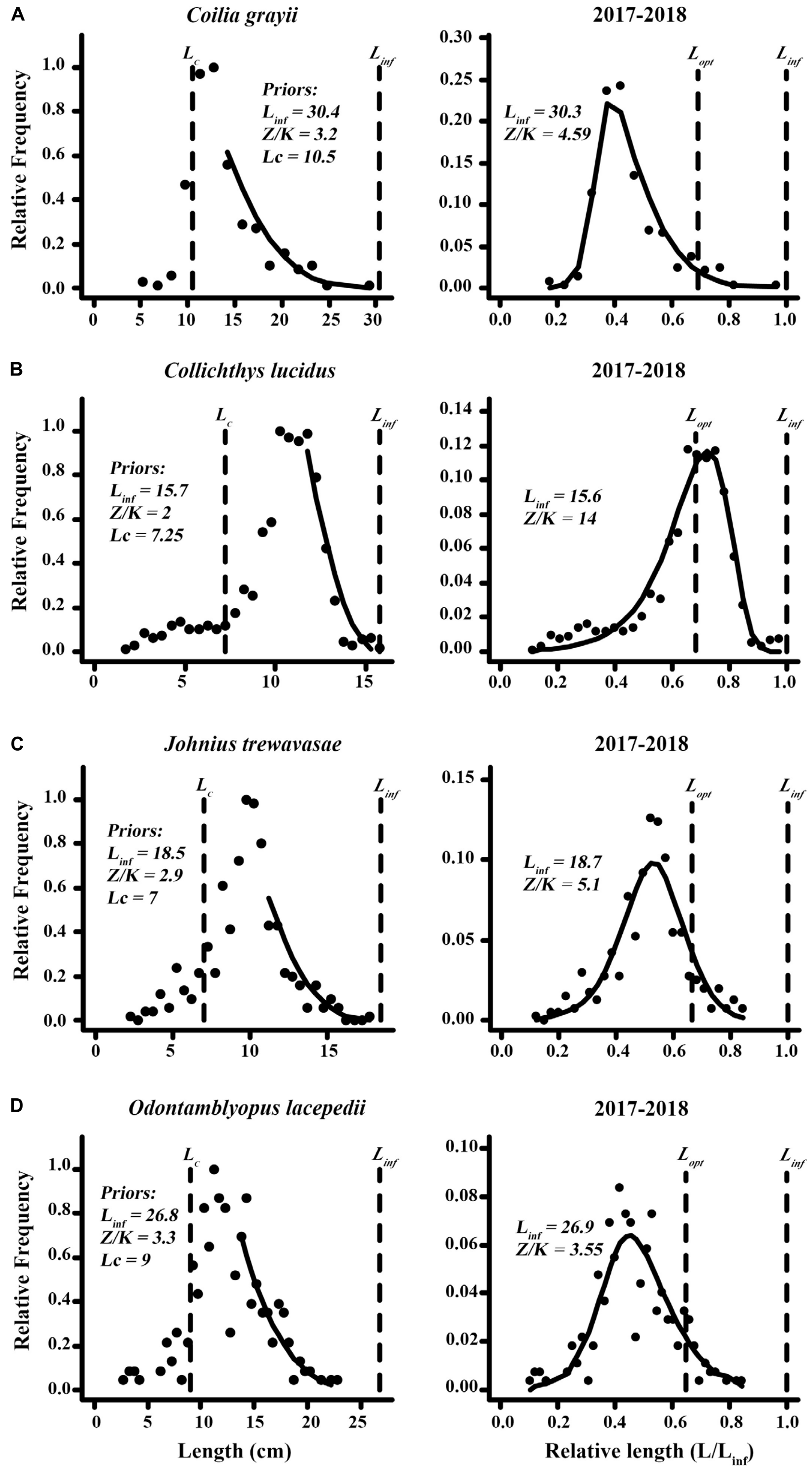


FIGURE 2 | Results of assessment of four fish species with an overexploited stock status in the Min River Estuary and its adjacent waters, Fujian Province, southern China, with length data in 2017 and 2018. **(A)** *Coilia grayii*, **(B)** *Collichthys lucidus*, **(C)** *Johnius trewavasae*, and **(D)** *Odontamblyopus lacepedii*. The left panels estimate the length at 50% first capture (L_c), the asymptotic length (L_{inf}), and the total mortality relative to somatic growth (*Z/K*) based on the catches of 2017 and 2018 as prior. The curves are fitted to fully selected length classes and provide the estimates of L_{inf} and *Z/K*. The right panels show the length-frequency data from 2017 and 2018. The curves show the fitness of the LBB master equation and provide the estimates of L_{inf} and *Z/K*. The L_{opt} is calculated from L_{inf} and *M/K*, where the biomass of the unexploited stock is maximum.

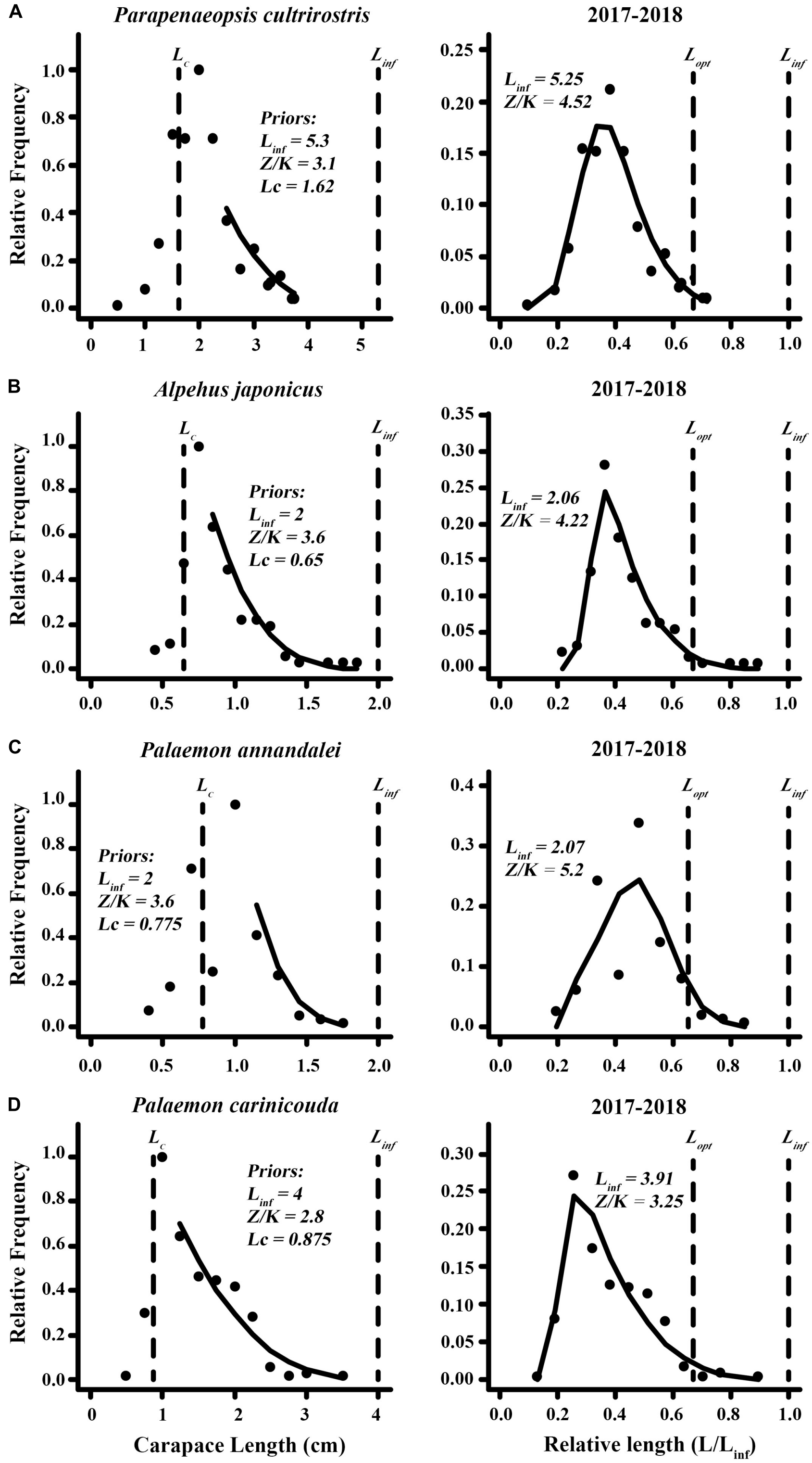


FIGURE 3 | Assessment results of four shrimp species with an overexploited stock status in the Min River Estuary and its adjacent waters, Fujian Province, southern China, with length data in 2017 and 2018. **(A)** *Parapenaeopsis cultrirostris*, **(B)** *Alpehus japonicus*, **(C)** *Palaemon annandalei*, and **(D)** *Palaemon carinicouda*. The left panels estimate the length at 50% first capture (L_C), the asymptotic length (L_{inf}), and the total mortality relative to somatic growth (Z/K) based on the catches of 2017 and 2018 as prior. The curves are fitted to fully selected length classes and provide the estimates of L_{inf} and Z/K. The right panels show the length frequency data from 2017 and 2018. The curves show the fitness of the LBB master equation and provide the estimates of L_{inf} and Z/K. L_{opt} is calculated from L_{inf} and M/K, where the biomass of the unexploited stock is maximum.

TABLE 2 | Fishery statuses of the 20 species assessed in the Min River Estuary and its adjacent waters, Fujian Province, southern China.

Species	L_{max} (cm)	L_{inf} (cm)	B/B_0	B/B_{MSY}	Status	Interval scale (cm)
Class Actinopterygii						
*Coilia mystus**,θ	21.0	20.9	0.70	1.90	Non-fully exploited	1.00
*Coilia grayii**	30.4	30.3	0.10	0.28	Overexploited	1.50
*Collichthys lucidus**,θ	15.6	15.6	0.13	0.34	Overexploited	0.50
*Johnius trewavasae**	18.5	18.7	0.15	0.42	Overexploited	0.50
*Chaeturichthys hexanema*θ	12.4	12.3	0.49	1.30	Non-fully exploited	0.50
*Odontamblyopus lacepedii*θ	22.8	26.9	0.26	0.71	Overexploited	0.50
*Cynoglossus abbreviatus**	32.0	33.3	0.30	0.83	Fully exploited	0.50
Cynoglossus sibogae	22.0	22.2	0.60	1.70	Non-fully exploited	1.50
Class Malacostraca						
*Oratosquilla oratoria**,θ	4.4	4.4	0.76	2.10	Non-fully exploited	0.20
Solenocera carssicornis	3.4	3.45	0.83	2.20	Non-fully exploited	0.25
*Metapenaeus joyneri**	4.8	5.01	0.43	1.20	Fully exploited	0.40
Atypopenaeus stenodactylus	2.1	2.13	0.80	2.10	Non-fully exploited	0.10
Trachypenaeus curvirostris	3.6	3.63	0.87	2.30	Non-fully exploited	0.20
Parapenaeopsis cultrirostris	5.3	5.25	0.10	0.26	Overexploited	0.20
*Parapenaeopsis hardwickii**,θ	6.4	6.67	0.39	1.10	Fully exploited	0.25
Parapenaeopsis tenella	3.3	3.43	0.34	0.91	Fully exploited	0.10
Metapenaeopsis barbata	3.8	3.86	0.38	1.00	Fully exploited	0.25
Alpehus japonicus	2.0	2.06	0.13	0.37	Overexploited	0.10
Palaemon annandalei	2.0	2.07	0.11	0.31	Overexploited	0.10
*Palaemon carinicouda**	4.0	3.91	0.18	0.50	Overexploited	0.25

Commercial food species; θSpecies with an index of relative importance (IRI) > 500 in catches of the present study (data not shown here). L_{max}, the maximum length, either standard length or carapace length, from the present study (also see **Table 1).*

based on the value of B/B_{MSY}; non-fully exploited status was assigned where $B/B_{MSY} > 1.2$, fully exploited status where $0.8 \leq B/B_{MSY} \leq 1.2$, and overexploited status where $B/B_{MSY} < 0.8$ (Amorim et al., 2019).

Length-frequency data were adjusted slightly at 0.5, 1.0, and 1.5 cm SL intervals for fish species, and at 0.1, 0.2, 0.3, and 0.4 cm CL intervals for shrimp species. Through such debugging, the interval that made the analysis fit best (i.e., the length-frequency points fall on the trend curve as much as possible) was selected, and the corresponding length-frequency data were saved in EXCEL in ".csv" format. Information such as species name, sampling method, and L_{inf} were saved in another ".csv" format file. More details and *R*-code[2] are available (Froese et al., 2018).

RESULTS

The dominant length groups of all but one species (the big head croaker *Collichthys lucidus*) were smaller than the length (L_{opt}) that maximizes the biomass of an unexploited cohort (e.g., **Figures 2**, **3**). The estimated L_{inf} values were larger than or equal to the maximum size in the present study (L_{max}) in 15 species, while they were smaller than the L_{max} in only five species (**Table 2**).

The 20 species assessed belonged to one of the three statuses: overexploited, fully exploited, or non-fully exploited (**Table 2**). Eight species (40%), i.e., four fishes and four shrimps, had estimated B/B_0 ratios ranging from 0.10 to 0.26 and B/B_{MSY} ratios ranging from 0.26 to 0.71, suggesting overexploited status. Five species (25%), i.e., one fish and four shrimps, were fully exploited, with estimated B/B_0 ratios ranging from 0.30 to 0.43 and B/B_{MSY} ratios ranging from 0.83 to 1.20. Seven species (35%), i.e., three fishes and four shrimps, were non-fully exploited, with estimated B/B_0 ratios ranging from 0.49 to 0.87 and B/B_{MSY} ratios ranging from 1.30 to 2.30.

DISCUSSION

This study is the first time that the LBB method has been used to assess commercial fishery stock status in the Min River Estuary and its adjacent waters, southern China. The results provided valuable information for understanding the current degree of fishery exploitation in the region. Among the four fish species that were overexploited, Gray's grenadier anchovy *Coilia grayii* in Engraulidae and the big head croaker *C. lucidus* in Sciaenidae require more attention (**Table 2**). *C. grayii* was listed as Least Concern in 2012 (Vidthayanon, 2012). It inhabits the waters near the mouths of the rivers and is a commercially important species in Fujian waters. *C. grayii* spawns in the mouth of the Min River every March–June and grows in the estuary year-round or offshore (Qiu, 1984). This is the first report on overexploitation of *C. grayii* stock in China. *C. lucidus*, an important food fish in China, inhabits estuaries and coastal waters down to a depth of 90 m over sandy and muddy

[2]See http://oceanrep.geomar.de/43182/

bottoms (Chu and Wu, 1985; see footnote 1). It dominates in the Min River Estuary and its adjacent waters based on the index of relative importance (*IRI*; Zhang, 2020). A decline in the lengths in commercial catches of *C. lucidus* has been noted; SL ranged from 3.5 to 20.5 cm in 2006/2007, from 3.0 to 16.0 cm in 2015, and from 1.9 to 15.6 cm in 2017/2018 (Wang et al., 2011; Kang et al., 2018b; the present study). The smaller individuals in both *C. lucidus* and *C. grayii* samples indicate the existence of nursery grounds in the Min River Estuary and its adjacent waters. All four overexploited shrimp species are small-sized, benthic or demersal, and of low commercial value.

Among the fully exploited species, the three-lined tongue sole *Cynoglossus abbreviates* in Cynoglossidae and the spear shrimp *Parapenaeopsis hardwickii* in Penaeidae are of local commercial importance. The B/B_{MSY} of *C. abbreviates* was 0.83, close to overexploited status. The abundance of *P. hardwickii* has increased over the past decade; the species was a general species in 2008 ($IRI < 100$) (Xu and Sun, 2013) and became a dominant species ($IRI > 500$) in 2017/2018 (Zhang, 2020).

Among the non-fully exploited species, Osbeck's grenadier anchovy *Coilia mystus* in Engraulidae is an important food fish in China and inhabits estuaries and coastal waters (Ni et al., 1999). It was listed as Endangered in 2018 (Hata, 2018). The stock of *C. mystus* in the Yangtze River Estuary, the most abundant region in China, almost collapsed (Liu et al., 2013). In the Min River Estuary and its adjacent waters, less than 600 km distance from the Yangtze River Estuary, *C. mystus* is a dominant species ($IRI > 500$) (Zhang, 2020); however, the sizes of *C. mystus* in commercial catches has shown a decline over the years from 5.0–26.4 cm SL in 2006/2007 to 7.0–21.0 cm SL in 2015 and to 4.0–21.0 cm SL in 2017/2018 (Wang et al., 2011; Kang et al., 2018b; the present study).

The current stock statuses of the 20 species revealed that some commercially important food fishes are overexploited in the Min River Estuary and its adjacent waters and that small-sized, non-commercial food species can also be overexploited. This is likely due to the non-selective fishery method using small mesh-sized nets employed in commercial demersal bottom fisheries along the coastal waters of China. About 200 species of fishes, crustaceans, and cephalopods have been reported from the Min River Estuary and its adjacent waters (Kang et al., 2018b; Zhang, 2020). It will be a challenge to find a way to continue exploiting the Min River Estuary for its fisheries resources without impacting the biodiversity that makes the estuary so productive. There is an urgent need for local and national fisheries authorities to focus on coastal fishery management.

DATA AVAILABILITY STATEMENT

The datasets analyzed in this article are not publicly available. Requests to access the datasets should be directed to LZ.

ETHICS STATEMENT

The animal study was reviewed and approved by Fuzhou Ocean and Fisheries Bureau of China.

AUTHOR CONTRIBUTIONS

LZ and QR wrote the first draft. ML, QX, BK, and XJ revised the manuscript. LZ, QR, XJ, and ML performed the data analyses. All authors conducted commercial catch sampling and measurement.

FUNDING

This work was supported by the National Natural Science Foundation of China (grant no. 41976091) and the Fuzhou Ocean and Fisheries Bureau of China (contract no. XDHT2017074A). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

ACKNOWLEDGMENTS

We thank Rui Guo, Zhi-jian Huang, Bai-an Lin, and Jian-jie Lin for sample collection and measurement.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00507/full#supplementary-material

REFERENCES

Afzaal, Z., Kalhoro, M. A., Buzdar, M. A., Nadeem, A., Saeed, F., Haroon, A., et al. (2016). Stock assessment of blue swimming crab *Portunus pelagicus* (Linnaeus, 1758) from Pakistani waters (Northern, Arabian Sea). *Pak. J. Zool.* 48, 1531–1541.

Al-Qishawe, M. M. S., Ali, T. S., and Abahussain, A. A. (2014). Stock assessment of white spotted rabbitfish (*Siganus canaliculatus* Park, 1797) in Jubail marine wildlife sanctuary, Saudi Arabia. *Int. J. Fish. Aquat. Stud.* 1, 48–54.

Amorim, P., Sousa, P., Jardim, E., and Menezes, G. M. (2019). Sustainability status of data-limited fisheries: global challenges for snapper and grouper. *Front. Mar. Sci.* 6:654. doi: 10.3389/fmars.2019.00654

Benjamin, D., and Kurup, B. M. (2012). Stock assessment of dolphinfish, *Coryphaena hippurus* (Linnaeus, 1758) off the southwest coast of India. *J Mar. Biol. Assoc. India* 54, 95–99. doi: 10.6024/jmbai.2012.54.1.01675-1671

Beverton, R. J. H., and Holt, S. J. (1957). *On the Dynamics of Exploited Fish Populations*. London: Ministry of Agriculture, Fisheries and Food. Fishery Investigations.

Chu, Y., and Wu, H. (1985). "Sciaenidae," in *Fishes of Fujian Province Editorial Subcommittee, The Fishes of Fujian Province (Part II)*, Ed. X. L. Chu, (China: Fujian Science and Technology Press), 135–136.

Dennis, G. D. (1991). The validity of length-frequency derived growth parameters from commercial catch data and their application to stock assessment of the yellowtail snapper (*Ocyurus chrysurus*). *Proc. Gulf Caribbean Fish. Inst.* 40, 126–138.

Dineshbabu, A. P., Sreedhara, B., and Muniyappa, Y. (2007). Fishery and stock assessment of *Portunus sanguinolentus* (Herbst) from south Karnataka coast. India. *J. Mar. Biol. Assoc. India* 49, 134–140.

FAO, (2018). *The State of World Fisheries and Aquaculture-Meeting the Sustainable Development Goals. Food and Agriculture Organization of the United Nations*. Rome: FAO.

Fournier, D. A., Hampton, J., and Sibert, J. R. (1998). MULTIFAN-CL: a length-based, age-structured model for fisheries stock assessment, with application to South Pacific albacore. *Thunnus alalunga*. *Can. J. Fish. Aquat. Sci.* 55, 2105–2116. doi: 10.1139/cjfas-55-9-2105

Fournier, D. A., Sibert, J. R., Majkowski, J., and Hampton, J. (1990). MULTIFAN a likelihood-based method for estimating growth parameters and age composition from multiple length frequency data sets illustrated using data for southern bluefin tuna (*Thunnus maccoyii*). *Can. J. Fish. Aquatic Sci.* 47, 301–317. doi: 10.1139/f90-032

Francis, R. C., Aires-da-Silva, A. M., Maunder, M. N., Schaefer, K. M., and Fuller, D. W. (2016). Estimating fish growth for stock assessments using both age–length and tagging-increment data. *Fish. Res.* 180, 113–118. doi: 10.1016/j.fishres.2015.06.011

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A. C., Dimarchopoulou, D., et al. (2018). A new approach for estimating stock status from length frequency data. *ICES J. Mar. Sci.* 75, 2004–2015. doi: 10.1093/icesjms/fsy078

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A. C., Dimarchopoulou, D., et al. (2019). On the pile-up effect and priors for L_{inf} and M/K: response to a comment by Hordyk et al. on "A new approach for estimating stock status from length frequency data". *ICES J. Mar. Sci.* 76, 461–465. doi: 10.1093/icesjms/fsy199

Fujian Province Atlas, (2001). *Geology Atlas*. Fuzhou: Fangzhi Press, 448.

Haist, V., Breen, P. A., and Starr, P. J. (2009). A multi-stock, length-based assessment model for New Zealand rock lobster (*Jasus edwardsii*). *N. Zeal. J. Mar. Freshw. Res.* 43, 355–371. doi: 10.1080/00288330909510006

Hata, H. (2018). *Coilia mystus. The IUCN Red List of Threatened Species 2018: e.T98894402A143840543.* doi: 10.2305/IUCN.UK.2018-2.RLTS.T98894402A143840543.en

Huang, L., Li, J., Zhang, Y., Xie, Y., Liu, Q., and Jin, X. (2010). Current fishery resource assessment in the Minjiang River Estuary and its neighboring waters. *J. Trop. Oceanogr.* 29, 142–148.

Jin, X., Dou, S., Shan, X., Wang, Z., Wan, R., and Bian, X. (2015). Hot spots of frontiers in the research of sustainable yield of Chinese inshore fishery. *Progr. Fish. Sci.* 36, 124–131. doi: 10.11758/yykxjz.20150119

Jin, X., Li, X., Zhao, X., Cheng, J., Li, S., and Zhang, H. (2012). *Technical Specification for Marine Fishery Resource Survey*. Beijing: Ministry of Agriculture of the People's Republic of China.

Kang, B., Liu, M., Huang, X.-X., Li, J., Yan, Y.-R., Han, C.-C., et al. (2018a). Fisheries in Chinese seas: What can we learn from controversial official fisheries statistics? *Rev. Fish Biol. Fish.* 28, 503–519. doi: 10.207/s11160-018-9518-1

Kang, B., Li, J., Zhao, C., He, X., Wang, J., and Zhang, Y. (2018b). *Ecological Environment and Fishery Resources in the Min River Estuary*. Beijing: China Agriculture Press, 189.

Liu, K., Xu, D., Duan, J., Zhang, M., Fang, D., Zhou, Y., et al. (2013). Fluctuation of biological characteristics and yield of *Coilia mystus* in fishing season after impoundment of the three gorges dam in Yangze River Estuary. *Resour. Environ. Yangze Basin* 22, 1282–1288.

Mäntyniemi, S., Uusitalo, L., Peltonen, H., Haapasaari, P., and Kuikka, S. (2013). Integrated, age-structured, length-based stock assessment model with uncertain process variances, structural uncertainty, and environmental covariates: case of Central Baltic herring. *Can. J. Fish. Aquat. Sci.* 70, 1317–1326. doi: 10.1139/cjfas-2012-0315

Mesnil, B. (2003). The catch-survey analysis (CSA) method of fish stock assessment: an evaluation using simulated data. *Fish. Res.* 63, 193–212. doi: 10.1016/S0165-7836-03-00072-9

Munro, J. L. (1983). A cost-effective data acquisition system for assessment and management of tropical multispecies, multi-gear fisheries. *Fishbyte* 1, 7–12.

Nadon, M. O., Ault, J. S., Williams, I. D., Smith, S. G., and DiNardo, G. T. (2015). Length-based assessment of coral reef fish populations in the main and northwestern Hawaiian Islands. *PLoS One* 10:e0133960. doi: 10.1371/journal.pone.0133960

Ni, Y., Wang, Y., Jiang, M., and Chen, Y. (1999). Biological characteristics of *Coilia mystus* in the Changjiang estuary. *J. Fish. Sci. China* 6, 69–71.

Pauly, D. (1998). Beyond our original horizons: the tropicalization of Beverton and Holt. *Rev. Fish Biol. Fish.* 8, 307–334.

Pauly, D., Ingles, J., and Neal, R. (1984). "Application to shrimp stocks of objective methods for the estimation of growth, mortality and recruitment-related parameters from length-frequency data (ELEFAN I and II)," in *Penaeid Shrimp, Their Biology and Management*, eds J. Gulland, and B. Rothschild, (Great Britain: New Books), 220–234.

Qiu, S. (1984). "Engraulidae," in *Fishes of Fujian Province Editorial Subcommittee, The fishes of Fujian Province (Part I)*, Ed. X. L. Chu, (China: Fujian Science and Technology Press), 140–157.

Quinn, T. J., and Deriso, R. B. (1999). *Quantitative Fish Dynamics*. New York, NY: Oxford University Press.

Rudd, M. B., and Thorson, J. T. (2018). Accounting for variable recruitment and fishing mortality in length-based stock assessments for data-limited fisheries. *Can. J. Fish. Aquat. Sci.* 75, 1019–1035. doi: 10.1139/cjfas-2017-0143

Sparre, P., and Venema, S. C. (1998). *Introduction to Tropical Fish Stock Assessment. Part 1: Manual*. FAO Fisheries Technical Paper No. 306.1, Rev. 2. Rome: FAO.

Vidthayanon, C. (2012). *Coilia grayii. The IUCN Red List of Threatened Species 2012: e.T166216A1120822*. doi: 10.2305/IUCN.UK.2012-1.RLTS.T166216A1120822.en

Wang, J., Zhang, Y., Huang, L., Li, J., and Xie, Y. (2011). Fishery biology of main economic fishes in Fujian coastal waters. *J. Jimei Univ.* 16, 161–166. doi: 10.19715/j.jmuzr.2011.03.001

Xu, Z., and Sun, Y. (2013). Comparison of shrimp density between the Minjiang estuary and Xinhua bay during spring and summer. *Acta Ecol. Sin.* 33, 7157–7165. doi: 10.5846/stxb201207261060

Zhang, L. (2020). *Fishery Nekton Resource and Community Diversity in Min River Estuary and its Adjacent Waters, Fujian Province, China*. MSc Dissertation, Xiamen University, Xiamen, China.

Zhu, J., Maunder, M. N., Aires-da-Silva, A. M., and Chen, Y. (2016). Estimation of growth within stock synthesis models: management implications when using length-composition data. *Fish. Res.* 180, 87–91. doi: 10.1016/j.fishres.2015.09.019

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Marine Science

ORIGINAL RESEARCH
published: 15 September 2020
doi: 10.3389/fmars.2020.00632

Stock Status Estimating of 5 Shark Species in the Waters Around Taiwan Using a Length-Based Bayesian Biomass Estimation (LBB) Method

Peilong Ju[1,2], Mingru Chen[1,3,4]*, Yongjun Tian[2,5,6]*, Yu Zhao[1], Shengyun Yang[1] and Jiamei Xiao[1]

[1] State Key Laboratory of Marine Environmental Science, and College of Ocean and Earth Sciences, Xiamen University, Xiamen, China, [2] Laboratory of Fisheries Oceanography, Fisheries College, Ocean University of China, Qingdao, China, [3] Xiamen City Key Laboratory of Urban Sea Ecological Conservation and Restoration (USER), Xiamen University, Xiamen, China, [4] China-ASEAN College of Marine Sciences, Xiamen University Malaysia, Sepang, Malaysia, [5] Frontiers Science Center for Deep Ocean Multispheres and Earth System, Ocean University of China, Qingdao, China, [6] Laboratory for Marine Fisheries Science and Food Production Processes, Pilot National Laboratory for Marine Science and Technology (Qingdao), Qingdao, China

OPEN ACCESS

Edited by:
Cui Liang,
Institute of Oceanology (CAS), China

Reviewed by:
Brett W. Molony,
Oceans and Atmosphere (CSIRO), Australia
Felipe Galván-Magaña,
Centro Interdisciplinario de Ciencias Marinas (IPN), Mexico

***Correspondence:**
Mingru Chen
mrchen@xmu.edu.cn
Yongjun Tian
yjtian@ouc.edu.cn

Specialty section:
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

Received: *04 January 2020*
Accepted: *09 July 2020*
Published: *15 September 2020*

Citation:
Ju P, Chen M, Tian Y, Zhao Y, Yang S and Xiao J (2020) Stock Status Estimating of 5 Shark Species in the Waters Around Taiwan Using a Length-Based Bayesian Biomass Estimation (LBB) Method. Front. Mar. Sci. 7:632. doi: 10.3389/fmars.2020.00632

Five shark stocks in the waters around Taiwan were assessed using the LBB method, addressing the present gap. Among them, only one filter-feeding shark, megamouth shark *Megachasma pelagios*, qualified as having a healthy status. Of the remaining filter-feeding shark, whale shark *Rhincodon typus*, was seriously overexploited, possibly even collapsed, spadenose shark *Scoliodon macrorhynchos*, and other two large sharks (dusky shark *Carcharhinus obscurus* and silky shark *Carcharhinus falciformis*) were also overexploited. These stock status estimates for the five shark species using the LBB method were consistent with international agreements such as IUCN, CITES and CMS.

Keywords: sharks, stock status, Taiwan waters, LBB, stock assessments

INTRODUCTION

Sharks and their relatives (chondrichthyans, herein "sharks") are more vulnerable to overfishing due to their conservative life-history traits, such as slow growth, old ages of reproduction, long gestation periods, and high levels of maternal investment (Cortés, 2000; Dulvy et al., 2014; Adams et al., 2018; Booth et al., 2019). On the other hand, sharks as predators not only play critical roles in maintaining the stability, functionality and productivity of ecosystems (McCann et al., 2005; Heupel et al., 2014), but also have important socio-economic roles in coastal communities (Booth et al., 2019).

The increasing global demand and high market value for shark fins exacerbates the depletion of low-productivity sharks (Cortés, 2000; Booth et al., 2019), which is more serious in Chinese waters (Eriksson and Clarke, 2015). Therefore, sharks have been listed in international agreements to regulate fishing and trade (Booth et al., 2019), such as the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). However, globally many sharks are still overfished (Davidson et al., 2016) and remain under-managed, particularly in many developing countries (Momigliano and Harcourt, 2014; Simpfendorfer and Dulvy, 2017). Indeed, it is estimated that a quarter of shark species are threatened with extinction (Dulvy et al., 2014).

As bycatch especially for pelagic longline fisheries in the high seas (Oliver et al., 2015), production of sharks is rarely recorded, or even reported in official fishery statistics at the species level (Clarke et al., 2006). Therefore, poor catches data make stock assessment more difficult.

The waters around Taiwan, one of the marine "hotspots" (Hobday and Pecl, 2014), has the fifth richest chondrichthyan faunas in the world, with at least 181 known species inhabiting there (Ebert et al., 2013). Yet most of the shark stocks in this area are not assessed and the majority of sharks have not been recorded in official fishery statistics. Thus, it is necessary to use other measures and not rely on catches to fill the gaps in shark stock assessment in the waters around Taiwan. To address this gap, a length-based Bayesian biomass estimation method (LBB) was applied to estimate stock status of 5 shark species in the waters around Taiwan. The results would benefit "shark" conservation and management.

MATERIALS AND METHODS

Data Source

The basic information and data source of 5 shark species during different time periods since 2000 were summarized in **Table 1**. The original total length data of spadenose shark (*Scoliodon macrorhynchos*) were from a Master thesis (Zhao, 2018). The original total length frequency data of silky shark (*Carcharhinus falciformis*) were from Joung et al. (2008). Two species data were read from figures in published scientific papers (dusky shark *Carcharhinus obscurus*: Joung et al., 2015; whale shark *Rhincodon typus*: Hsu et al., 2014) using OriginPro 2018C. The length data of megamouth shark (*Megachasma pelagios*) were from the Fisheries Agency[1].

General Description of the LBB Method

The length-based Bayesian biomass estimation (LBB), a new method for the analysis of length- frequency data from the commercial fishery, was developed by Froese et al. (2018). LBB is applicable for species that grow throughout their lives, such as most of the commercial fish and invertebrates, and require no input in addition to length-frequency data. It estimates asymptotic length (L_{inf}), length at first capture (L_c), relative natural mortality (M/K), and relative fishing mortality (F/M) which means over the age range represented in the length-frequency sample. If a good estimate of L_{inf} from an independent study is available, this value can be introduced by the user, thus decreasing uncertainty in LBB results (Froese et al., 2018). With these parameters as input, standard fisheries' equations can be used to estimate depletion or current exploited biomass relative to unexploited biomass (B/B_0). These parameters also allow the estimation of the length at first capture that would maximize catch and biomass for the given fishing effort (L_{c_opt}), and estimation of a proxy for the relative biomass capable of producing maximum sustainable yields (B_{MSY}/B_0). Relative biomass estimates of LBB were not significantly different from the "true" values in simulated data and were similar to independent estimates from full stock assessments (Froese et al., 2018). Further details and more complete information about LBB can be found in Froese et al. (2018) and Froese et al. (2019).

Using the LBB method here, priors for L_{inf}, Z/K and L_c were estimated according to accumulated length data (**Figure 1A**). The fitting curves were used to estimate L_{inf}, L_c, Z/K, M/K, and F/K, and L_{opt} was calculated based on L_{inf} and M/K (**Figure 1B**). To reduce uncertainty in LBB results, L_{inf} in bold values were introduced from the corresponding data sources referenced (**Table 2**).

[1]www.fa.gov.tw

TABLE 1 | The basic data information of five sharks in the waters around Taiwan.

Scientific name (Common name)	Region	Period	Source
Scoliodon macrorhynchos (Spadenose shark)	Southern Taiwan Strait	2016–2018	Zhao, 2018
Carcharhinus falciformis (Silky shark)	Northeastern Taiwan waters	2000–2002	Joung et al., 2008
Carcharhinus obscurus (Dusky shark)	Northeastern Taiwan waters	2002–2003	Joung et al., 2015
Rhincodon typus (Whale shark)	Eastern Taiwan waters	2001–2006	Hsu et al., 2014
Megachasma pelagios (Megamouth shark)	Hualien (Eastern Taiwan waters)	2013–2019	Fisheries Agency

RESULTS

The outputs of five shark species produced by LBB are shown in **Figure 1** and summarized in **Table 2**. The proxies for B/B_{MSY} (1, Froese et al., 2018; Palomares et al., 2018) and B/B_0 (0.4–0.5, Froese et al., 2018) can be thought as the lower bounds of desirable stock sizes. Therefore, the stock status of five shark species can be defined based on the two proxies and summarized in **Table 2**. Indeed, among these 5 stocks, one filter-feeding shark, megamouth shark *Megachasma pelagios*, is in healthy status ($B/B_{MSY} > 1$, $B/B_0 > 0.4$; **Table 2**), the other filter-feeding shark species such as whale shark *Rhincodon typus* are seriously overexploited, possibly even collapsed (B/B_{MSY} and $B/B_0 < 0.1$; **Table 2**). The others 3 stocks are overfished (the degree of overfishing for the small shark, spadenose shark *Scoliodon macrorhynchos* is higher than that in two large sharks: dusky shark (*Carcharhinus obscurus*), and silky shark (*Carcharhinus falciformis*).

DISCUSSION

LBB is a new method for the assessment of data-poor stocks with missing or unreliable catch data. The most important limitation is that the length-frequency data should represent the composition of the exploited stock (Froese et al., 2018). For this study, all the length data were collected over at least 2 years and most data were from population growth studies; therefore, the length-frequency data fully meets the requirements of LBB.

A key problem of shark stock assessment is the incomplete reporting of shark catches, because a large number of sharks are caught and discarded at sea (Stevens et al., 2000; Clarke et al., 2006; Worm et al., 2013). Nevertheless, it is estimated

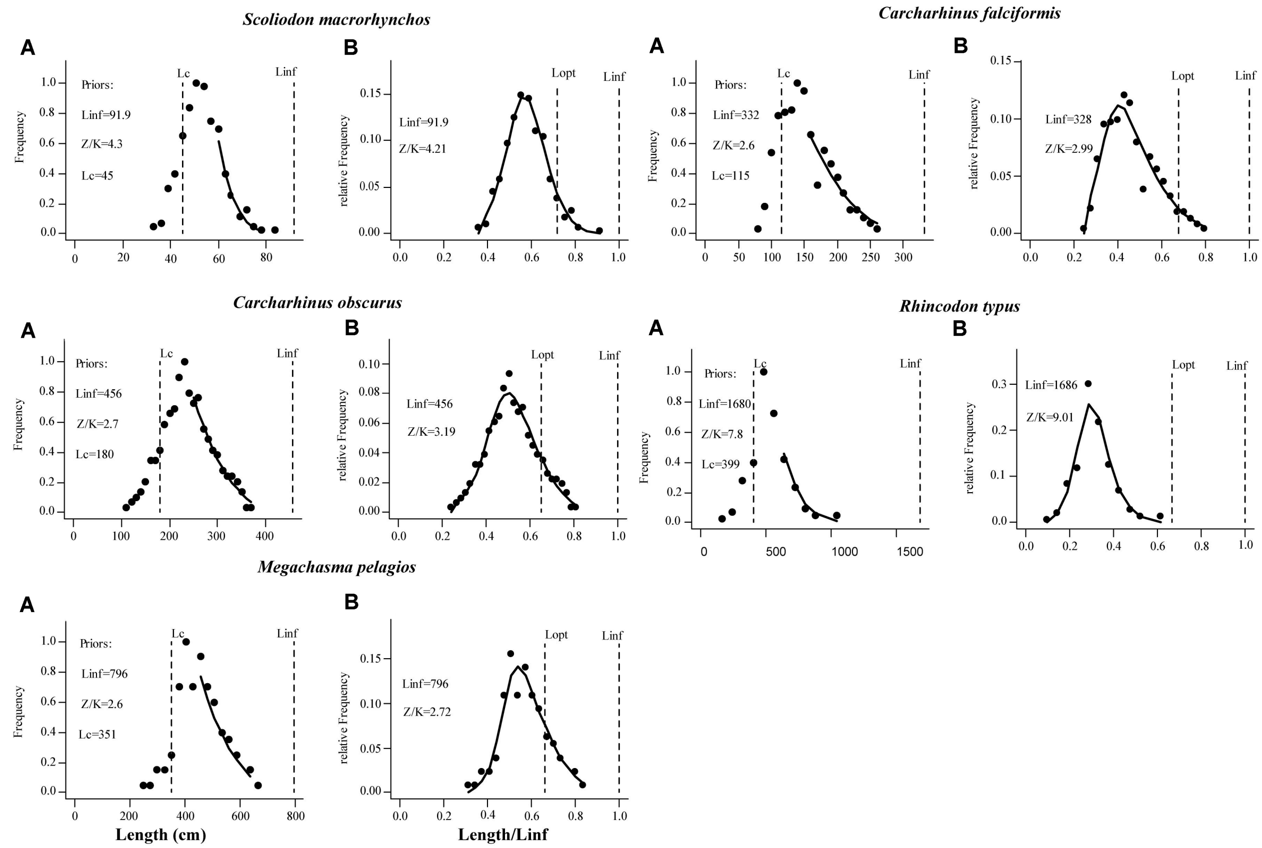


FIGURE 1 | Graphical output produced by LBB for the five species. Panels **(A)** show the accumulated length frequency (LF) data used to estimate priors for L_{inf}, Z/K and L_c. Panels **(B)** show L_{inf}, Z/K and L_{opt} estimated by the fitting curve. L_{inf} is asymptotic length, Z is the total mortality, K is somatic growth rate from the von Bertalanffy growth equation, L_c is the length at first capture, L_{opt} is the length in the unfished population.

TABLE 2 | Length reference points (L_{inf}, L_c and L_{c_opt}), F/M, F/K, Z/K and relevant biomass (B/B_0 and B/B_{MSY}) and their 95% confidence intervals (italic number in brackets) of 5 sharks species estimated by the LBB method.

Common name	L_{inf} (cm)	L_c (cm)	L_{c_opt} (cm)	F/M	F/K	Z/K	B/B_0	B/B_{MSY}	Stock status
Spadenose shark	91.9 (*90.2–93.7*)	45.9	60	2.59 (*1.79–3.52*)	3.02 (*2.46–3.46*)	4.2 (*3.83–4.54*)	0.15 (*0.09–0.22*)	0.4 (*0.23–0.58*)	overfished
Silky shark	**328** (*321–333*)	117	185	1.1 (*0.66–1.63*)	1.5 (*1.14–1.92*)	3.01 (*2.82–3.2*)	0.26 (*0.13–0.43*)	0.71 (*0.36–1.2*)	overfished
Dusky shark	**456** (*449–464*)	184	245	0.94 (*0.65–1.45*)	1.57 (*1.24–1.97*)	3.22 (*2.95–3.48*)	0.33 (*1.79–3.52*)	0.91 (*0.53–1.5*)	overfished
Whale shark	**1686** (*1650–1720*)	407	1060	4.99 (*3.72–6.39*)	7.5 (*6.91–8.23*)	9.04 (*8.63–9.66*)	0.03 (*0.02–0.04*)	0.07 (*0.05–0.1*)	Collapsed
Megamouth shark	796 (*776–808*)	358	425	0.74 (*0.44–1.18*)	1.18 (*0.81–1.58*)	2.72 (*2.48–2.94*)	0.41 (*0.19–0.69*)	1.1 (0.52–1.9)	Healthy

The bold values of L_{inf} are introduced from Joung et al. (2008) for silky shark, Joung et al. (2015) for dusky shark and Hsu et al. (2014) for whale shark. L_{c_opt} is the length at first capture that would maximize catch and biomass for the given fishing effort. F, fishing mortality; M, natural mortality; B_0, unexploited biomass. Total length is used in these 5 species.

that about 63–273 million sharks are killed globally per year, and the exploitation rates exceed the average rebound rate for most sharks (Worm et al., 2013). As a result, many sharks are overfished globally (Davidson et al., 2016), and their populations have rapidly decreased regionally (Musick et al., 2000; Baum et al., 2003; Ferretti et al., 2010). Although chondrichthyan faunas are rich in the waters around Taiwan (Ebert et al., 2013), stock status of sharks is still unevaluated, and stock assessments are focused on age and growth studies (e.g., Joung et al., 2008; Hsu et al., 2014; Joung et al., 2015).

The Megamouth shark stock in Taiwan waters is in healthy status based on LBB results (**Table 2**). The Megamouth shark is the third biggest filter-feeding shark (the other two sharks: basking shark *Cetorhinus maximus* and whale shark *Rhincodon typus*) (Nakaya et al., 2008). Although they are distributed widely in the Pacific and Atlantic Oceans (Froese and Pauly, 2019), they are rarely seen. There is no detailed information about this stock or population so far, therefore, this study is the first analyses for stock assessment. The healthy status of the megamouth shark may be supported by being listed as Least Concern (LC) in

International Union for Conservation of Nature (IUCN) Red List of Threatened Species (Kyne et al., 2019). More data are required for accurate estimates.

Unlike the megamouth shark, another filter-feeding whale shark in the Taiwan waters is overexploited and the stock has even possibly collapsed, according to LBB results, despite this species being fully protected in Taiwan waters since November 2007 (Hsu et al., 2012). Although the whale shark is estimated as Endangered (IUCN, Pierce and Norman, 2016) and listed in Appendix II of CITES and Convention on the Conservation of Migratory Species of Wild Animals (CMS), the stock status is still in an unsustainable state in Asia due to the growing international demand for their fins, meat and liver oil (Hsu et al., 2012, 2014), despite the species being ovoviviparous and producing up to 300 pups per litter. Therefore, the stock assessment of the species can provide the basic information for stock status, and several fisheries reference points would be beneficial to fisheries' management of whale sharks in Taiwan waters.

The Spadenose shark is a commercial small demersal shark species, abundant in the southwestern Taiwan waters (Chen et al., 2001). The intersexuality of this species was reported in the southern Taiwan strait (Zhao et al., 2017). However, this stock has not been assessed due to lack of inclusion in official fishery statistics for China Mainland and Taiwan Province. The Spadenose shark may be overfished in the coastal and offshore fisheries and overexploited on the China Mainland (Kang et al., 2018) and Taiwan Province (Chen et al., 2018; Liao et al., 2019). Correspondingly, this stock has been assessed to be grossly overfished with an LBB estimated depletion rate of 85% ($B/B_0 = 0.15$) being reasonable.

Two large "sharks," including the dusky shark and silky shark are also assessed to be overfished. Both of these species were estimated as Vulnerable in IUCN, and the latter species is also listed in Appendix II of CITES and CMS. The dusky shark is viviparous with a litter size of 3–14 pups. Dusky sharks in the U.S. waters have been overfished since 1990 (Sulikowski et al., 2020). The medium sized fins make dusky shark a major target species in Taiwan waters (Joung et al., 2015). The mean annual landing of the dusky shark is 210 metric tons which accounts for 11.5% of the total shark landings from1990 to 2008 in northeastern Taiwan (Joung et al., 2015). The high commercial values of the fins may lead the dusky shark to be overexploited in northeastern Taiwan waters. Silky shark is abundant with 1–16 pups, and the annual landing about 241 tonnes in northeastern Taiwan waters (Joung et al., 2008). However, the smaller body size (mean body weight) suggested that the silky shark stock might be overexploited in northeastern Taiwan waters (Joung et al., 2008). Consequently, the silky shark stock status estimated by LBB is reasonable.

CONCLUSION

Five shark stocks in the waters around Taiwan were evaluated using the LBB method. The resulting estimates indicate that only megamouth shark stock is in healthy status, while whale shark, spadenose shark (small shark) and other two large sharks (dusky shark and silky shark) are overfished. The stock status of the five sharks estimated using the LBB method are consistent with international agreements such as IUCN, CITES, and CMS. Consequently, stock status estimated by LBB are credible. In addition, this study fills gaps in shark stock status assessment in the Taiwan waters and provides the basic fisheries with reference points for conservation and management of these sharks. Meanwhile, further investigative work on shark resources should be both continued and utilized, since these top predators in the marine ecosystem play important roles to both ecosystems and human society.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are included in the article/**Supplementary Material**.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because although our research was about shark stock assessment, all the data for stock assessment were from the scientific papers or thesis and Fisheries Agency.

AUTHOR CONTRIBUTIONS

PJ, YZ, and JX collected data. PJ analyzed data and drafted this original manuscript. MC, YT, and SY edited the manuscript. All authors contributed to the article and approved the submitted version.

FUNDING

MC, YZ, SY, and JX were partly funded by the National Key R&D Program of China (No. 2018YFC1406301), the Natural Science Foundation of Fujian Province, China (No. 2018J01066), and Xiamen University Malaysia Research Fund (No: XMUMRF/2020-C5/ICAM/0007). PJ and YT were partially supported by National Key Research and Development Project (No. 2018YFD0900902) and National Natural Science Foundation of China (Nos. 41930534 and 41861134037).

ACKNOWLEDGMENTS

The authors thank Dr. Maria Lourdes Palomares, Dr. Rainer Froese, Dr. Cui Liang, and Dr. Daniel Pauly for the constructive comments on LBB results. The authors also thank Prof. Robin Robertson for editing the manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00632/full#supplementary-material

REFERENCES

Adams, K. R., Fetterplace, L. C., Davis, A. R., Taylor, M. D., and Knott, N. A. (2018). Sharks, rays and abortion: the prevalence of capture-induced parturition in elasmobranchs. *Biol. Conserv.* 217, 11–27. doi: 10.1016/j.biocon.2017.10.010

Baum, J. K., Myers, R. A., Kehler, D. G., Worm, B., Harley, S. J., and Doherty, P. A. (2003). Collapse and conservation of shark populations in the Northwest Atlantic. *Science* 299, 389–392. doi: 10.1126/science.1079777

Booth, H., Squires, D., and Milner-Gulland, E. J. (2019). The neglected complexities of shark fisheries, and priorities for holistic risk-based management. *Ocean Coast. Manage.* 182:104994. doi: 10.1016/j.ocecoaman.2019.104994

Chen, J. L., Lin, Y. S., and Chuang, C. T. (2018). Improving the management of Taiwanese fishery resource conservation zones based on public perceptions and willingness to pay for ecosystem services. *J. Coast. Conserv.* 22, 385–398. doi: 10.1007/s11852-017-0586-5

Chen, M. R., Qiu, S. Y., and Yang, S. Y. (2001). The reproductive biology of the spadenose shark, *Scoliodon laticaudus*, from southern Fujian coastal waters. *Acta Oceanologica Sinica* 23, 92–98.

Clarke, S. C., McAllister, M. K., Milner-Gulland, E. J., Kirkwood, G. P., Michielsens, C. G. J., Agnew, D. J., et al. (2006). Global estimates of shark catches using trade records from commercial markets. *Ecol. Lett.* 9, 1115–1126. doi: 10.1111/j.1461-0248.2006.00968.x

Cortés, E. (2000). Life history patterns and correlations in sharks. *Rev. Fish. Sci.* 8, 299–344. doi: 10.1080/10408340308951115

Davidson, L. N. K., Krawchuk, M. A., and Dulvy, N. K. (2016). Why have global shark and ray landings declined: improved management or overfishing? *Fish Fish.* 17, 438–458. doi: 10.1111/faf.12119

Dulvy, N. K., Fowler, S. L., Musick, J. A., Cavanagh, R. D., Kyne, P. M., Harrison, L. R., et al. (2014). Extinction risk and conservation of the world's sharks and rays. *eLife* 3:e00590. doi: 10.7554/eLife.00590.001

Ebert, D. A., Ho, H.-C., White, W. T., and Carvalho, M. R. D. (2013). Introduction to the systematics and biodiversity of sharks, rays, and chimaeras (Chondrichthyes) of Taiwan. *Zootaxa* 3752, 5–19. doi: 10.11646/zootaxa.3752.1.3

Eriksson, H., and Clarke, S. (2015). Chinese market responses to overexploitation of sharks and sea cucumbers. *Biol. Conserv.* 184, 163–173. doi: 10.1016/j.biocon.2015.01.018

Ferretti, F., Worm, B., Britten, G. L., Heithaus, M. R., and Lotze, H. K. (2010). Patterns and ecosystem consequences of shark declines in the ocean. *Ecol. Lett.* 13, 1055–1071. doi: 10.1111/j.1461-0248.2010.01489.x

Froese, R., and Pauly, D. (eds) (2019). *FishBase. World Wide Web Electronic Publication*. www.fishbase.org, version (08/2019)

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A. C., Dimarchopoulou, D., et al. (2018). Estimating stock status from length frequency data. *ICES J. Mar. Sci.* 75, 2004–2015. doi: 10.1093/icesjms/fsy078

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A. C., Dimarchopoulou, D., et al. (2019). On the pile-up effect and priors for L_{inf} and M/K: response to a comment by Hordyk et al. on "A new approach for estimating stock status from length frequency data". *ICES J. Mar. Sci.* 76, 461–465. doi: 10.1093/icesjms/fsy199

Heupel, M. R., Knip, D. M., Simpfendorfer, C. A., and Dulvy, N. K. (2014). Sizing up the ecological role of sharks as predators. *Mar. Ecol. Prog. Ser.* 495, 291–298. doi: 10.3354/meps10597

Hobday, A. J., and Pecl, G. T. (2014). Identification of global marine hotspots: sentinels for change and vanguards for adaptation action. *Rev. Fish Biol. Fisher.* 24, 415–425. doi: 10.1007/s11160-013-9326-6

Hsu, H. H., Joung, S. J., Hueter, R. E., and Liu, K. M. (2014). Age and growth of the whale shark (*Rhincodon typus*) in the north-western Pacific. *Mar. Freshwater Res.* 65, 1145–1154. doi: 10.1071/MF13330

Hsu, H. H., Joung, S. J., and Liu, K. M. (2012). Fisheries, management and conservation of the whale shark Rhincodon typus in Taiwan. *J. Fish Biol.* 80, 1595–1607. doi: 10.1111/J.1095-8649.2012.03234.X

Joung, S.-J., Chen, C.-T., Lee, H.-H., and Liu, K.-M. (2008). Age, growth, and reproduction of silky sharks. Carcharhinus falciformis, in northeastern Taiwan waters. *Fish. Res.* 90, 78–85. doi: 10.1016/j.fishres.2007.09.025

Joung, S.-J., Chen, J.-H., Chin, C.-P., and Liu, K.-M. (2015). Age and growth of the dusky shark. *Carcharhinus obscurus*, in the Western North Pacific Ocean. *Terr. Atmos. Ocean. Sci.* 26, 153–160. doi: 10.3319/TAO.2014.10.15.01(Oc)

Kang, B., Liu, M., Huang, X.-X., Li, J., Yan, Y.-R., Han, C.-C., et al. (2018). Fisheries in Chinese seas: what can we learn from controversial official fisheries statistics? *Rev. Fish. Biol. Fisher.* 28, 503–519. doi: 10.1007/s11160-018-9518-1

Kyne, P. M., Liu, K. M., and Simpfendorfer, C. (2019). *Megachasma Pelagios. the IUCN Red List of Threatened Species 2019*. e.T39338A124402302. doi: 10.2305/IUCN.UK.2019-1.RLTS.T39338A124402302.en

Liao, C. P., Huang, H. W., and Lu, H. J. (2019). Fishermen's perceptions of coastal fisheries management regulations: key factors to rebuilding coastal fishery resources in Taiwan. *Ocean Coast. Manage.* 172, 1–13. doi: 10.1016/j.ocecoaman.2019.01.015

McCann, K. S., Rasmussen, J. B., and Umbanhowar, J. (2005). The dynamics of spatially coupled food webs. *Ecol. Lett.* 8, 513–523. doi: 10.1111/j.1461-0248.2005.00742.x

Momigliano, P., and Harcourt, R. (2014). "Shark conservation, governance and management: the science-law disconnect," in *Sharks: Conservation, Governance and Management*, eds N. Klein and E. Techera (New York, NY: Earthscan press), 89–106. doi: 10.4324/9780203750292

Musick, J. A., Burgess, G., Cailliet, G., Camhi, M., and Fordham, S. (2000). Management of Sharks and Their Relatives (Elasmobranchii). *Fisheries* 25, 9–13. doi: 10.1577/1548-8446(2000)025<0009:mosatr>2.0.co;2

Nakaya, K., Matsumoto, R., and Suda, K. (2008). Feeding strategy of the megamouth shark *Megachasma pelagios* (Lamniformes:Megachasmidae). *J. Fish. Biol.* 73, 17–34. doi: 10.1111/j.1095-8649.2008.01880.x

Oliver, S., Braccini, M., Newman, S. J., and Harvey, E. S. (2015). Global patterns in the bycatch of sharks and rays. *Mar. Policy* 54, 86–97. doi: 10.1016/j.marpol.2014.12.017

Palomares, M. L. D., Froese, R., Derrick, B., Nöel, S.-L., Tsui, G., Woroniak, J., et al. (2018) "A preliminary global assessment of the status of exploited marine fish and invertebrate populations," in *A Report Prepared by the Sea Around Us for OCEANA* (Vancouver: The University of British Columbia), 64.

Pierce, S. J., and Norman, B. (2016). *Rhincodon Typus. The IUCN Red List of Threatened Species 2016*. e.T19488A2365291. doi: 10.2305/IUCN.UK.2016-1.RLTS.T19488A2365291.en

Simpfendorfer, C., and Dulvy, N. K. (2017). Bright spots of sustainable shark fishing. *Curr. Biol.* 27, R97–R98. doi: 10.1016/j.cub.2016.12.017

Stevens, J. D., Bonfil, R., Dulvy, N. K., and Walker, P. A. (2000). The effects of fishing on sharks, rays, and chimaeras (chondrichthyans), and the implications for marine ecosystems. *ICES J. Mar. Sci.* 57, 476–494. doi: 10.1006/jmsc.2000.0724

Sulikowski, J. A., Golet, W., Hoffmayer, E. R., Driggers, W. B. III, Natanson, L. J., Carlson, A., et al. (2020). Observing post-release mortality for dusky sharks, *Carcharhinus obscurus*, captured in the U.S. *pelagic longline* fishery. *Fish. Res.* 221:105341. doi: 10.1016/j.fishres.2019.105341

Worm, B., Davis, B., Kettemer, L., Ward-Paige, C. A., Chapman, D., Heithaus, M. R., et al. (2013). Global catches, exploitation rates, and rebuilding options for sharks. *Mar. Policy* 40, 194–204. doi: 10.1016/j.marpol.2012.12.034

Zhao, Y., Chen, M., Jiang, C., Yang, S., and Xiao, J. (2017). Occurrence of an Intersexual Pacific Spadenose Shark Scoliodon macrorhynchos from the Southern Taiwan Strait. *Mar. Coast. Fish.* 9, 573–576. doi: 10.1080/19425120.2017.1383326

Zhao, Y. (2018). *Age, Growth and Reproductive Biology of the Pacific Spadenose Shark Scoliodon Macrorhynchos from the southern Taiwan Strait*. Master thesis, Xiamen: Xiamen University.

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Marine Science

BRIEF RESEARCH REPORT
published: 12 January 2021
doi: 10.3389/fmars.2020.518627

Check for updates

Using LBB Tools to Assess Miter Squid Stock in the Northeastern South China Sea

Xuehui Wang[1]*, Yinglin He[2], Feiyan Du[1,3], Mengna Liu[1,4], Weilie Bei[2], Yancong Cai[1,5] and Yongsong Qiu[1,5]

[1] South China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences, Guangzhou, China, [2] China Blue Sustainability Institute, Haikou, China, [3] Guangdong Provincial Key Laboratory of Fishery Ecology and Environment, Guangzhou, China, [4] College of Marine Sciences, Shanghai Ocean University, Shanghai, China, [5] Key Laboratory of Open-Sea Fishery Development, Ministry of Agriculture and Rural Affairs, Guangzhou, China

Based on length frequency data of miter squid (*Uroteuthis chinensis*) collected in the northeastern South China Sea in 1975–1977, 1997–1999, and 2018–2019, asymptotic length, optimal length at first capture, relative mortality, and relative biomass of the stock were estimated using length-based Bayesian biomass estimation (LBB). The LBB-estimated asymptotic length for 2018–2019 was smaller. Optimal lengths at first capture for the later far exceeded average lengths in catches because of a major increase in fishing intensity. Between 1975 and 1977, relative total mortality (Z/K) was low, but it increased in the latter two periods, while relative natural mortality (M/K) showed a downward trend. Relative biomasses (B/B_0 and B/B_{msy}) indicated that the stock was close to unexploited between 1975 and 1977, but they declined to the levels of 6% and 4% in the later periods, which correspond to growth in fishing horsepower. Indeed, by 2018, fishing horsepower increased by nearly four times the optimal level. The analysis suggests that the stock of miter squid has been overfished since the mid-1980s and is now under heavy fishing pressure. To recover the stock, it is imperative to reduce fishing intensity and enforce size-at-first-capture regulations.

Keywords: length frequency, LBB, data-limitation, stock status, *Uroteuthis chinensis*, northeastern South China Sea

OPEN ACCESS

Edited by:
Daniel Pauly,
Sea Around Us, Canada

Reviewed by:
Nazli Demirel,
Istanbul University, Turkey
Cui Liang,
Institute of Oceanology (CAS), China

****Correspondence:***
Xuehui Wang
wxhscs@163.com

Specialty section:
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

Received: *09 December 2019*
Accepted: *11 December 2020*
Published: *12 January 2021*

Citation:
Wang X, He Y, Du F, Liu M, Bei W, Cai Y and Qiu Y (2021) Using LBB Tools to Assess Miter Squid Stock in the Northeastern South China Sea. Front. Mar. Sci. 7:518627. doi: 10.3389/fmars.2020.518627

INTRODUCTION

Fishing activity dates back many centuries in coastal waters, but the exploitation of virtually all coastal stocks started to occur around 1990 (Brander, 2013). Increased fishing intensity affects the life histories of fishes and marine invertebrates (henceforth: fish), leading to rapid declines in fish stocks, and it also impacts entire marine ecosystems (Vincent and Hall, 1996; Pauly et al., 1998; Hutchings, 2000; Kuparinen and Merilä, 2007). Due to the over-exploitation of fish stocks, many governments and non-government organizations (NGOs) agree there is a need for science-based management. Science-based fishery management requires evaluation of sustainable fishery catches based on the existing yield, survey, or life history data of target fish (Dick and MacCall, 2011; Costello et al., 2012; Thorson et al., 2013; Froese et al., 2017). However, most fishery stock assessment methods require numerous parameters to be input for estimation, which limits their broad application. Therefore, fishery stock assessment methods that require inputs of simple parameters or variables are beneficial for the development of fishery stock assessments (Froese et al., 2018).

The size composition or length frequency distribution of a fish population has long been used as a data source with which to assess stock status for fishery management (Beverton and Holt, 1957; Pauly and Morgan, 1987; Gulland and Rosenberg, 1992; Wang et al., 2012; Froese et al., 2018), and it has also been used as a major (if not the only) data source to assess fisheries in data-limited situations (Dick and MacCall, 2011; Costello et al., 2012; Martell and Froese, 2013; Thorson et al., 2013; Free et al., 2017; Froese et al., 2017, 2018; Zhou et al., 2017). The length-based Bayesian biomass estimation method (LBB) differs from other methods of fishery stock assessment, as it does not require data on age, maturity, recruitment, growth, mortality, catch per unit effort (CPUE), or effort. Instead, the LBB only requires data that represents the length frequency distribution of the evaluated population (Froese et al., 2018). Thus, it is considered a suitable method for stock assessment of the data-limited miter squid fishery in the northeastern South China Sea (neSCS).

Using the LBB method, Baldé et al. (2019) successfully estimated optimal lengths at first capture for two *Sardinella* stocks in the Senegal waters. Pons et al. (2020) evaluated the performance of three length-only assessment methods in data-limited fisheries, the Length-Based Spawning Potential Ratio (LBSPR, Hordyk et al., 2015), the Length-Based Integrated Mixed Effects (LIME, Rudd and Thorson, 2018), and the LBB. They concluded that, compared with the other two methods, LBB performed better in estimating the depletion levels of heavily and moderately fished stocks, especially for the short-lived species. Estimations using both the LBB and LIME for long-lived species exposed to low fishing mortality generally resulted in biased estimates (Pons et al., 2020; see also ICCAT, 2019). This suggests that LBB would be a suitable method for the assessment of the short-lived, heavily-fished miter squid stock in the neSCS.

The neSCS (also known as the Shantou-Taiwan bank fishing ground or Minnan-Taiwan bank fishing ground) is located in the southwest of the Taiwan Strait (21°50′–23°30′N, 116°00′–119°30′E) at the junction of the East China Sea and the SCS, and it covers an area of about 50×10^3 km^2 (**Figure 1**). The fishing ground is located in a unique geographical location with complex influences from current systems, such as the Zhejiang-Fujian Coastal Current, the Eastern Guangdong Coastal Current, the Kuroshio Current's SCS Branch, and the SCS Warm Current (Jan et al., 2002; Tang et al., 2002; Hu et al., 2003, 2010; Jiang et al., 2011). The convergence of these currents, the topographic upwellings they induced (Hu et al., 2003), and the influence of tropical cyclones (Qiu et al., 2010) create favorable feeding conditions for marine organisms. Cephalopods are the dominant taxon caught there, and the miter squid *Uroteuthis chinensis* (Gray) is the major target species of the fishery.

The miter squid belongs to the phylum Mollusca, class Cephalopoda, order Teuthoidea, and family Loliginidae[1]. It is mainly distributed in the continental shelf of the SCS and south-central Taiwan Strait. The miter squid in the Taiwan bank fishing ground is the most abundant, and it supports the largest squid fishery in coastal China. The squids are harvested by jigging, trawl, light purse seine, and light lift net operations. Before and during the 1980s, they were mainly harvested by fishing boats from the Nan'ao County (**Figure 1**), and the highest landing reached 5.1×10^4 tons in 1985 (Li and Wu, 1988). However, landings have since dropped, and annual landings from this fishing ground were estimated at 2.0–2.5 $\times 10^4$ tons by the 2000s (Zhang et al., 2008). Studies on miter squid in the neSCS ever involved its biology, stock status, and fishery management (Ou, 1981, 1983; Lan, 1985; Zhang et al., 2008; Chen, 2016), but a few studies focused on its population parameters and stock assessment. Based on length frequency data collected during the periods 1975–1977, 1997–1999, and 2018–2019 in the neSCS, this study estimates the population parameters of the squid and assesses its stock status using the LBB method. The analysis may provide useful information for the management of the fishery and help toward its sustainable exploitation.

[1]http://www.molluscabase.org

MATERIALS AND METHODS

Data Collection

We analyzed length frequency data from the neSCS to assess the stock status of the miter squid in the periods from 1975 to 1977, 1997 to 1999, and 2018 to 2019, respectively. Data for 1975–1977 came from trawl surveys conducted in spring–autumn months and were digitized from a survey report (Investigation Team of Marine Fish Resources of Southern Fujian Fishing Ground (ITMFRSFFG), 1980). The L/F data from 1997 to 1999 were collected in a quarterly trawl survey. Data for 2018–2019 were collected during the implementation of a fishery improvement project (FIP), and the squid samples from commercial catches were supplied by a fish processing factory as coordinated by the China Blue Sustainability Institute; these samples were also collected from trawl fishing. The cod-end meshes of the trawl gears were 6.0 cm, 2.0 cm, and 1.8 cm, respectively, for samples from 1975 to 1977, 1997 to 1999, and 2018 to 2019. The sampling frequency and sample sizes are summarized in **Table 1**, and details are provided in the **Supplementary Material**.

During sample collection in 1997–1999 and 2018–2019, all the squids were retained for measurement when <50 squids were captured in any trawl haul; otherwise, 50 squids were collected randomly for subsequent lab measurement. Squids were frozen immediately and stored upon collection, and they were then defrosted and measured in the lab. The mantle length and wet weight were measured to the nearest 0.1 cm and 0.1 g, respectively.

The LBB Method

LBB is a method for assessing the status of a fishery based on relative length. The principle of the LBB method is that the absolute values of age and biomass can be replaced by their relative values. The key formulas of the LBB method in the present analysis are shown here, but details of the specific framework and a full array of formulas of LBB are given in Froese et al. (2018).

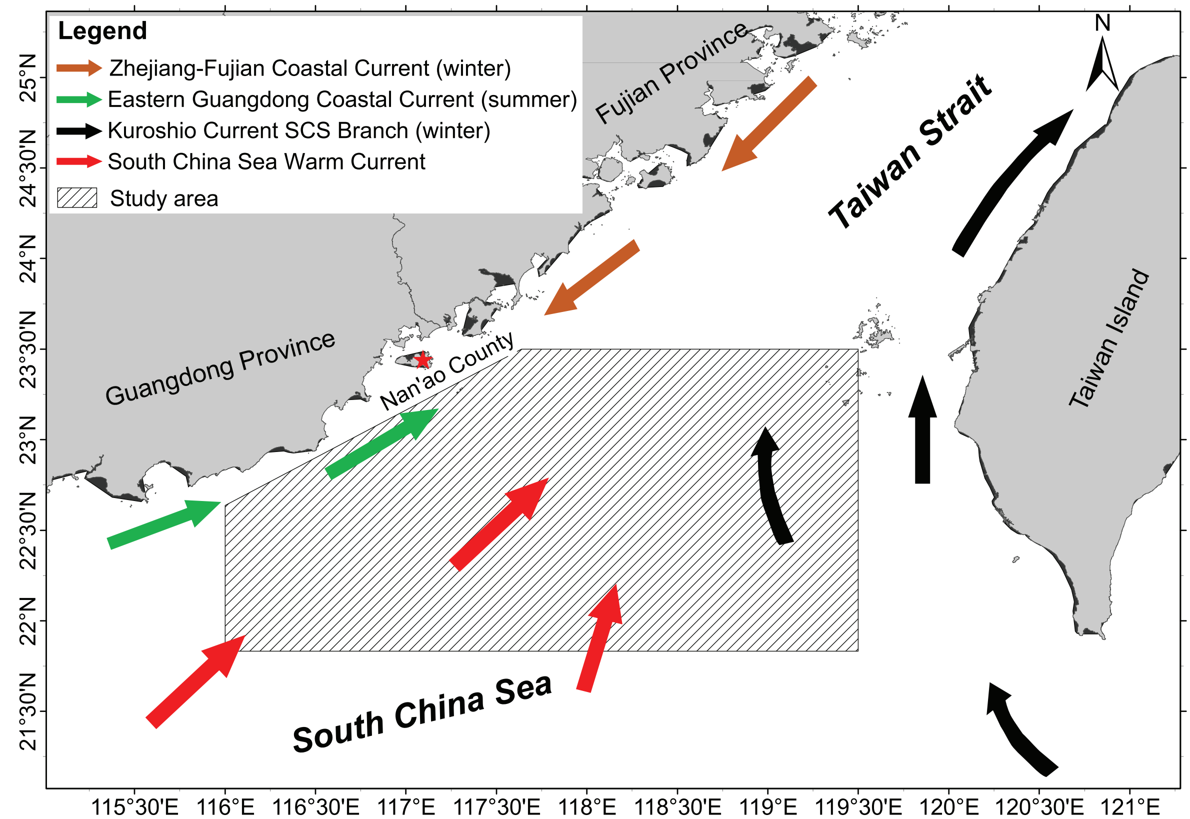


FIGURE 1 | Study area in the northeast South China Sea and the current systems [Redrawn from Cai and Shi (2009) and Hu et al. (2010)].

TABLE 1 | Sampling areas, sample sizes, and sampling frequency in different years.

Years	Regions	Sample sizes	Sampling frequency	Research vessel
1975–1976	116°–119°E, 21°20–24°N	713	April, 1975; April, May, and September, 1976; April, June, July, August, and September, 1977	F/V: Minyu 301, Minfeng and Xiayu 507
1997–1999	115°–119°25′E, 20°47.5′–23°34′N	1526	December, 1997; January, July, August, October, and November, 1998; January, May, and June, 1999	R/V: BeiDou
2018–2019	116°00′–119°30′E, 21°50′–23°30′N	1882	Monthly, from July, 2018 to June, 2019	Commercial fishing vessels

Growth in length is expressed by the von Bertalanffy growth function (von Bertalanffy, 1938).

$$L_t = L_{\text{inf}}[1 - e^{-K(t-t_0)}] \quad (1)$$

where L_t is the mantle length at age t, L_{inf} is the asymptotic mantle length, k is the rate by which L_{inf} is approached, and t_0 is the theoretical age at zero mantle length.

The number of squids surviving to a specific length is estimated by the following formula:

$$N_L = N_{L_{\text{start}}}\left(\frac{L_{\text{inf}}-L}{L_{\text{inf}}-L_{\text{start}}}\right)^{Z/K} \quad (2)$$

where N_L is the number of survivors to length L, N_{Lstart} is the number at length L_{start} with full selection, i.e., the length at which all individuals entering the gear are retained by it and Z/K is the ratio of the total mortality rate (Z) to the growth coefficient (K), M is the natural mortality, F is the fishing mortality, and $Z = M + F$ (Froese et al., 2018).

The optimal length at first capture L_{c_opt} for a specific fishing mortality (F) can be obtained from,

$$L_{\text{c\_opt}} = \frac{L_{\text{inf}}(2 + 3\frac{F}{M})}{(1 + \frac{F}{M})(3 + \frac{M}{K})} \quad (3)$$

The Y'/R, yield per recruitment equation is expressed by indexes of L_c/L_{inf}, F/K, M/K, and F/M (Beverton and Holt, 1966; Froese et al., 2018), where L_c is the mean length at first capture. Assuming that fishing mortality F is proportional to fishing effort, the index of $CPUE'/R$ can be obtained from Y'/R dividing F/M (Beverton and Holt, 1966; Froese et al., 2018):

$$\frac{CPUE'}{R} = \frac{Y'/R}{F/M} = \frac{1}{1+F/M}(1-L_c/L_{\mathrm{inf}})^{M/K}$$

$$\left(1-\frac{3\,(1-L_c/L_{\mathrm{inf}})}{1+\frac{1}{M/K+F/K}}+\frac{3\,(1-L_c/L_{\mathrm{inf}})^2}{1+\frac{2}{M/K+F/K}}-\frac{(1-L_c/L_{\mathrm{inf}})^3}{1+\frac{3}{M/K+F/K}}\right) \quad (4)$$

When the stock is unexploited, the relative biomass in the potentially exploited phase of the population can be expressed:

$$\frac{B_0' > L_c}{R} = (1-L_c/L_{\mathrm{inf}})^{M/K}$$

$$\left(1-\frac{3\,(1-L_c/L_{\mathrm{inf}})}{1+\frac{1}{M/K}}+\frac{3\,(1-L_c/L_{\mathrm{inf}})^2}{1+\frac{2}{M/K}}-\frac{(1-L_c/L_{\mathrm{inf}})^3}{1+\frac{3}{M/K}}\right) \quad (5)$$

where, $B_0{}' > L_c$ denotes the exploitable fraction ($>L_c$) of the unexploited biomass (B_0). The ratio B/B_0 is obtained from formulas (4) and (5) (Beverton and Holt, 1966; Froese et al., 2018):

$$\frac{B}{B_0} = \frac{\frac{CPUE'}{R}}{\frac{B_0'>L_c}{R}} = \frac{CPUE'}{B_0' > L_c} \quad (6)$$

The present data analysis was performed using the R-code LBB_20.R, which was obtained from http://oceanrep.geomar.de/44832/. In this study, we hypothesized that the squid stock in 1975–1977 represented the unexploited biomass (B_0) when the fishery has not yet been developed because Chinese offshore fishing was relatively undeveloped in the 1970s.

RESULTS

The population parameters and relative biomass of the squid estimated by LBB are shown in **Table 2** and **Figure 2**. The results indicated a slight difference in the estimated asymptotic mantle length (L_{inf}) of the squid during the periods 1975–1977, 1997–1999, and 2018–2019 (41.1 cm, 41.8 cm, and 36.6 cm, respectively). The optimal mantle length at first capture (L_{c_opt}) estimated by LBB increased from 17 cm (41% of L_{inf}) in 1975–1977 to 25 cm (60% of L_{inf}) in 1997–1999 and 23 cm (63% of L_{inf}) in 2018–2019. Relative total mortality (Z/K) showed an upward trend over the three periods, i.e., 2.1, 4.6, and 6.0, respectively. In the period 1975–1977, the estimated relative fishing mortality was $F/M = 0.02 \approx 0$, but increased in the later two periods, while the relative natural mortality M/K showed a downward trend. The estimated relative biomass $B/B_0 = 0.96 \approx 1$ and $B/B_{msy} = 2.8$ in 1975–1977 were much higher than those in 1997–1999 and in 2018–2019.

TABLE 2 | Population parameters of miter squid estimated by LBB.

Parameters	1975–1977	1997–1999	2018–2019
L_{inf} (cm)	41.1 (40.7–41.7)	41.8 (41.2–42.5)	36.6 (36.1–37.3)
L_{c_opt} (cm)	17	25	23
Z/K	2.1 (1.96–2.18)	4.6 (4.48–4.79)	6.0 (5.78–6.30)
F/M	0.02 (0.01–0.09)	2.00 (1.67–2.69)	3.22 (2.45–4.35)
M/K	2.02 (1.89–2.12)	1.54 (1.26–1.74)	1.44 (1.17–1.72)
B/B_0	0.96 (0.15–4.94)	0.06 (0.05–0.08)	0.04 (0.03–0.06)
B/B_{msy}	2.8 (0.42–14.2)	0.17 (0.12–0.23)	0.12 (0.08–0.17)

The mean length (L_{mean}; **Figure 2A**) and relative biomass (B/B_0; **Figure 2H**) of the squid were above the levels of moderate exploitation in the period of 1975–1977, which indicated that the squid was underexploited. However, in the periods of 1997–1999 and 2018–2019, with the apparent increase in relative fishing intensity (F/M; **Figure 2G**), L_{mean} and B/B_0 showed a sharp decline and remained in very low levels.

The apparent increases in Z/K and F/M and decreases in L_{mean}, B/B_0, and B/B_{msy} well correspond to the growth in horsepower of marine motorized fishing boats from the nearby Fujian and Guangdong Provinces, an indicator of overall fishing intensity. Here, we use horsepower of marine motorized fishing boats as a general indicator of increasing fishing pressure and assume that fishing pressure on miter squid shows parallel changes, because fishing horsepower specific to miter squid fishery is not available. In particular, both B/B_0 and B/B_{msy} showed an inversed decline with increasing horsepower of the fishing boats (**Figure 3**; both $R^2 = 1.00$, $P < 0.01$), and the level of $B/B_{msy} = 1$ corresponds to a horsepower level of 1.24×10^6 kW and $B/B_0 = 34\%$. If we consider the horsepower level in 1984 as optimal, the horsepower level of 4.87×10^6 kW in 2018 would be nearly four times the optimal level. This indicates that the squid stock has long been overexploited since the mid-1980s and is now strongly over-fished.

DISCUSSION

The LBB method provides a new tool for stock assessment in a data-limited fishery. Compared with other methods of fish stock assessment, the advantage of the LBB method is that it only needs length-frequency data (Froese et al., 2018). Length frequency data are also the most readily available and are not affected by weighting difficulties on unstable vessels or the sampled fish or squid having been gutted. Thus, they have a low incidence of error (Wang et al., 2011). Another advantage of the LBB method is that it can estimate the relative standing biomass B/B_0 and B/B_{msy}, both of which are important indicators of stock status and fishing intensity, and their trends can be related to that of fishing effort.

The LBB method and the software developed on the basis is capable of determining the length at first capture

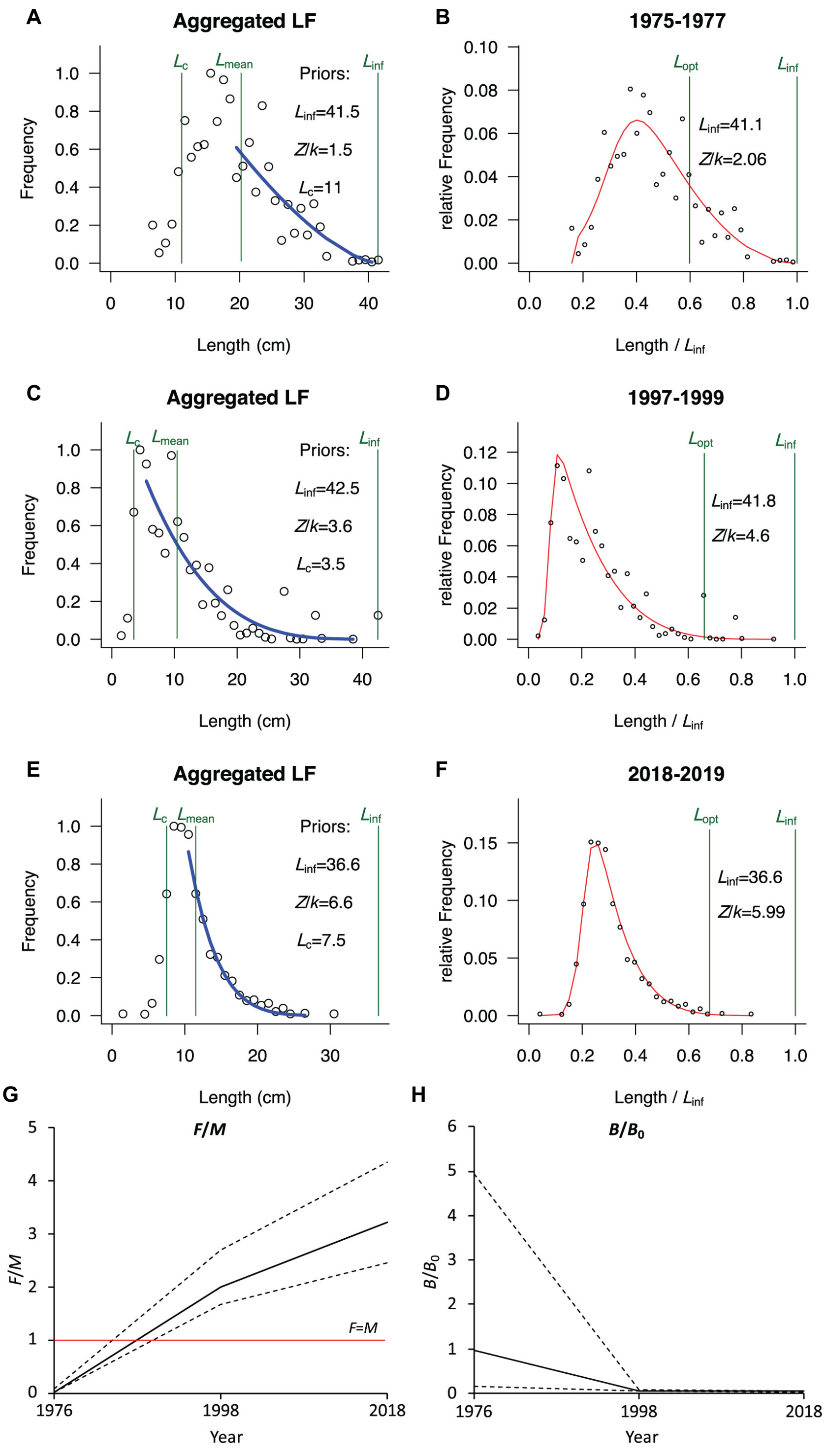


FIGURE 2 | Trends of population parameters and relative biomass of the miter squid in the neSCS based on LBB estimation. **(A,C,E)** The accumulated length frequency data used to estimate priors L_{inf}, L_c, L_{mean}, and Z/k, respectively, from 1975 to 1977, 1997 to 1999, and 2018 to 2019. **(B,D,F)** The relative length frequency data used to fit the red curves which are in turn used to estimate Z/k, M/k, F/k, L_c, and L_{inf}. The L_{opt} is calculated based on L_{inf} and M/k. **(G)** Changes in relative fishing intensity F/M, and **(H)** changes in relative biomass B/B_0.

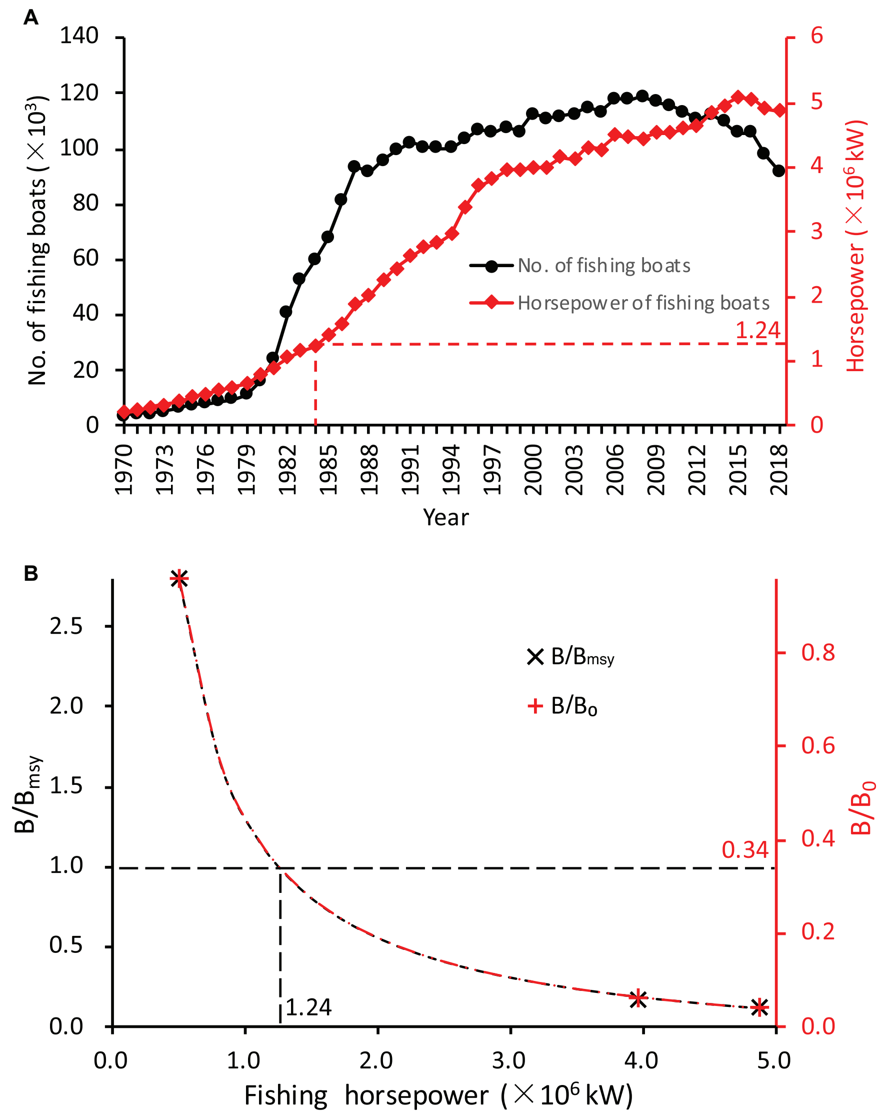


FIGURE 3 | Growth in fishing intensity and its impact on relative biomass of the miter squid stock. **(A)** Growth in marine motorized fishing boats from the Fujian and Guangdong Provinces from 1970 to 2018 [data from China Fishery Statistical Yearbook (Fishery Management Bureau of Ministry of Agriculture and Rural Affair (FMBMARA), 1970–2018)]. **(B)** Decline of relative biomass (B/B_{msy} and B/B_0) with increasing fishing horsepower; $B = B_{msy}$ corresponds to $B = 0.34B_0$ and fishing horsepower level of 1.24 × 10^6 kW in 1984.

(L_c) with the only input of aggregated length frequency and use the portion of the aggregated frequency of length $>L_c$ (full selected length) for the estimation of stock parameters. This ensures that the estimation of stock parameters will not be biased by changes in selectivity of the sampling gears. The use of less-selective trawl fishing methods and replicate samples collected from different seasons in the present study also ensures wide coverage of the length-frequency spectrum, including length data from the small-size juvenile squids, meeting the only requirement that the collection of samples can represent the length frequency of the evaluated fishery population (Froese et al., 2018). The LBB-estimated L_c were 11 cm, 3.5 cm, and 7.5 cm, respectively, for the periods 1975–1977, 1997–1999, and 2018–2019 (**Figures 2A,C,E**), entailing that >90% of the length frequency samples was be used for the estimation of stock parameters.

The estimated asymptotic mantle lengths (L_{inf}) of the miter squid from the LBB were similar in the 1970s (41.1 cm) and 1990s (41.8 cm) but was only 36.6 cm by the period 2018–2019. The apparent decrease in the estimated asymptotic length might be attributed to fishing-induced miniaturization. Zhang et al. (2008) and Chen (2016) also suggested that there was a tendency for miniaturization of squid in the neSCS, with the average mantle length decreasing from 21.0 cm in the 1970s to 10.4 cm in the

1990s, and the average mantle length was 11.5 cm in 2018–2019 (**Figure 2**). In addition to being a clear indication of growth overfishing, this also suggests a genetic selection toward smaller sizes.

LBB can estimate optimal length at first capture (L_{c_opt}) according to length frequency distribution that reflects the stock status. The squid's mantle length frequency data from the 1970s were collected during a period when most of the fishing boats were not motorized and fishing intensity was low, and the LBB estimation recommended a lower L_{c_opt} of 17.0 cm (41% of L_{inf}). With the increase in fishing intensity, the L_{c_opt} estimated for the periods 1997–1999 and 2018–2019 increased to 25.0 cm (60% of L_{inf}) and 23.0 cm (63% of L_{inf}), respectively, both of which are much larger than the average mantle length of 10.4 cm between 1997 and 1999 and 11.5 cm between 2018 and 2019. This indicates that, in addition to high fishing intensity since the mid-1980s, the capture of undersized juveniles is another major problem in the fishery.

Simulation of the squid fishery development using LBB method showed that the standing stock was close to the virgin stock ($B/B_0 = 0.96 \approx 1$) in the 1970s, which verified our assumption. The standing stock (B) at that time was the largest, at 2.8 times B_{msy}. The increase in fishing intensity was the major factor leading to a decline in the stock biomass. Base on the LBB simulation, the fishing intensity was relatively low ($F/M = 0.02 \approx 0$) in the 1970s. Then, with the increase in fishing intensity, the F/M increased, reaching 2.00 between 1997 and 1999 and 3.22 between 2018 and 2019. Consequently, the standing stock biomass (B) between 1997 and 1999 and between 2018 and 2019 has decreased to 6 and 4%, respectively, of the unexploited stock (B_0) level (**Figure 2** and **Table 2**), indicating that the stock has been under severe overexploitation. The overfishing has also resulted in the decline of catches. With rapid increases in the number of marine motorized fishing boats and their horsepower in Fujian and Guangdong provinces since the 1980s (**Figure 3**), the annual yield of the squid increased rapidly to culminated ($>5 \times 10^4$ tons) in 1985 (**Figure 4**), but it since decreased to about 2.0–2.5 $\times 10^4$ tons by the 2000s (Zhang et al., 2008).

The LBB simulation confirms that the squid stock is strongly overexploited. To recover the squid stock, it is imperative to reduce the fishing intensity and to stipulate and enforce the regulation of size at first capture.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because the research species belongs to the commercial animal, and does not involve ethical experiments, and complies with relevant laws.

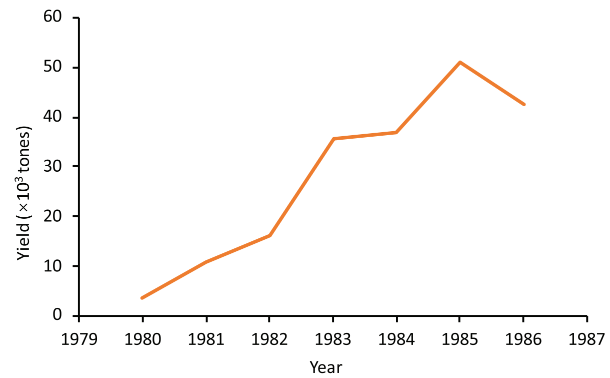


FIGURE 4 | Yield of miter squid in the Shantou-Taiwan Bank fishing ground by Nan'ao County during 1980–1986 (Li and Wu, 1988). The location of Nan'ao County is indicated in **Figure 1**.

AUTHOR CONTRIBUTIONS

XW: data collecting, formal analysis, and writing the original draft. YH and WB: squid specimens coordinator in 2018–2019 and founder. FD and YQ: frame design and review and editing. ML: data collecting and squid specimens measuring. YC: **Figure 1** redrawing. All authors contributed to the article and approved the submitted version.

FUNDING

This work was supported by the China Blue Sustainability Institute, Science and Technology Basic Resources Investigation Program of China (2017FY201405 and 218FY100105) and Central Public-interest Scientific Institution Basal Research Fund, CAFS (Nos. 2019HY-JC0203, 2019HY-XKQ03, and 2019GH02).

ACKNOWLEDGMENTS

We are grateful to Dr. Daniel Pauly, Dr. Maria Lourdes D. Palomares, Dr. WeiWei Xian, Dr. Rainer Froese, Dr. Cui Liang, and Dr. Lu Zhai for their help in applying the LBB method. We thank Yu Liu, Mengji Chen, Lanxiang Ke, Liya Fu, Shouxin Wang, Hong Li, and Miaodi Wang for their participation in biological measurement during the period 2018–2019. We acknowledge Shantou Wanchengxin Aquatic Products Co., Ltd. for providing the squid samples. We also thank two reviewers for their useful comments on this study.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.518627/full#supplementary-material

REFERENCES

Baldé, B. S., Fall, M., Kantoussan, J., Sow, F. N., Diouf, M., and Brehmer, P. (2019). Fish-length based indicators for improved management of the sardinella fisheries in Senegal. *Reg. Stud. Mar. Sci.* 31:100801. doi: 10.1016/j.rsma.2019.100801

Beverton, R. J. H., and Holt, S. J. (1957). *On the Dynamics of Exploited Fish Populations: Series II*, Vol. XIX. London: Fishery Investigations, 533.

Beverton, R. J. H., and Holt, S. J. (1966). *Manual of Methods for Fish Stock Assessment, Part II – Tables of Yield Functions*. FAO Fisheries Technical Paper No. 38 (Rev. 1). Rome: FAO, 10.

Brander, K. (2013). Climate and current anthropogenic impacts on fisheries. *Clim. Change* 119, 9–21. doi: 10.1007/s10584-012-0541-2

Cai, Z., and Shi, Q. (2009). *Preliminary Study on the Origin of Taiwan Strait*. Xiamen: Xiamen University Press, 13–32 (in Chinese).

Chen, F. (2016). Survey of mitre squid resource in Minnan-Taiwan Bank fishing ground and suggestions for sustainable utilization. *Fish. Inform. Strategy* 31, 270–277 (in Chinese).

Costello, C., Ovando, D., Hilborn, R., Gaines, S. D., Deschenes, O., and Lester, S. E. (2012). Status and solutions for the world's unassessed fisheries. *Science* 338, 517–520. doi: 10.1126/science.1223389

Dick, E. J., and MacCall, A. D. (2011). Depletion-based stock reduction analysis: a catch-based method for determining sustainable yields for data-poor fish stocks. *Fish. Res.* 110, 331–341. doi: 10.1016/j.fishres.2011.05.007

Fishery Management Bureau of Ministry of Agriculture and Rural Affair (FMBMARA) (1970–2018). *Fishery Statisticcal Yearbook of China*. Beijing: FMBMARA (in Chinese).

Free, C. M., Jensen, O. P., Wiedenmann, J., and Deroba, J. J. (2017). The refined ORCS approach: a catch-based method for estimating stock status and catch limits for data-poor fish stocks. *Fish. Res.* 193, 60–70.

Froese, R., Demirel, N., Coro, G., Kleisner, K. M., and Winker, H. (2017). Estimating fisheries reference points from catch and resilience. *Fish Fish.* 18, 506–526. doi: 10.1111/faf.12190

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A. C., Dimarchopoulou, D., et al. (2018). A new approach for estimating stock status from length frequency data. *ICES J. Mar. Sci.* 76, 350–351. doi: 10.1093/icesjms/fsy139

Gulland, J. A., and Rosenberg, A. A. (1992). *A Review of Length-Based Approaches to Assessing Fish Stocks*. FAO Fisheries Technical Paper, No. 323. Rome: FAO, 100.

Hordyk, A., Ono, K., Valencia, S., Loneragan, N., and Prince, J. (2015). A novel length-based empirical estimation method of spawning potential ratio (SPR), and tests of its performance, for small-scale, data-poor fisherie. *ICES J. Mar. Sci.* 72, 217–231. doi: 10.4135/9781412953924.n678

Hu, J., Kawamura, H., Hong, H., and Pan, W. (2003). A review of research on the upwelling in the Taiwan Strait. *Bull. Mar. Sci.* 73, 605–628.

Hu, J., Kawamura, H., Li, C., Hong, H., and Jiang, Y. (2010). Review on current and seawater volume transport through the Taiwan Strait. *J. Oceanogr.* 66, 591–610. doi: 10.1007/s10872-010-0049-1

Hutchings, J. A. (2000). Collapse and recovery of marine fishes. *Nature* 406, 882–885. doi: 10.1038/35022565

ICCAT (2019). *Report of the 2019 ICCAT Working Group on Stock Assessment Methods Meeting (WGSAM)*. Available online at: https://iccat.int/Documents/Meetings/Docs/2019/REPORTS/2019_WGSAM_ENG.pdf (accessed December 2, 2019).

Investigation Team of Marine Fish Resources of Southern Fujian Fishing Ground (ITMFRSFFG) (1980). *Investigation Report of Fish Resources of Minnan-Taiwan Bank*. Xiamen: ITMFRSFFG, 398–410 (in Chinese).

Jan, S., Wang, J., Chern, C., and Chao, S. (2002). Seasonal variation of the circulation in the Taiwan Strait. *J. Mar. Syst.* 35, 249–268. doi: 10.1016/s0924-7963(02)00130-6

Jiang, Y., Chai, F., Wan, Z., Zhang, X., and Hong, H. (2011). Characteristics and mechanisms of the upwelling in the southern Taiwan Strait: a three-dimensional numerical model study. *J. Oceanogr.* 67, 699–708. doi: 10.1007/s10872-011-0080-x

Kuparinen, A., and Merilä, J. (2007). Detecting and managing fisheries-induced evolution. *Trends Ecol. Evol.* 22, 652–659. doi: 10.1016/j.tree.2007.08.011

Lan, X. (1985). Squid stocks in the coastal waters of southern Fujian and eastern Guangdong Provinces. *Mar. Fish.* 7, 208–209 (in Chinese).

Li, Q., and Wu, K. (1988). Production status and prospect of squid in fishing season in the Taiwan Bank fishing ground. *Mar. Fish.* 6, 257–259 (in Chinese).

Martell, S., and Froese, R. (2013). A simple method for estimating MSY from catch and resilience. *Fish Fish.* 14, 504–514. doi: 10.1111/j.1467-2979.2012.00485.x

Ou, R. (1981). Preliminary observations on the embryonic development of the squid, *Loligo chenensis* Gray. *Transact. Oceanol. Limnol.* 3, 51–59 (in Chinese).

Ou, R. (1983). Preliminary study on the stages of gonad maturity of the squid, *Loligo chinensis* Gray. *Mar. Sci.* 1, 44–46 (in Chinese).

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., and Torres, F. (1998). Fishing down marine food webs. *Science* 279, 860–863. doi: 10.1126/science.279.5352.860

Pauly, D., and Morgan, G. R. (1987). Length-based methods in fisheries research. *ICLARM Conf. Proc.* 13:486.

Pons, M., Cope, J. M., and Kell, L. T. (2020). Comparing performance of catch-based and length-based stock assessment methods in data-limited fisheries. *Canad. J. Fish. Aquat. Sci.* 77, 1026–1037. doi: 10.1139/cjfas-2019-0276

Qiu, Y., Lin, Z., and Wang, Y. (2010). Responses of fish production to fishing and climate variability in the northern South China Sea. *Prog. Oceanogr.* 85, 197–212. doi: 10.1016/j.pocean.2010.02.011

Rudd, M. B., and Thorson, J. T. (2018). Accounting for variable recruitment and fishing mortality in length-based stock assessments for data-limited fisheries. *Canad. J. Fish. Aquat. Sci.* 75, 1019–1035. doi: 10.1139/cjfas-2017-0143

Tang, D., Kester, D. R., Ni, I. H., Kawamura, H., and Hong, H. (2002). Upwelling in the Taiwan Strait during the summer monsoon detected by satellite and shipboard measurements. *Remote Sens. Environ.* 83, 457–471. doi: 10.1016/s0034-4257(02)00062-7

Thorson, J. T., Minto, C., Minte-Vera, C. V., Kleisner, K. M., and Longo, C. (2013). A new role for effort dynamics in the theory of harvested populations and data-poor stock assessment. *Canad. J. Fish. Aquat. Sci.* 70, 1829–1844. doi: 10.1139/cjfas-2013-0280

Vincent, A. C. J., and Hall, H. J. (1996). The threatened status of marine fishes. *Trends Ecol. Evol.* 11, 360–361. doi: 10.1016/0169-5347(96)30041-4

von Bertalanffy, L. (1938). A quantitative theory of organic growth (inquiries on growth laws. II). *Hum. Biol.* 10, 181–213.

Wang, X., Qiu, Y., Du, F., Lin, Z., Sun, D., and Huang, S. (2012). Population parameters and dynamic pool models of commercial fishes in the Beibu Gulf, northern South China Sea. *Chin. J. Oceanol. Limnol.* 30, 105–117. doi: 10.1007/s00343-012-1017-y

Wang, X., Qiu, Y., Zhu, G., Du, F., Sun, D., and Huang, S. (2011). Length-weight relationships of 69 fish species in the Beibu Gulf, northern South China Sea. *J. Appl. Ichthyol.* 27, 959–961. doi: 10.1111/j.1439-0426.2010.01624.x

Zhang, Z., Ye, S., Hong, M., Shen, C., and Su, X. (2008). Biological characteristics of the Chinese squid (*Loligo chinensis*) in minnan-taiwan shallow fishing ground. *J. Fuj. Fish.* 3, 1–5 (in Chinese). doi: 10.37828/em.2020.27.1

Zhou, S., Punt, A. E., Ye, Y., Ellis, N., Dichmont, C. M., Haddon, M., et al. (2017). Estimating stock depletion level from patterns of catch history. *Fish Fish.* 18, 742–751. doi: 10.1111/faf.12201

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Marine Science

ORIGINAL RESEARCH
published: 07 July 2020
doi: 10.3389/fmars.2020.00430

Assessing Northwest Pacific Fishery Stocks Using Two New Methods: The Monte Carlo Catch-MSY (CMSY) and the Bayesian Schaefer Model (BSM)

*Qing-qiang Ren and Min Liu**

State Key Laboratory of Marine Environmental Science and College of Ocean and Earth Sciences, Xiamen University, Xiamen, China

The CMSY and Bayesian Schaefer model (BSM) methods were applied to assess data-limited fishery stocks in the Japan Sea and surrounding areas of the Northwest Pacific. Ten stocks including 4 fish species and 5 cephalopod species were assessed; the CMSY method was used in 3 stocks with catch data only, and the BSM method in 7 stocks with both catch time series and catch per unit effort (CPUE) data available. The two methods estimated the maximum intrinsic rate of population increase (*r*) and carrying capacity of each stock, which allowed the computation of maximum sustainable yield (MSY), and exploited biomass relative to the biomass at maximum sustainable yield (B/B_{MSY}). All 10 stocks were overfished, if to a different extent, and one, the spear squid (*Heterololigo bleekeri*) has collapsed. The reference points estimated here may be used as indicator for fishery management in this ecoregion.

Keywords: data-limited stock assessment, CMSY and BSM methods, the Northwest Pacific, fish, cephalopod

OPEN ACCESS

Edited by:
Cui Liang,
Institute of Oceanology (CAS), China

Reviewed by:
Jiangfeng Zhu,
Shanghai Ocean University, China
Brett W. Molony,
CSIRO Oceans and Atmosphere (O&A), Australia

Correspondence:
Min Liu
minliuxm@xmu.edu.cn

Specialty section:
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

Received: *02 February 2020*
Accepted: *18 May 2020*
Published: *07 July 2020*

Citation:
Ren Q and Liu M (2020) Assessing Northwest Pacific Fishery Stocks Using Two New Methods: The Monte Carlo Catch-MSY (CMSY) and the Bayesian Schaefer Model (BSM). Front. Mar. Sci. 7:430. doi: 10.3389/fmars.2020.00430

INTRODUCTION

Global marine fishery catches fluctuated from 75 to 85 million tonnes since the late 1980s (FAO, 2018). From 1950 to 2012, both nominal fishing effort and capacity have increased from 1950 to 2012, especially in Asia and developing countries (Bell et al., 2016). Meanwhile, fishing fleets increased from 1.7 to 3.7 million vessels between 1950 to 2015, and effective catch per unit of effort (CPUE) has decreased substantially since 1950 (Rousseau et al., 2019).

Major stock collapses due to overfishing began to occur in the 1970s, and this became worse in the 1980s and 1990s (Pauly, 2008). Due to excessive fishing effort, the percentage of fish stocks being overfished within a decade after a fishery was fully developed increased from 26% in the 1950s to 35% in the 1980s. Nearly 50% of 900 important exploited species were overfished, collapsed or abandoned due to overfishing in 1999 (Froese and Kesner-Reyes, 2002), and the number of sustainably exploited stocks decreased from 90% in 1974 to 67% in 2015 (FAO, 2018). Large predatory fishes are strongly depleted, with their current biomass at only 10% of their pre-industrial levels (Myers and Worm, 2003).

While global fish fisheries declined, the populations of commercially exploited cephalopods have increased due to reduced predation by fish, thus allowing an increased fishing pressure to generate higher catches (Caddy and Rodhouse, 1998; Arkhipkin et al., 2015). Cephalopod fisheries increased from 1 million metric tons (mt) in the 1970s to over 4.3 mt in 2007 and fluctuating thereafter (Jereb et al., 2010; Arkhipkin et al., 2015; FAO, 2018). In the Japan Sea (which is surrounded by the

Korean Peninsula, the Japanese islands and the Russian coast, forming a semi-enclosed marginal sea), small pelagic fish and cephalopods jointly contributed 52% of the total catch (Zhang et al., 2004). The growing interest in cephalopod fisheries is mainly due to the high value of their catch, and, for fisheries scientists, to their response to ecosystem changes (Rodhouse, 2001).

The lack of scientific knowledge about the development, fluctuation and status of the exploited stocks has often prevented the implementation of fisheries management plans (Ludwig et al., 1993). To help overcome this state of affairs, the CMSY and Bayesian state-space Schaefer surplus production model (BSM) methods were developed to allow the assessment of data-limited fishery stocks (Froese et al., 2017). These methods have been applied to 397 stocks in 14 European ecoregions by Froese et al. (2018).

The CMSY method relies mainly on catch time series and some ancillary information ("priors"), while the BSM method relies on catch time series and (relative) abundance data, such as catch/effort (CPUE) data. The CMSY and BSM methods generate estimates of the intrinsic growth rate of a population (r) along with an estimate of its carrying capacity (k); from these, time series of biomass (B) and fishing mortality (F) can be computed, including the biomass (B_{MSY}) from which maximum sustainable yield (MSY) can be extracted given F_{MSY}. These results can help understand the status of exploited fishery stocks and be used to design fishery management plans.

The Northwest Pacific is a very productive fishing area, from which 22% of the global catch was taken in 2017; however, only a small fraction of the stocks therein are exploited optimally (FAO, 2018, 2019).

In this contribution, we assessed 10 data-limited stocks in the Japan Sea and surrounding areas of the Northwest Pacific using the CMSY and BSM methods, to provide reference points for the fishery management in this ecoregion. We also compared the results obtained by the CMSY and BSM in 7 stocks with both catch and CPUE time series.

MATERIALS AND METHODS

The CMSY method was applied to assess the status of fishery stocks in the Northwest Pacific (Froese et al., 2017). In addition, the Bayesian state-space Schaefer surplus production model (BSM) (Meyer and Millar, 1999; Millar and Meyer, 1999) that is part of CMSY R-code was applied to account for variability in both population dynamics (process error) and measurement and sampling (observation error) (Thorson et al., 2014; Froese et al., 2017). The probability distributions of the parameters were sampled by the JAGS software with the Markov chain Monte Carlo method (Plummer, 2003). Three sampling chains were included in basic parameter settings, with a chain length of 60,000 steps each and a burn-in phase of 30,000 steps; every 10th value was used to reduce autocorrelation (Froese et al., 2017). All estimated posterior parameters were assumed to be approximately log-normally distributed; the median was used as central value with 95% confidence intervals approximated by 2.5th and 97.5th percentiles to find values at which test statistics attain less than 0.05 significance (Gelman et al., 1995; McAllister et al., 2001; Owen, 2013; Froese et al., 2017). All data files and R-code of the method were available in Supplement of Froese et al. (2017).

Catch and abundance data used in this contribution were derived from the published literature on 10 stocks, including 4 fish species and 5 cephalopod species (**Table 1**). All 10 stocks were located in the Japan Sea, or in neighboring areas of the Northwest Pacific Ocean (**Figure 1**). Catch time series were the only input for 1 fish stock and 2 cephalopod stocks, which were assessed with the CMSY method (**Table 1**). The other 7 stocks, including 3 fish and 4 cephalopod stocks with catch and CPUE time series were assessed with the BSM method (**Table 1**).

The CMSY and BSM methods estimate parameters, including MSY, B_{MSY} and F_{MSY} based on the most probable *r*-*k* pairs filtered by a Monte Carlo test (Froese et al., 2017). The viable *r*-*k* pairs found by the CMSY and BSM methods generate triangular-shaped clouds in the plot's log space, in which the most probable *r*-*k* pair (and its approximate 95% confidence limits) is found in the tip of the triangle (**Figure 2**).

A Bayesian state-space implementation of the BSM is then developed to verify the *r* and *k* according to catch and abundance data (i.e., biomass and CPUE) in Eq. 1:

$$B_{t+1} = B_t + \mathrm{r}\,(1 - \mathrm{B_t}/k)B_t - \mathrm{C}_t \quad (1)$$

where B_t is the biomass in year t, B_{t+1} is the exploited biomass in year $t + 1$, r is the intrinsic rate of population increase, k is the carrying capacity (i.e., the mean unexploited stock size), and C_t is the catch data in year t.

When a stock is severely depleted with its biomass below $0.25k$, Eq. 1 is modified to account for depensation or reduced recruitment in Eq. 2:

$$B_{t+1} = B_t + \left(4rB_t/k\right)(1 - B_t/k)\,\mathrm{B}_t - \mathrm{C}_t|\mathrm{B}_t/k < 0.25 \quad (2)$$

where the term $4rB_t/k$ expresses the assumption the intrinsic population growth rate declines linearly with biomass below half the biomass associated with MSY.

Resilience information in FishBase[1] and SeaLifeBase[2] were translated into the prior of *r*-ranges (**Table 2**).

The maximum catch (C) was divided by the upper and lower bounds of r; these values were then used to inform the lower and upper bounds of k:

$$k_{low} = \max(C)/r_{high};\ k_{high} = 4\max(C)/r_{low} \quad (3)$$

Eq. 3 accounts for the stock with lower prior biomass at the end of the given time series, while as for the high biomass, it was modified:

$$k_{low} = 2\max(C)/r_{high};\ k_{high} = 12\max(C)/r_{low} \quad (4)$$

All available r values were assigned to bins in log-space with equal width, of which the most probable was derived from the 75th

[1]www.fishbase.org
[2]www.sealifebase.org

TABLE 1 | Summary of catch and CPUE data of 10 fish and cephalopod stocks in the Northwest Pacific region under assessment.

Scientific name (common name)	Ecoregion	Habitat	Data year		References
			Catch	CPUE	
Arctoscopus japonicus (Japanese sandfish)	Japan Sea	Bathy-demersal	1974–2004	1974–2004	Tian et al., 2011
Doederleinia berycoides (Blackthroat seaperch)	Japan Sea	Demersal	1975–2006	1975–2006	Tian et al., 2011
Pleurogrammus azonus (Okhotsk atka mackerel)	Japan Sea	Demersal	1974–2004	1974–2004	Tian et al., 2011
Seriola quinqueradiata (Japanese amberjack)	Japan Sea	Demersal	1950–2008	–	Tian et al., 2012
Heterololigo bleekeri (Spear squid)	Japan Sea	Demersal	1975–2006	–	Tian, 2009
Ommastrephes bartramii (Neon flying squid)	Northwest Pacific	Bentho-pelagic	1994–2017	1998–2015	Lei et al., 2019
Sepia esculenta (Golden cuttlefish)	Japan Sea	Demersal	1975–2006	1975–2006	Tian et al., 2011
Todarodes pacificus (Japanese flying squid)	Japan Sea	Bentho-pelagic	1979–2014	1995–2014	Fang and Chen, 2018
	Northwest Pacific		1979–2014	1990–2014	Fang and Chen, 2018
Uroteuthis edulis (Swordtip squid)	Japan Sea	Demersal	1975–2006	–	Tian et al., 2011

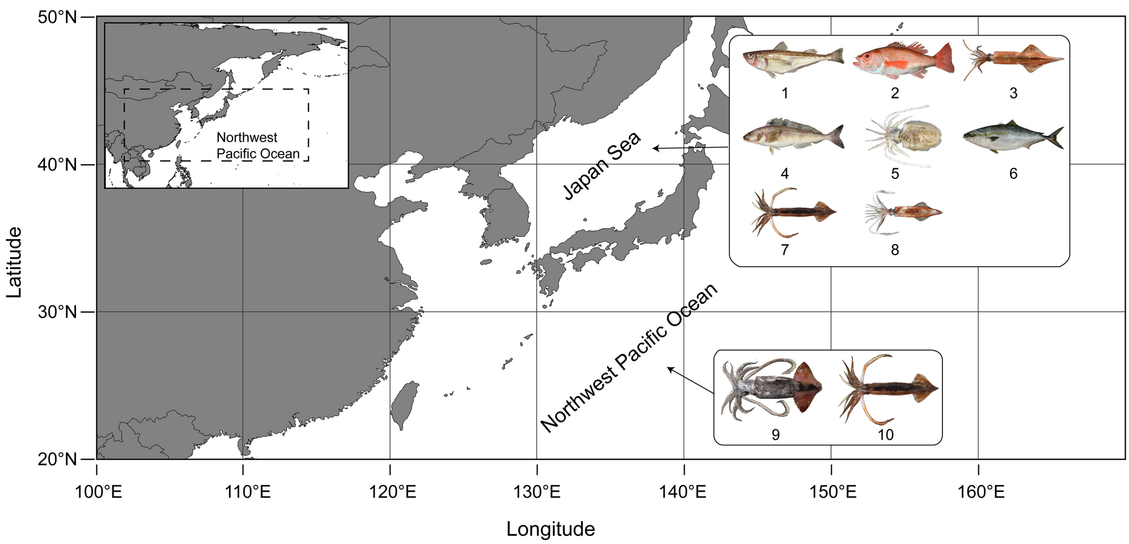


FIGURE 1 | The areas of the 10 fishery stocks (see **Table 1** for details) in the Northwest Pacific Ocean. (Pictures of species assessed come from www.zukan-bouz.com). 1: *A. japonicus*, 2: *D. berycoides*, 3: *H. bleekeri*, 4: *P. azonus*, 5: *S. esculenta*, 6: *S. quinqueradiata*, 7: *T. pacificus* (East Sea), 8: *U. edulis*, 9: *O. bartramii*, 10: *T. pacificus* (Northwest Pacific).

percentile of the mid-values of occupied bins. If the r value was higher than the 50th percentile of mid-values of occupied bins, the most probable k value is derived from a linear regression:

$$MSY = rk/4 \rightarrow \log(k) = \log(4MSY) + (-1)\log(r) \quad (5)$$

The range and density of the viable r values fitted inversely in Eq. 6 and a uniform distribution between 0.001 irf and 0.02 irf was used to describe the standard deviation of r in log-space:

$$irf = 3/\left(r_{high} - r_{low}\right) \quad (6)$$

where irf is an inverse range factor to determine the prior density of r, r_{high} and r_{low} are defined as above.

The k values are assumed to have a log-normal distribution, the standard deviation of which was assumed to be a quarter of the distance between the central value and the lower bound of the k range (McAllister et al., 2001).

The abundance estimation is attainable for data-limited stocks by a catchability coefficient q in Eq. 7, by which the Schaefer model used to transform the CPUE into biomass:

$$CPUE_t = qB_t \quad (7)$$

where $CPUE_t$ and B_t are mean catch per unit effort and biomass in year t, respectively, and q is the catchability coefficient.

The dynamic of abundance as CPUE is expressed by Eq. 8:

$$CPUE_{t+1} = CPUE_t + r(1 - CPUE_t/qk)CPUE_t - qC_t \quad (8)$$

where the variables and parameters are defined as in Eqs. 1 and 7, and the prior q is derived from Eq. 9:

$$Y = rB(1 - B/k) \quad (9)$$

where Y is the equilibrium yield for B, and other parameters are defined as in Eq. 1.

The lower and higher priors for q are derived from Eqs 10 and 11 for stocks with recent high biomass:

$$q_{low} = 0.25 r_{pgm} CPUE_{mean}/C_{mean} \quad (10)$$

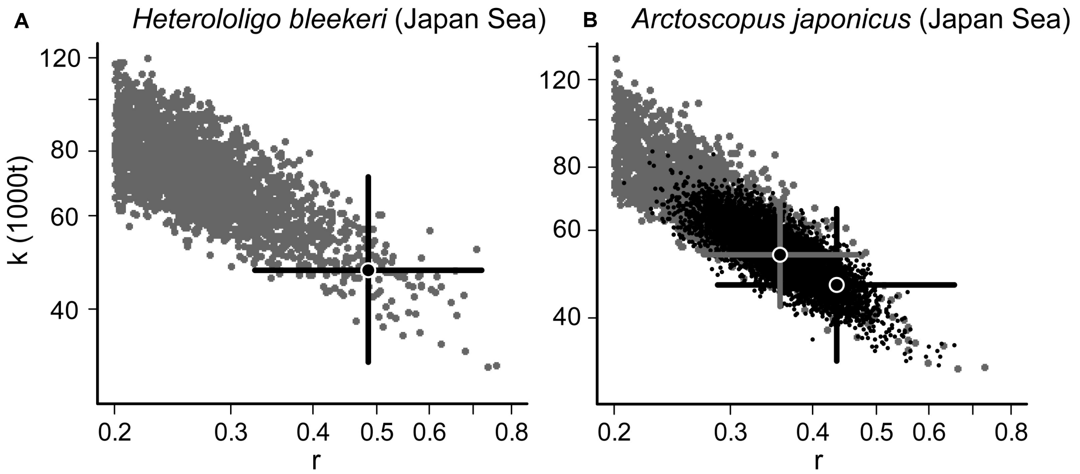


FIGURE 2 | Viable *r-k* pairs of spear squid (*Heterololigo bleekeri*) (Japan Sea) **(A)** and Japanese sandfish *(Arctoscopus japonicus*) (Japan Sea) **(B)** obtained from the CMSY (gray) and the BSM (black) methods. The most reliable *r-k* pair and its approximate 95% confidence limits are indicated by a black cross for the CMSY method **(A,B)**; for the BSM method, the corresponding cross is gray **(B)**.

TABLE 2 | Suggested resilience categories translated into range of rate of population increase (*r*) as provided in FishBase and SeaLifeBase of stocks under assessment (www.fishbase.org, www.sealifebase.org and Froese et al., 2017).

Resilience category	*r* range	Stock
High	0.6–1.5	*D. berycoides*, *T. pacificus* (Japan Sea), *T. pacificus* (Northwest Pacific)
Medium	0.2–0.8	*A. japonicus*, *H. bleekeri*, *O. bartramii*, *P. azonus*, *S. esculenta*, *S. quinqueradiata*, *U. edulis*
Low	0.05–0.5	None
Very low	0.015–0.1	None

TABLE 3 | Default range of biomass relative to *k* at the start (B_{start}/k) and the end (B_{end}/k) of the time series of stocks under assessment.

Prior biomass	*B/k*	Stock	
		B_{start}/k	B_{end}/k
Low	0.01–0.4	None	*A. japonicus*, *D. berycoides*, *O. bartramii*, *P. azonus*, *S. esculenta*, *S. quinqueradiata*, *T. pacificus* (East Sea), *T. pacificus* (Northwest Pacific), *U. edulis*
	0.01–0.2	None	*H. bleekeri*
Medium	0.2–0.6	None	None
High	0.5–0.9	*A. japonicus*, *D. berycoides*, *H. bleekeri*, *O. bartramiiP. azonus*, *S. esculenta*, *T. pacificus* (East Sea), *T. pacificus* (Northwest Pacific), *U. edulis* (East Sea)	None
	0.8–1.0	None	None
Very high	0.9–1.0	*S. quinqueradiata*	None

$$q_{high} = 0.5 r_{high} CPUE_{mean}/C_{mean} \tag{11}$$

where q_{low} and q_{high} are the lower and upper prior catchability coefficient for stocks with high recent biomass, respectively, r_{pgm} is the geometric mean of r, r_{high} is the upper prior range for r, $CPUE_{mean}$ is the mean CPUE over the last 5 or 10 years, and C_{mean} is mean catch over the same period.

For stocks with recent low biomass, the multipliers were changed to 0.5 for q_{low} and to 1.0 for q_{high}. Mean catch and CPUE were applied to species with medium and high resilience over the past 5 years and to species with low or very low resilience over the past 10 years.

TABLE 4 | Stock status categories corresponding to the range of B/B_{MSY} of stocks under assessment (Palomares et al., 2018).

Stock status	B/B_{MSY}
Healthy	≥1.0
Overfished	0.5–1.0
Strongly overfished	0.2–0.5
Collapsed	0.0–0.2

TABLE 5 | Summary of *r*, *k*, MSY, B_{end}/k and B/B_{MSY}, with confidence limits (in brackets) estimated by the CMSY and the BSM methods for the 10 stocks in the Northwest Pacific.

Stock	*r*	*k* (10^3 t)	*MSY* (10^3 t·year^{-1})	B/B_{MSY}
A. japonicus	0.36 (0.27 – 0.47)	53.5 (42.2 – 67.9)	4.78 (4.09 – 5.59)	0.54 (0.44 – 0.67)
D. berycoides	0.32 (0.24 – 0.43)	6.77 (5.33 – 8.60)	0.55 (0.46 – 0.66)	0.51 (0.43 – 0.61)
H. bleekeri	0.49 (0.33 – 0.72)	47.5 (31.6 – 71.3)	5.78 (4.51 – 7.40)	0.12 (0.02 – 0.38)
O. bartramii	0.51 (0.36 – 0.72)	633 (479 – 836)	80.2 (67.5 – 95.2)	0.77 (0.32 – 0.99)
P. azonus	0.65 (0.51 – 0.81)	20 (16.4 – 24.5)	3.24 (2.77 – 3.79)	0.76 (0.60 – 0.89)
S. esculenta	0.31 (0.23 – 0.42)	45.2 (34.9 – 58.4)	3.51 (2.74 – 4.50)	0.52 (0.41 – 0.65)
S. quinqueradiata	0.57 (0.41 – 0.79)	256 (163 – 401)	36.1 (28.4 – 46)	0.54 (0.06 – 0.79)
T. pacificus (Japan Sea)	1.06 (0.94 – 1.18)	305 (271 – 342)	80.3 (75.2 – 85.7)	0.37 (0.29 – 0.49)
T. pacificus (NW Pacific)	1.3 (1.12 – 1.51)	709 (618 – 814)	230 (219 – 243)	0.81 (0.64 – 0.98)
U. edulis	1.06 (0.78 – 1.44)	14.7 (11.0 – 19.6)	3.90 (3.20 – 4.75)	0.48 (0.05 – 0.79)

B_{start}/k and B_{end}/k were the priors of relative biomass at the start and the end of each time series, and their ranges were estimated depending on the assumed depletion level (Froese et al., 2017; FAO, 2019). B_{start}/k of the Japanese amberjack with available fishery data starting from the 1950s was set as 0.9 to 1.0 (Tian et al., 2012), and the other 9 stocks were set as 0.5–0.9 due to the increased depletion in recent decades (**Table 3**; Pauly et al., 2002; Tian et al., 2011; Watson et al., 2013, 2014; Arkhipkin et al., 2015; FAO, 2019). The B_{end}/k of spear squid was set as 0.01 to 0.2 due to high depletion (Tian, 2009; Arkhipkin et al., 2015), with the other 9 stocks set as 0.01 to 0.4, according to the increasing fishing pressure and efforts in recent years (Tian et al., 2011; Watson et al., 2013, 2014; Arkhipkin et al., 2015; FAO, 2019).

The relative total biomass in the last year (B/B_{MSY}) was used to assess the exploitation level and the stock status estimated by the CMSY and BSM methods (**Table 4**; Palomares et al., 2018).

RESULTS

The B/B_{msy} values in the last year for all 10 stocks assessed were less than 1, indicating the occurrence of overfishing (**Table 5**). All stocks were depleted, but the trends were different (**Figures 3**, **4**).

All 4 fish stocks were subject to ongoing overfishing, as shown in **Figures 3A–D**. The Japanese sandfish and blackthroat seaperch had similar trends in estimated biomass, with a substantial decrease since 1975 (**Figures 3A,B**). The relative biomass (B/B_{MSY}) were 0.54 and 0.51 for them at the end of the time series, respectively (**Table 5**). The Okhotsk atka mackerel has been subject to ongoing overfishing since the early 1980s with B/B_{MSY} reaching 0.76 at the end of time series (**Figure 3C** and **Table 5**). The Japanese amberjack was in a healthy condition and had a biomass above the one that can produce MSY before the 2000s, but was overfished after that (**Figure 3D** and **Table 5**).

Of the 6 cephalopod stocks, 3 were overfished, 2 were endangered by reduced recruitment ($0.2 < B/B_{MSY} < 0.5$) and 1 has collapsed ($B/B_{MSY} < 0.2$; **Table 5**). The spear squid was severely depleted and subject to unsustainable exploitation ($B/B_{MSY} = 0.12$; **Table 5**). The catches and exploitation levels were different for golden cuttlefish *Sepia esculenta* stock and swordtip squid stock from the Japan Sea; however, the estimated biomasses for both stocks have declined sharply to below B_{MSY} since the 1980s (**Figures 4B,E**). The value of B/B_{MSY} of neon flying squid was below 0.5 in 2010, which lasted for several years (**Figure 4A**). Two Japanese flying squid stocks have been overfished since the late 1980s and late 1990s, respectively (**Figures 4C,D**).

The CMSY results could be reproduced using the BSM method (**Table 6**). Overall, the 5th–95th percentile ranges were narrower for *r*, *k*, *MSY*, and B/B_{MSY} from BSM than that from CMSY. Thus, only the estimates *r* of okhotsk atka mackerel (*P. azonus*) and *MSY* of golden cuttlefish (*S. esculenta*) had wider ranges in BSM. The 95% confidence limits of the CMSY estimates for *r*, *k* and *MSY* of all 7 stocks included the most probable BSM estimate.

DISCUSSION

Many stock assessment models require plenty of data making their implementation generally limited to valuable species or very abundant species (Harley et al., 2011, 2014); however, less attention is paid to other species (Pauly, 2006; Costello et al., 2012; Costello and Ovando, 2019). However, science-based catch or effort limits are vital information for effective fishery management (Melnychuk et al., 2017). MSY is often used as a reference point for fishery stock assessment, and the status of the fishery is commonly reported in terms of B/B_{MSY} (Schaefer, 1954; Costello and Ovando, 2019). Understanding of the nature of stock dynamics is of great significance for the prevention of stock depletion and for rebuilding depleted stocks. In this study, two recent data-limited stock assessment methods were applied to estimate the exploitation status of 10 fishery stocks in the Northwest Pacific. A key advantage of using these two methods was that they work in data limited situations (catch time series for CMSY, catch time series CPUE for BSM), yet produce results that can support policy and management decisions at national and regional levels. Also note that before applying BSM method, we standardized the CPUE data by accounting for "technological creep" (Palomares and Pauly, 2019), i.e., the gradual increase of effective over nominal effort.

Demersal Fishes

Fisheries catches in the Japan Sea reached its peak in the 1980s, followed by an abrupt decrease due to the collapse of the Pacific sardine *Sardinops sagax*, and the

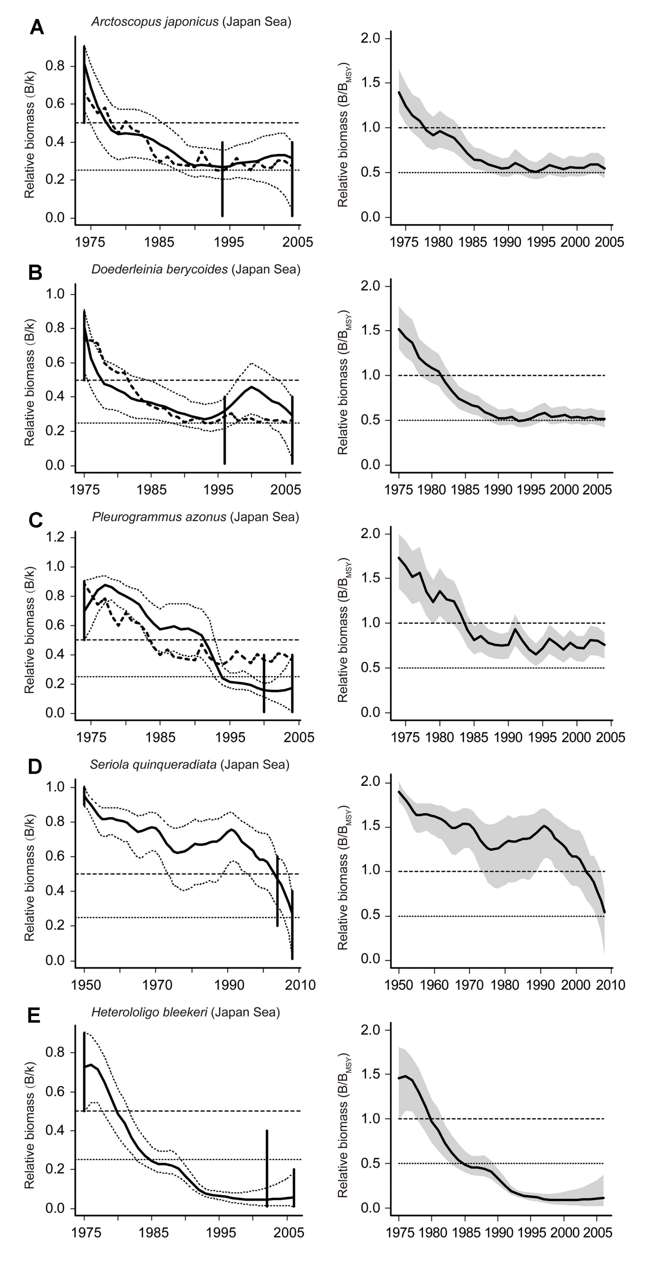


FIGURE 3 | Estimated biomass and the development of relative biomass of 5 stocks assessed (**A–C** in BSM, **D,E** in CMSY). Estimated biomass trajectories (left panels) from CPUE by BSM (bold dashed line) and catch by CMSY (bold solid line), with the 95% confidence limits (dashed lines), and vertical lines represented the prior biomass ranges. The trajectories of relative total biomass (B/B_{MSY}) are shown (right panel) with the gray areas indicating uncertainty.

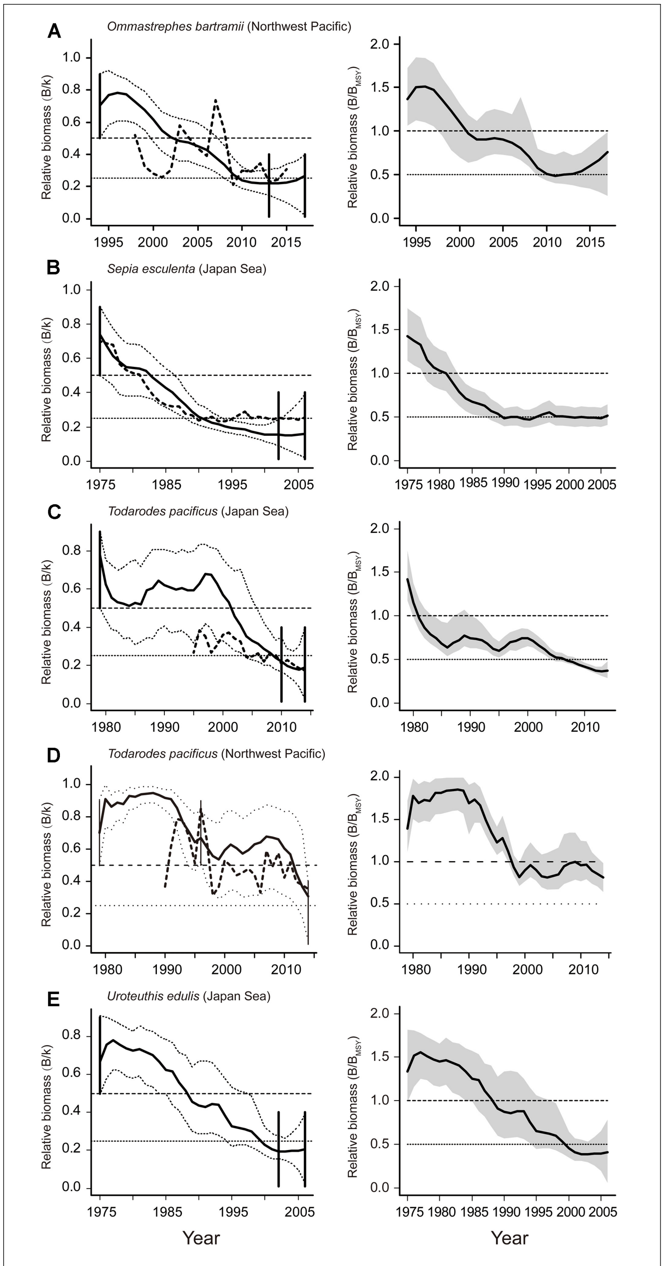


FIGURE 4 | Estimated biomass and the development of relative biomass of 5 stocks assessed (**A–D** in BSM, **E** in CMSY). Estimated biomass trajectories (left panels) from CPUE by BSM (bold dashed line) and catch by CMSY (bold solid line), with 95% confidence limits (dashed lines), and vertical lines represented prior biomass ranges. The trajectories of relative total biomass (B/B_{MSY}) are shown (right panels) with the gray areas indicating uncertainty.

decline of demersal fish and invertebrate fisheries resulting from overfishing (Tian et al., 2006). The variations in demersal fish communities were strongly associated with the oceanographic conditions; the Tsushima Warm Current experienced changes from a colder to a warmer regime in the late 1980s, which had a strong effect on the ecosystems of the region and the fish communities therein (Tian et al., 2006, 2008, 2011).

Japanese sandfish, a cold-water species, was one of the most important commercial resources in Japan (Watanabe et al., 2011: Yoon et al., 2018). In the northern and western Sea of Japan, the Japanese sandfish stock decreased sharply after the mid-1970s and was severely depleted during the 1980s (Watanabe et al., 2011). This confirms the results of this study, which showed that Japanese sandfish stock decreased rapidly from 1974 on. Blackthroat seaperch, a high-value species

TABLE 6 | Results of CMSY and BSM analyses of 7 stocks with catch time series and CPUE available (confidence limits in brackets).

Stock	Results of CMSY analyses			Results of BSM analyses		
	r (year^{-1})	k (10^3 t)	MSY (10^3t·year^{-1})	r (year^{-1})	k (10^3 t)	MSY (10^3 t·year^{-1})
A. japonicus	0.44 (0.29 – 0.66)	46.5 (32.7 – 66.1)	5.06 (4.1 – 6.23)	0.36 (0.27 – 0.47)	53.5 (42.2 – 67.9)	4.78 (4.09 – 5.59)
D. berycoides	0.46 (0.31 – 0.68)	4.83 (3.39 – 6.9)	0.55 (0.45 – 0.67)	0.32 (0.24 – 0.43)	6.77 (5.33 – 8.60)	0.55 (0.46 – 0.66)
O. bartramii	0.53 (0.36 – 0.77)	638 (427 – 955)	84.4 (69.9 – 102)	0.51 (0.36 – 0.72)	633 (479 – 836)	80.2 (67.5 – 95.2)
P. azonus	0.65 (0.55 – 0.77)	23.1 (17.8 – 29.9)	3.74 (3.1 – 4.52)	0.65 (0.51 – 0.81)	20 (16.4 – 24.5)	3.24 (2.77 – 3.79)
S. esculenta	0.43 (0.28 – 0.66)	38.3 (27.4 – 54.6)	4.14 (3.44 – 4.97)	0.31 (0.23 – 0.42)	45.2 (34.9 – 58.4)	3.51 (2.74 – 4.50)
T. pacificus JS	1.21 (0.92 – 1.6)	278 (214 – 359)	83.9 (70.9 – 99.3)	1.06 (0.94 – 1.18)	305 (271 – 342)	80.3 (75.2 – 85.7)
T. pacificus NWP	1.36 (1.12 – 1.66)	524 (385 – 714)	179 (143 – 223)	1.3 (1.12 – 1.51)	709 (618 – 814)	230 (219 – 243)

exhibited a similar dynamic, and also ended up being overfished in the 1980s. The catches of Japanese amberjack showed an increasing trend from the 1950s, mainly due to an increase of effort by the purse seine fishery, which resulted in the this stock being overfished in the Japan Sea (Tian et al., 2012).

Cephalopods

As finfish landings have declined, invertebrate fisheries, especially for cephalopods, have grown and become more important in global fisheries (Anderson et al., 2011: Rodhouse et al., 2014). Therefore, more attention is being paid to invertebrate fisheries, which also need careful management to avoid the same fate as many finfish fisheries (Anderson et al., 2011; Doubleday et al., 2016). It was hypothesized that the growth of cephalopod catches might be related to the release of predation and competition pressure as a result of fish stock depletions (Caddy and Rodhouse, 1998). Cephalopod populations increased from the early 1950s to mid-2010 but declined after that (Doubleday et al., 2016; FAO, 2018). Cephalopods, particularly squids, are generally short-lived. Their abundance and distribution are greatly influenced by oceanographic conditions (Sakurai et al., 2000; Chen et al., 2006). For instance, the regime shift of the Tsushima Warm Current in the late 1980s had a strong effect on the Japan Sea, which may have affected the abundance and distribution of squids (Tian et al., 2006, 2008; Tian, 2007).

Since the late 1980s, the effort of Japanese fleets targeting squid has decreased continuously (Arkhipkin et al., 2015). The swordtip squid stock was not overfished in the southwest of the Japan Sea in the 1980s, but a recent stock assessment indicated that it remained at a low level and the total allowable catch (TAC) should be reduced (Yoda and Fukuwaka, 2013; Arkhipkin et al., 2015).

The catch of spear squid from the southwestern Sea of Japan was generated mainly by pair trawlers, and it decreased from a peak of 13,700 t in 1977 to 16 t in 2003, and remained low level thereafter (Tian, 2009; Arkhipkin et al., 2015). The abundance of southern stocks decreased abruptly around 1990 both in the Japan Sea and the wider North Pacific (Arkhipkin et al., 2015), which was closely associated with the rising water temperature (Tian et al., 2013). The spear squid fishery collapsed in the late 2000s in the Japan Sea (Tian, 2007, 2009), and also declined in the wider North Pacific (Bower and Ichii, 2005).

Neon flying squid is widely distributed from subtropical to cold temperate waters, but is only commercially fished in the Pacific Ocean (Arkhipkin et al., 2015). The fishing mortality of the winter/spring cohort exerted by the jigging fishery appeared to be sustainable, but the biomass decreased from 2001 to 2005 (Chen et al., 2008). The western winter-spring cohort in the Northwest Pacific was over-exploited in 2010 (Ding et al., 2019). Our results showed that the Neon flying squid stock was overfished since the 2000s, in agreement with the literature.

The autumn cohort and winter cohort of the Japanese flying squid, of great commercial importance in Japan, are commonly assessed separately. The former was mainly fished from June to December in the Japan Sea, while the latter is fished from July to December in the Pacific and from January to March in the Sea of Japan (Arkhipkin et al., 2015). This stock was managed since 1998, based on relatively high TACs issued by the Japanese Fisheries Agency (Arkhipkin et al., 2015). The fishery for Japanese flying squid in the Sea of Japan experienced a rapid decline in the late 1970s. However, it has partly recovered since the mid-1980s due to the implementation of management measures, such as the implementation of Total Allowable Catch since 1998 (Fang and Chen, 2018).

Comparison of Results Between CMSY and BSM

Of 7 stocks, the most probable BSM estimates of r, k, and MSY were within the 95% confidence limits of the CMSY estimates, suggesting a good agreement between two methods. Froese et al. (2017) applied BSM and CMSY to 28 data-limited stocks with catch and CPUE available and indicated that estimates were not significantly different for 25 of them. As expected, the 5th–95th percentile ranges of most CMSY estimates were wider than those provided by the BSM method. Estimates from available catch and CPUE data sets can thus be corroborated, and combining them can lead to narrower confidence intervals, indicating the use of CPUE estimate is an important step in reducing the uncertainty of r, k and MSY as estimated from a catch time series.

CONCLUSION

This contribution assessed 10 commercial fishery stocks in the Northwest Pacific, especially the Japan Sea, using the CMSY and BSM methods. The results indicated that all 10 stocks were overfished at different levels according to the values of B/B_{MSY}, with one squid stock (the spear squid) having collapsed. More studies should be conducted to understand the fisheries in the Northwest Pacific region, which are essential for future fishery management.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article can be obtained in the **Supplementary Material**.

AUTHOR CONTRIBUTIONS

QR wrote the first draft. ML revised the manuscript. QR and ML performed the data analyses. Both authors contributed to the article and approved the submitted version.

FUNDING

This work was supported by the National Programme on Global Change and Air-Sea Interaction (GASI-02-PAC-YD spr/sum/aut). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

ACKNOWLEDGMENTS

The authors thank two reviewers for helpful comments.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00430/full#supplementary-material

REFERENCES

Anderson, S. C., Flemming, J. M., Watson, R., and Lotze, H. K. (2011). Rapid global expansion of invertebrate fisheries: trends, drivers, and ecosystem effects. *PLoS One* 6:e14735. doi: 10.1371/journal.pone.0014735

Arkhipkin, A. I, Rodhouse, P. G. K., Pierce, G. J., Sauer, W., Sakai, M., Allcock, L., et al. (2015). World squid fisheries. *Rev. Fish. Sci. Aquacult.* 23, 92–252. doi: 10.1080/23308249.2015.1026226

Bell, J. D., Watson, R. A., and Yimin, Y. Y. (2016). Global fishing capacity and fishing effort from 1950 to 2012. *Fish Fish.* 18, 489–505. doi: 10.1111/faf.12187

Bower, J. R., and Ichii, T. (2005). The red flying squid (*Ommastrephes bartramii*): a review of recent research and the fishery in Japan. *Fish. Res.* 76, 39–55. doi: 10.1016/j.fishres.2005.05.009

Caddy, J. F., and Rodhouse, P. G. (1998). Cephalopod and groundfish landings: evidence for ecological change in global fisheries? *Rev. Fish Biol. Fish.* 8, 431–444.

Chen, C. S., Pierce, G. J., Wang, J., Robin, J. P., Poulard, J. C., Pereira, J., et al. (2006). The apparent disappearance of Loligo forbesi from the south of its range in the 1990s: trends in Loligo spp. abundance in the northeast Atlantic and possible environmental influences. *Fish. Res.* 78, 44–54. doi: 10.1016/j.fishres.2005.12.002

Chen, X., Chen, Y., Tian, S., Liu, B., and Qian, W. (2008). An assessment of the west winter–spring cohort of neon flying squid (*Ommastrephes bartramii*) in the Northwest Pacific Ocean. *Fish. Res.* 92, 221–230. doi: 10.1016/j.fishres.2008.01.011

Costello, C., and Ovando, D. (2019). Status, institutions, and prospects for global capture fisheries. *Ann. Rev. Environ. Resour.* 44, 177–200. doi: 10.1146/annurev-environ-101718-033310

Costello, C., Ovando, D., Hilborn, R., Gaines, S. D., Deschenes, O., and Lester, S. E. (2012). Status and solutions for the world's unassessed fisheries. *Science* 338, 517–520. doi: 10.1126/science.1223389

Ding, Q., Cao, J., and Chen, X. J. (2019). Stock assessment of the western winter-spring cohort of *Ommastrephes bartramii* in the Northwest Pacific Ocean using a Bayesian hierarchical DeLury model based on daily natural mortality during 2005-2015. *Sci. Mar.* 83, 155–166. doi: 10.3989/scimar.04783.10A

Doubleday, Z. A., Prowse, T. A., Arkhipkin, A., Pierce, G. J., Semmens, J., Steer, M., et al. (2016). Global proliferation of cephalopods. *Curr. Biol.* 26, R406–R407. doi: 10.1016/j.cub.2016.04.002

Fang, Z., and Chen, X. J. (2018). Review on fishery of Japanese flying squid Todarodes pacificus. *Mar. Fish.* 40, 102–116. doi: 10.13233/j.cnki.mar.fish.2018.01.012

FAO (2018). *The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable Development Goals*. Rome: FAO.

FAO (2019). *FAO Yearbook. Fishery and Aquaculture Statistics 2017/FAO annuaire*. Rome: FAO.

Froese, R., Demirel, N., Coro, G., Kleisner, K. M., and Winker, H. (2017). Estimating fisheries reference points from catch and resilience. *Fish Fish.* 18, 506–526. doi: 10.1111/faf.12190

Froese, R., and Kesner-Reyes, K. (2002). "Impact of fishing on the abundance of marine species," in *Proceedings of the ICES Council Meeting Report CM*, Burnaby, 1-12.

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A. C., Dimarchopoulou, D., et al. (2018). Status and rebuilding of European fisheries. *Mar. Pol.* 93, 159–170. doi: 10.1016/j.marpol.2018.04.018

Gelman, A., Carlin, J., Stern, H., and Rubin, D. (1995). *Bayesian Data Analysis*. New York, NY: Chapman and Hall.

Harley, S., Nick, D., Hampton, J., and McKechnie, S. (2014). *Stock Assessment of Bigeye Tuna in the Western and Central Pacific Ocean. WCPFC-SC10-2014/SA-WP-01*. Majuro: Republic of the Marshall Islands.

Harley, S., Williams, P., Nicol, S., and Hampton, J. (2011). *The Western and Central Pacific Tuna fishery: 2010 Overview and Status of stocks. Tuna Fisheries Assessment Report No.* 11. Noumea, New Caledonia: Secretariat of the Pacific Community, 37.

Jereb, P., Vecchione, M., and Roper, C. F. E. (2010). "Family Loliginidae," in *Cephalopods of the world. An annotated and illustrated catalogue of cephalopod species known to date. Volume 2. Myopsid and Oegopsid Squids. FAO Species Catalogue for Fishery Purposes. No. 4, Vol. 2*, eds P. Jereb and C. F. E. Roper (Rome: FAO), 38–117.

Lei, L., Wang, J. T., Chen, X. J., and Lu, H. J. (2019). Standardizing CPUE of Ommastrephes bartramii in the Northwest Pacific Ocean based on environmental factors of habitat. *Haiyang Xuebao* 41, 134–141. doi: 10.3969/j.issn.0253-4193.2019.01.013

Ludwig, D., Hilborn, R., and Walters, C. (1993). Uncertainty, resource exploitation, and conservation: lessons from history. *Science* 260, 17–36. doi: 10.1126/science.260.5104.17

McAllister, M. K., Pikitch, E. K., and Babcock, E. A. (2001). Using demographic methods to construct Bayesian priors for the intrinsic rate of increase in the Schaefer model and implications for stock rebuilding. *Can. J. Fish. Aquat. Sci.* 58, 1871–1890. doi: 10.1139/cjfas-58-9-1871

Melnychuk, M. C., Peterson, E., Elliott, M., and Hilborn, R. (2017). Fisheries management impacts on target species status. *Proc. Natl. Acad. Sci. U.S.A.* 114, 178–183. doi: 10.1073/pnas.1609915114

Meyer, R., and Millar, R. B. (1999). BUGS in Bayesian stock assessments. *Can. J. Fish. Aquat. Sci.* 56, 1078–1087. doi: 10.1139/f99-043

Millar, R. B., and Meyer, R. (1999). Non-linear state space modelling of fisheries biomass dynamics by using Metropolis-Hastings within-Gibbs sampling. *J. R. Stat. Soc.* 49, 327–342. doi: 10.1111/1467-9876.00195

Myers, R. A., and Worm, B. (2003). Rapid worldwide depletion of predatory fish communities. *Nature* 423, 280–283. doi: 10.1038/nature01610

Owen, A. B. (2013). *Monte Carlo Theory, Methods and Examples*. Palo Alto, CA: Online Standford University publication.

Palomares, M. L. D., Froese, R., Derrick, B., Nöel, S.-L., Tsui, G., Woroniak, J., et al. (2018). "A preliminary global assessment of the status of exploited marine fish and invertebrate populations, in *A Report Prepared by the Sea Around Us for OCEANA*, (Washington, DC: OCEANA), 60.

Palomares, M. L. D., and Pauly, D. (2019). On the creeping increase of vessels' fishing power. *Ecol. Soc.* 24, 31. doi: 10.5751/ES-11136-240331

Pauly, D. (2006). Major trends in small-scale marine fisheries, with emphasis on developing countries, and some implications for the social sciences. *Mar. Studies.* 4, 7–22.

Pauly, D. (2008). Global fisheries: a brief review. *J. Biol. Res. Thessaloniki* 9, 3–9.

Pauly, D., Christensen, V., Guénette, S., Pitcher, T. J., Sumaila, U. R., Walters, C. J., et al. (2002). Towards sustainability in world fisheries. *Nature* 418, 689–695. doi: 10.1038/nature01017

Plummer, M. (2003). "JAGS: A program for analysis of Bayesian graphical models using Gibbs sampling," in *Proceedings of the 3rd International Workshop on Distributed Statistical Computing (DSC 2003) March 20-22, Vienna, 2003*, eds K. Hornik, F. Leisch, and A. Zeileis (Vienna: Vienna Technical University), 20–22.

Rodhouse, P. G. (2001). Managing and forecasting squid fisheries in variable environments. *Fish. Res.* 54, 3–8. doi: 10.1016/S0165-7836(01)00370-8

Rodhouse, P. G., Pierce, G. J., Nichols, O. C., Sauer, W. H., Arkhipkin, A. I., Laptikhovsky, V., et al. (2014). Environmental effects on cephalopod population dynamics: implications for management of fisheries. *Adv. Mar. Biol.* 67, 99–233. doi: 10.1016/B978-0-12-800287-2.00002-0

Rousseau, Y., Watson, R. A., Blanchard, J. L., and Fulton, E. A. (2019). Evolution of global marine fishing fleets and the response of fished resources. *Proc. Natl. Acad. Sci. U.S.A.* 116, 12238–12243. doi: 10.1073/pnas.1820344116

Sakurai, Y., Kiyofuji, H., Saitoh, S., Goto, T., and Hiyama, Y. (2000). Changes in inferred spawning areas of Todarodes pacificus (Cephalopoda: Ommastrephidae) due to changing environmental conditions. *ICES J. Mar. Sci.* 57, 24–30. doi: 10.1006/jmsc.2000.0667

Schaefer, M. B. (1954). Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Int. Am. Trop. Tuna Commission Bull.* 1, 23–56.

Thorson, J. T., Ono, K., and Munch, S. B. (2014). A Bayesian approach to identifying and compensating for model misspecification in population models. *Ecology* 95, 329–341. doi: 10.1890/13-0187.1

Tian, Y. (2007). Long-term changes in the relative abundance and distribution of spear squid, Loligo bleekeri, in relation to sea water temperature in the south-western Japan Sea during the last three decades. *GIS* 3, 27–46.

Tian, Y. (2009). Interannual–interdecadal variations of spear squid Loligo bleekeri abundance in the southwestern Japan Sea during 1975–2006: impact of the trawl fishing and recommendations for management under the different climate regimes. *Fish. Res.* 100, 78–85. doi: 10.1016/j.fishres.2009.06.005

Tian, Y., Kidokoro, H., and Fujino, T. (2011). Interannual-decadal variability of demersal fish assemblages in the Tsushima Warm Current region of the Japan Sea: impacts of climate regime shifts and trawl fisheries with implications for ecosystem-based management. *Fish. Res.* 112, 140–153. doi: 10.1016/j.fishres.2011.01.034

Tian, Y., Kidokoro, H., and Watanabe, T. (2006). Long-term changes in the fish community structure from the Tsushima warm current region of the Japan/East Sea with an emphasis on the impacts of fishing and climate regime shift over the last four decades. *Prog. Oceanogr.* 68, 217–237. doi: 10.1016/j.pocean.2006.02.009

Tian, Y., Kidokoro, H., Watanabe, T., Igeta, Y., Sakaji, H., and Ino, S. (2012). Response of yellowtail, Seriola quinqueradiata, a key large predatory fish in the Japan Sea, to sea water temperature over the last century and potential effects of global warming. *J. Mar. Syst.* 91, 1–10. doi: 10.1016/j.jmarsys.2011.09.002

Tian, Y., Kidokoro, H., Watanabe, T., and Iguchi, N. (2008). The late 1980s regime shift in the ecosystem of Tsushima warm current in the Japan/East Sea: evidence from historical data and possible mechanisms. *Prog. Oceanogr.* 77, 127–145. doi: 10.1016/j.pocean.2008.03.007

Tian, Y., Nashida, K., and Sakaji, H. (2013). Synchrony in the abundance trend of spear squid Loligo bleekeri in the Japan Sea and the Pacific Ocean with special reference to the latitudinal differences in response to the climate regime shift. *ICES J. Mar. Sci.* 70, 968–979. doi: 10.1093/icesjms/fst015

Watanabe, K., Sakuramoto, K., Sugiyama, H., and Suzuki, N. (2011). Dynamics of two sailfin sandfish (*Arctoscopus japonicus*) stocks in the Sea of Japan, and their management. *Can. J. Fish. Aquatic Sci.* 68, 458–468. doi: 10.1139/F10-161

Watson, R., Zeller, D., and Pauly, D. (2014). Primary productivity demands of global fishing fleets. *Fish Fish.* 15, 231–241. doi: 10.1111/faf.12013

Watson, R. A., Cheung, W. W., Anticamara, J. A., Sumaila, R. U., Zeller, D., and Pauly, D. (2013). Global marine yield halved as fishing intensity redoubles. *Fish Fish.* 14, 493–503. doi: 10.1111/j.1467-2979.2012.00483.x

Yoda, M., and Fukuwaka, M. (2013). *Stock Assessment and Evaluation for Swordtip Squid (fiscal year 2012). In: Marine Fisheries stock assessment and evaluation for Japanese waters (fiscal year 2012/2013)*. Japan: Fisheries Agency and Fisheries Research Agency of Japan, 1697–1708.

Yoon, E. A., Lee, K., Oh, W., Choi, J., Hwang, K., and Kang, M. (2018). Target-strength Measurements of Sandfish *Arctoscopus japonicus*. *Ocean Sci. J.* 53, 73–79. doi: 10.1007/s12601-017-0057-9

Zhang, C. I., Lee, J. B., Seo, Y. I., Yoon, S. C., and Kim, S. (2004). Variations in the abundance of fisheries resources and ecosystem structure in the Japan/East Sea[J]. *Progr. Oceanogr.* 61, 245–265. doi: 10.1016/j.pocean.2004.06.009

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Marine Science

ORIGINAL RESEARCH
published: 29 July 2020
doi: 10.3389/fmars.2020.00623

Assessments of 15 Exploited Fish Stocks in Chinese, South Korean and Japanese Waters Using the CMSY and BSM Methods

Cui Liang[1,2,3]*, *Weiwei Xian*[1,2,3]* and *Daniel Pauly*[4]*

[1] CAS Key Laboratory of Marine Ecology and Environmental Sciences, Institute of Oceanology, Chinese Academy of Sciences, Qingdao, China, [2] Laboratory for Marine Ecology and Environmental Science, Qingdao National Laboratory for Marine Science and Technology, Qingdao, China, [3] Center for Ocean Mega-Science, Chinese Academy of Sciences, Qingdao, China, [4] Sea Around Us, Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, BC, Canada

OPEN ACCESS

Edited by:
*Liping Liu,
Shanghai Ocean University, China*

Reviewed by:
*Jason Marc Cope,
National Marine Fisheries Service (NOAA), United States
Yajie Liu,
UiT The Arctic University of Norway, Norway*

***Correspondence:**
*Cui Liang
liangc@qdio.ac.cn
Weiwei Xian
wwxian@qdio.ac.cn
Daniel Pauly
d.pauly@oceans.ubc.ca*

Specialty section:
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

Received: *25 September 2019*
Accepted: *08 July 2020*
Published: *29 July 2020*

Citation:
Liang C, Xian W and Pauly D (2020) Assessments of 15 Exploited Fish Stocks in Chinese, South Korean and Japanese Waters Using the CMSY and BSM Methods. Front. Mar. Sci. 7:623. doi: 10.3389/fmars.2020.00623

The status of 15 marine fish and invertebrate populations exploited by Chinese, South Korean or Japanese fishing fleets were assessed, using two newly developed computer-intensive methods, CMSY and BSM. The results show that among the 15 populations in question, 2 have collapsed, 3 are grossly over-fished and 9 are overfished. Also, we compared results of the CMSY and BSM methods, and it shows that, while the CPUE data for use with the BSM method lead to narrower confidence intervals and may modify the shape of the biomass trajectory, they do not lead to over- or underestimates of terminal B/B_{MSY} values. These results, although still tentative because the methods used to generate them are relatively new, generally match what is known of the status and exploitation of the populations in question, which makes CMSY and BSM to be promising stock assessment approaches in data-sparse situations. Based on our results, a consistent signal is obtained, thus suggesting that a reduction in fishing pressure would be necessary to restore the abundance status of these 15 populations.

Keywords: data-sparse stock, North-East Asia, CMSY, BSM, stock assessment

INTRODUCTION

Fisheries data assembled by the Food and Agriculture Organization (FAO) suggest that the landings of the world's marine fisheries declined slowly since 1996 (FAO, 2018), while marine catches, as reconstructed by the *Sea Around Us* by adding discards and other illegal, unreported and undocumented (IUU), declined by about 1.2 million tons per year since 1996 (Pauly and Zeller, 2016, 2019). This situation is even more severe for Asian fisheries (Lam and Pauly, 2019), given the high pressure on Asian fish stocks (Anticamara et al., 2011; Watson et al., 2013).

However, in developing countries, and notably in most regions of Asia, most fish populations exploited by even large-scale fisheries remain unassessed (Froese et al., 2012; Geng et al., 2018), precluding the rebuilding of their biomass. Fortunately, this state of affairs can be mitigated, at least in part, by the systematic application of newly developed methods for evaluating the status of exploited fish stocks for use in data-sparse situations, especially the Monte Carlo method CMSY (catch-maximum sustainable yield) developed by Froese et al. (2017). Unlike complex stock assessment methods requiring fisheries-independent data sets, such as obtained from research surveys, and catch-at-age data, the recently proposed CMSY method uses only a time series of catches and ancillary qualitative information to quantify biomass, exploitation rate, Maximum Sustainable Yield (MSY) and related fisheries reference points for a given population. As this method is still relatively new, we performed various comparison with the results of other methods applied to some of the stocks studied here, and performed sensitivity analyses which complement those performed by Froese et al. (2017).

Specifically, we applied and compared CMSY and the related Bayesian Schaefer model (BSM; Froese et al., 2017) methods to 15 fish and invertebrate populations exploited by Chinese, South Korean or Japanese fishing fleets in Northeast Asia to assess the status of their fisheries. Also, we compared results of CMSY and BSM methods; BSM uses catch-per-unit-effort (CPUE) data and offers a chance to explore the information content when adding that data. Sensitivity analyses were also performed to test model sensitivity to input parameters.

MATERIALS AND METHODS

Data Sources

The data source and basic information of the 15 fish and invertebrate stocks covered here are given in **Table 1** (**Supplementary Tables S1, S2**; see **Supplementary Material**). Most data were read off from figures in published scientific papers using OriginPro 8.5. When reading off data from graphs using OriginPro 8.5, small errors were inevitable; tests on simulated data suggest that the magnitude of errors is well below 5%.

General Description of CMSY and BSM Methods

The CMSY method can be seen as an accounting exercise where, starting from an assumed biomass, annual catches are subtracted from the stock's biomass and its annual biological production is added to it. This results in a biomass trajectory whose shape is determined by the catches and by the stock's growth rate, as determined by an assumed value of intrinsic population growth rate (*r*; "resilience") and by how close the biomass is to carrying capacity (*k*). The Monte Carlo component of the methods is then used to generate thousands of such trajectories, each with different assumed values of *r* and *k*, and to identify the trajectories that provide viable solutions, i.e., trajectories that do no "crash" the stock, and which meet various criteria ("priors").

In the cases where relative abundance data (i.e., CPUE) were available in addition to catch data, a Bayesian state-space implementation of the Schaefer surplus-production model (BSM) was applied. Note that the time series of abundance may be shorter than those for catches. The CMSY and BSM methods assumes that population growth, in nature, follows a logistic curve, as assumed in the commonly used Schaefer surplus-production model (Schaefer, 1954, 1957). Therefore, in the subsequent year (t+1), the biomass (B_{t+1}) follows the equation:

$$B_{t+1} = B_t + r\left(1 - B_t/k\right) B_t - C_t \quad (1)$$

where B_t is the biomass at year t, r is the intrinsic rate of population increase, k is the carrying capacity (assumed equivalent to the unexploited population size), and C_t is the catch in year t.

When the stock size is severely depleted (biomass falls below 0.25*k*) (Froese et al., 2017), Equation (1) is slightly modified to account for "depensation," i.e., reduced recruitment at low biomass levels (Myers et al., 1995), as shown in Equation (2):

$$B_{t+1} = B_t + \left(4rB_t/k\right)\left(1 - B_t/k\right) B_t - C_t \mid B_t/k < 0.25 \quad (2)$$

The term 4 B_t/k assumes a linear decline of recruitment below half of the biomass that is capable of producing MSY.

Given a time series of catches and qualitative stock status information, the CMSY method, using a Monte-Carlo approach, identifies viable population biomass trajectories (*i*) compatible with the catch time series, (*ii*) compatible with assumed priors on biomass reductions, and (*iii*) occur within prior ranges of *r* and *k*, corresponding to viable *r-k* pairs. A parameter pair is deemed "viable" if its corresponding biomass trajectories are compatible with the catch series, i.e., neither collapses nor exceeds the maximum of the percentage of carrying capacity assumed to have remain at the end of the time series under consideration. Typically, the variable *r-k* pairs occupy a triangular-shaped cloud in a bivariate plot of *r* vs. *k*; the most probable *r* and k pair generally occurs near the tip of the triangle (Froese et al., 2017).

Determining the Boundaries of the *r-k* Space

To assign default values to *r*-ranges for the 15 stocks in question, the resilience estimates as provided in FishBase[1] or SeaLifeBase[2] for the species in question were translated into the r-ranges, as shown in **Table 2**. For species without resilience information in FishBase or SeaLifeBase, we used information of their taxonomically close species and/or set a wider-range.

For stocks with low prior biomass at the end of the time series, simulation performed by Froese et al. (2017) suggest that the range of carrying capacity within which viable values can be expected to occur is given by:

$$k_{low} = max\left(C\right)/r_{high};\ \ k_{high} = 4max\left(C\right)/r_{low} \quad (3)$$

where k_{low} and k_{high} are the lower and upper bounds of the prior range of k, max(C) is the maximum catch in the time series, and r_{low} and r_{high} are the lower and upper bound of the range of r-values that the CMSY method explores.

For stocks with high prior biomass at the end of the time series, i.e., lightly depleted stocks, Equation (4) was applied.

$$k_{low} = 2max\left(C\right)/r_{high};\ \ k_{high} = 12max\left(C\right)/r_{low} \quad (4)$$

where the variables and parameters are defined as in Equation (3), with both equations as per Froese et al. (2017).

[1]www.fishbase.org
[2]www.sealifebase.org

TABLE 1 | Summary of data available for the stock assessments presented here.

Scientific name (Common name)	Region	Exploited country/region	Catch	Additional data*	Source	Method
Clupea pallasii (Pacific herring)	Yellow Sea-East China Sea-East/Japan Sea	China-Japan-South Korea	1953–2003	None	Gong et al. (2007)†	CMSY
Cololabis saira (Pacific saury)	Japanese waters	Japan	1935–2017	CPUE (1971–2014)	Catch from Yatsu (2019)†; CPUE from Liu S. et al. (2019)†	BSM
Decapterus maruadsi (Japanese scad)	Chinese waters	China	1980–2014	CPUE (1980–2014)	Ma et al. (2019)†	BSM
Gadus macrocephalus (Pacific cod)	Southern East/Japan Sea	South Korea	1970–2006	None	Chung et al. (2013)†	CMSY
Heterololigo bleekeri (spear squid)	Southern Japan Sea	Japan	1975–2010	CPUE (1995–2010)	Catch and CPUE from Tian et al. (2013)†	BSM
Heterololigo bleekeri (spear squid)	Southern Pacific coast	Japan	1978–2010	CPUE (1995–2010)	Catch and CPUE from Tian et al. (2013)†	BSM
Marsupenaeus japonicus (kuruma prawn)	East China Sea	Japan	1965–2008	CPUE (1990–2006)	Catch and CPUE from Hamasaki and Kitada (2013)†	BSM
Mugil cephalus (flathead gray mullet)	Taiwan Strait	Taiwan	1967–2009	CPUE (1967–2009)	Catch and CPUE from Lan et al. (2014)†	BSM
Loligo vulgaris (European squid)	Yellow Sea-East China Sea-East/Japan Sea	China-Japan-South Korea	1952–2003	None	Gong et al. (2007)†	CMSY
Planiliza haematocheila (so-iuy mullet)	Chinese waters	China	1990–2017	CPUE (1990–2017)	Catch from China Fishery Statistical Yearbook (Fisheries and Fishery Administration of the Ministry of Agriculture [FFAMA], 1979–2017); CPUE from Kang et al. (2018)†	BSM
Scomber japonicus (chub mackerel)	Chinese waters	China	1979–2017	CPUE (1979–2017)	Catch from China Fishery Statistical Yearbook (Fisheries and Fishery Administration of the Ministry of Agriculture [FFAMA], 1979–2017); CPUE from Kang et al. (2018)†	BSM
Scomber japonicus (chub mackerel)	Japanese waters	Japan	1915–2016	None	Yatsu (2019)†	CMSY
Scomber japonicus (chub mackerel)	South Korean waters	South Korea	1970–2002	CPUE (1995–2002)	Catch and CPUE from Choi et al. (2004)†	BSM
Scomberomorus niphonius (Japanese Spanish mackerel)	South Korean waters	South Korea	1971–2010	None	Lee et al. (2011)†	CMSY
Trachurus japonicus (Japanese jack mackerel)	South Korean waters	South Korea	1955–1998	CPUE (1988–1995)	Catch and CPUE from Zhang and Lee (2001)†	BSM

**Note that the CPUE data were corrected for the increase in fishing power by assuming an annual increase of 2% (Palomares and Pauly, 2019). †Represents data that were read off from published papers.*

TABLE 2 | Ranges suggested by FishBase (www.fishbase.org) for population growth rate (year^{-1}).

Resilience (*r*)	prior r range	Range assumed for the stocks in Table 1
High	0.6–1.5	*C. saira*; *D. maruadsi*
Medium	0.2–0.8	*T. japonicus*; *H. bleekeri*; *S. japonicus*; *S. niphonius*; *C. pallasii*; *L. vulgaris*; *M. japonicus*; *P. haematocheila*; *M. cephalus*
Low	0.05–0.5	*G. macrocephalus*
Very low	0.015–0.1	—

Setting Prior Biomass Ranges

The CMSY and BSM methods also require priors for biomass relative to carrying capacity (k). This includes a prior biomass range relative to unexploited biomass (B/k) at the beginning and end of the time series, i.e., B_{start}/k and B_{end}/k, respectively. Should there be an intermediate year in the time series where biomass is considered to be extraordinary, e.g., particular low or high, then relative intermediate biomass for that particular year should also be entered as a prior (Froese et al., 2017).

Table 3 presents suggested ranges of B_{start}/k for the 15 stocks under assessment. Note that for species whose time series of

TABLE 3 | Suggested fractions B_{start}/k for the period before catch data became available*.

Relative biomass at the start	Suggested prior	Range assumed for the stocks in Table 1
Very high	0.6–1	*C. pallasii*; *C. saira*; *L. vulgaris*; *S. japonicus* (in Japanese waters); *T. japonicus*;
High	0.4–0.8	*D. maruadsi*; *G. macrocephalus*; *H. bleekeri* (in Southern Japan Sea and Southern Pacific coast); *M. japonicus*; *M. cephalus*; *P. haematocheila*; *S. japonicus* (in Korean waters and Chinese waters); *S. niphonius*;
Medium	0.2–0.6	—
Low	0.01–0.4	—
Very low	0.01–0.2	—

**Supplementary Material* to Froese et al. (2017).

TABLE 4 | Suggested ranges of the fraction B_{end}/k for the period prior to catches being available*.

Relative biomass at the end	Suggested prior	Range assumed for the stocks in Table 1
High	0.4–0.8	—
Medium	0.2–0.6	—
Low	0.01–0.4	*C. pallasii*; *C. saira*; *D. maruadsi*; *G. macrocephalus*; *L. vulgaris*; *M. japonicus*; *P. haematocheila*; *S. japonicus* (in Japanese, Korean and Chinese waters); *S. niphonius*; *T. japonicus*
Very low	0.01–0.2	*H. bleekeri*; *M. cephalus*

*See **Supplementary Material** to Froese et al. (2017).

catch data starts before 1960, high initial biomass was assumed (B_{start}/k = 0.6–1), given that the fishing technology deployed at the time was rudimentary (Froese et al., 2017). In all other cases, we assumed a relative high biomass (B_{start}/k = 0.4–0.8), in view of the fact that from the 1970s to the 1990s, industrial fishing effort had strongly increased in Northeast Asia (Anticamara et al., 2011), and the technological sophistication of that effort had also increased (Engelhard, 2016; Palomares and Pauly, 2019).

Table 4 presents suggested ranges of B_{end}/k. Given the intensity of the research areas of each species and the results of published research papers, we chose a relative low biomass (i.e., $B_{end/k}$ = 0.01–0.4) at the end of the time series for *C. pallasii* (Gong et al., 2007), *C. saira* (Yatsu, 2019), *D. maruadsi* (Zheng et al., 2003), *G. macrocephalus* (Chung et al., 2013), *L. vulgaris* (Gong et al., 2007), *M. japonicus* (Hamasaki and Kitada, 2013), *P. haematocheila* (Shi et al., 2010), *S. japonicus* (Cheng and Lin, 2004; Choi et al., 2004; Yatsu, 2019), *T. japonicus* (Zhang and Lee, 2001). For the other stocks, the sources suggested a very low biomass (B_{end}/k = 0.01–0.2): *H. bleekeri* (Tian, 2009), *M. cephalus* (Shi et al., 2010).

To examine the potential impact of a "wrong" choice of r range (**Supplementary Table S3**; see **Supplementary Material**) and of the B_{start}/k and B_{end}/k ranges (**Supplementary Table S3**; see **Supplementary Material**), sensitivity analyses were performed consisting of evaluating the effect on estimates of B/B_{MSY} of the input originally drawn from these tables ("original"), compared with the input from the table row above ("Higher") and below ("Lower") the original selection.

RESULTS

All 15 stocks in question were analyzed by CMSY method. The BSM method was also applied to the 10 stocks for which CPUE data were available (**Table 1**).

Japanese jack mackerel (*Trachurus japonicus*), a widely distributed and commercially exploited species along the coastal waters of South Korea, is used here to illustrate the CMSY and BSM outputs (**Figure 1**).

Figure 1A shows the viable *r-k* pairs found by CMSY (gray dots) and BSM methods (black dots). The best *r-k* pair and its approximate 95% confidence interval (CI), as estimated using CMSY are represented by a solid cross, while a dotted cross represents the best *r-k* pair and its approximate CI as estimated by the BSM method.

Figure 1B shows the biomass trajectory estimated by CMSY (solid line) and BSM (dotted line). **Figure 1C** shows the catches relative to the BSM estimate of MSY and its CI. In absolute terms, the MSY estimate was 18800 t per year, with a CI ranging from 15800 to 22300 t per year. **Figure 1D** shows the estimated trend of relative biomass. This biomass trend is similar to the detailed stock assessment of Zhang and Lee (2001).

The estimated biomass trajectories for five stocks without CPUE data are presented in **Figure 2**. **Figure 3**, which pertains to populations with CPUE data in addition to catch time series, shows on the left the biomass trajectories estimated (using CMSY) from the catch data alone, while displaying, on the right, the biomass trajectories estimated using BSM from catch data and CPUE data. The added CPUE data reduce the CIs and modify the shape of the biomass trajectories. However, **Figure 4**, which compares 10 pairs of B_{end}/B_{MSY} estimates with and without CPUE data shows that, except for spear squid *Heterololigo bleekeri* in the southern Pacific coast of Japan, the added CPUE data do not change the B_{end}/B_{MSY} values to a large extent.

Based on B/B_{MSY} in the final year of a time series, stock status for 15 populations can be defined (**Table 5**). Among the 15 populations in question, 2 populations have collapsed, 3 populations are grossly over-fished and 9 populations are overfished (**Table 6**). **Figure 5** shows that our results were very similar to the estimates from detailed stock assessments.

Figure 6 shows the results of the sensitivity analyses performed for 3 of 15 populations in question, i.e., Pacific cod *Gadus macrocephalus*, Japanese jack mackerel *Trachurus japonicus* and chub mackerel *Scomber japonicus*, to explore the robustness of our assessment to both bias and mis-specified priors. Herein, each stock was assessed with priors (r, B_{start}/k, B_{end}/k) that were less and more stringent (as defined in **Tables 2–4**; see also **Supplementary Table S3**).

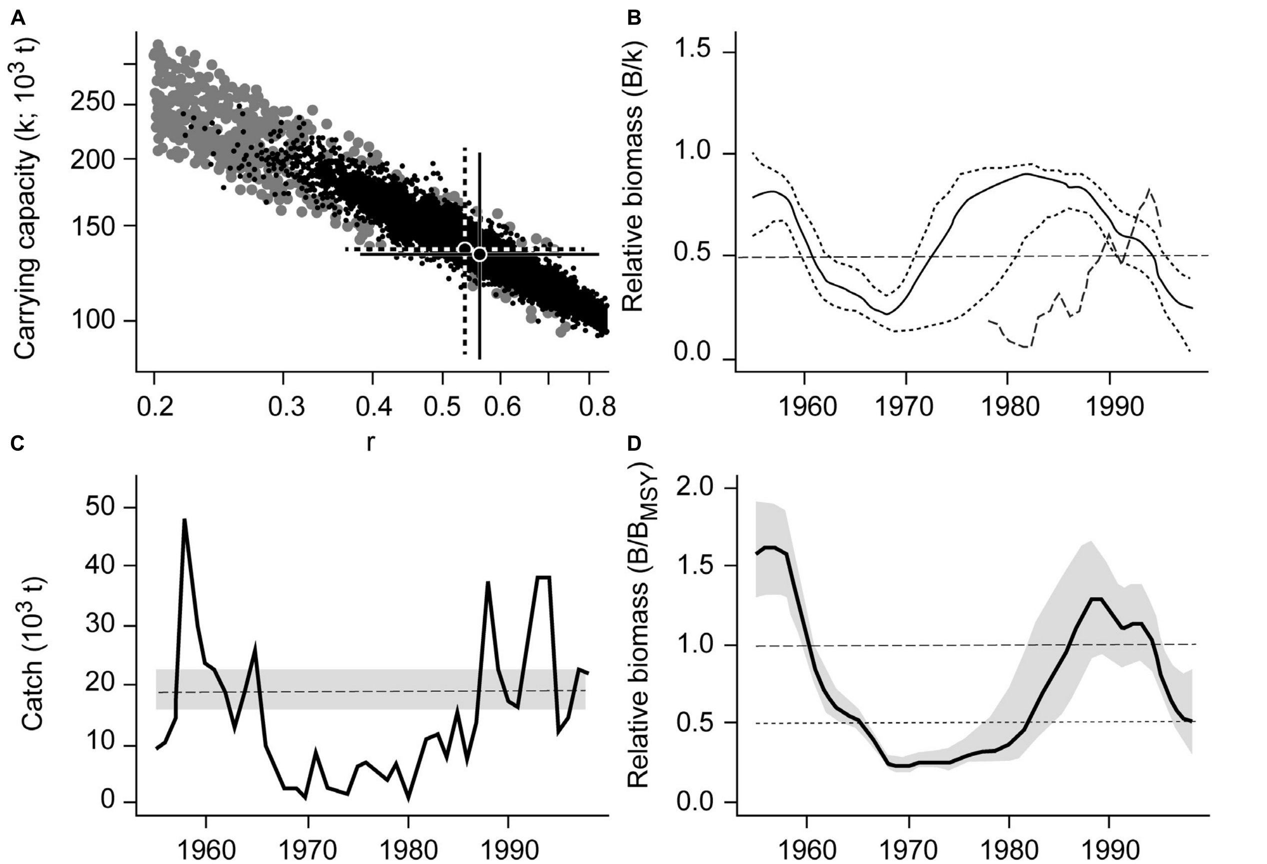


FIGURE 1 | Results of the CMSY and BSM analyses for the Japanese jack mackerel (*Trachurus japonicus*) in South Korean waters. **(A)** viable *r-k* pairs identified by the CMSY and BSM methods. **(B)** Biomass trajectory estimated by CMSY (solid black line), with the two dotted lines being its CIs, and available abundance data scaled to the BSM estimate of *k* (broken line). **(C)** Catches relative to the BSM estimate of MSY, with the 95% confidence interval in gray. **(D)** Estimated relative biomass trajectory (B/B_{MSY}), with the gray area indicating the confidence interval.

Among three parameters, B_{start}/k, B_{end}/k *and r*, B_{end}/k *was* the one with the largest effect on the results (**Figure 6A**), implying that a reliable prior of biomass range relative to unexploited biomass at the end of the time series is important. However, if an independent estimate for B_{end}/k is not available, setting the prior for B_{end}/k as "Not Available" would result in an average bias of 4.84% compared with the original selection (**Supplementary Table S3**; see **Supplementary Material**), which means that it has less impact on estimates than a problematic prior. Meanwhile, as is shown in **Figure 6**, setting B_{end}/k as "Not Available" would not have much effect on selecting other priors (**Figure 6** and **Supplementary Table S3**). Sensitivity analyses for all stocks would be needed for more comprehensive understanding of the effects of priors.

DISCUSSION

China, South Korea, and Japan are all surrounded by productive oceans, which has allowed seafood to become an essential source of animal protein in these three countries (Kim, 2010). However, declines in most of these fishery resources have occurred, caused by intensive fishing pressure (Kang, 2006). Indeed, these declines threaten the supply of fishery products, in spite of restrains on some fishing operations, including gear limitations, fishing areas and seasons, mesh size restriction, etc., that were adopted by China, South Korea and Japan (Asada, 1973; Lee et al., 2006; Shen and Heino, 2014).

In the late 1990s, Japan and South Korea introduced fisheries management systems based on Total Allowable Catch (TAC) (Zhang and Lee, 2001; Matsuda et al., 2010; Tanoue, 2015), while China, suffering from severe decline of its coastal resources (Liang and Pauly, 2017a,b), is also seeking for ways to effectively manage and restore its inshore fisheries. TAC management systems and stock rebuilding require stock assessments to provide baselines for rebuilding efforts. While detailed stock assessments are uncommon through most of East Asia, due to limited data and expertise, this shortfall is most severe in China (Zhang et al., 2017; Liu Z. et al., 2019).

However, the recent development of computer-intensive methods such as CMSY and BSM (Froese et al., 2017), which rely mainly on catch and relative abundance data, offers a window into the dynamics of exploited stocks. This contribution, which applied the CMSY and BSM methods to 15 commercially

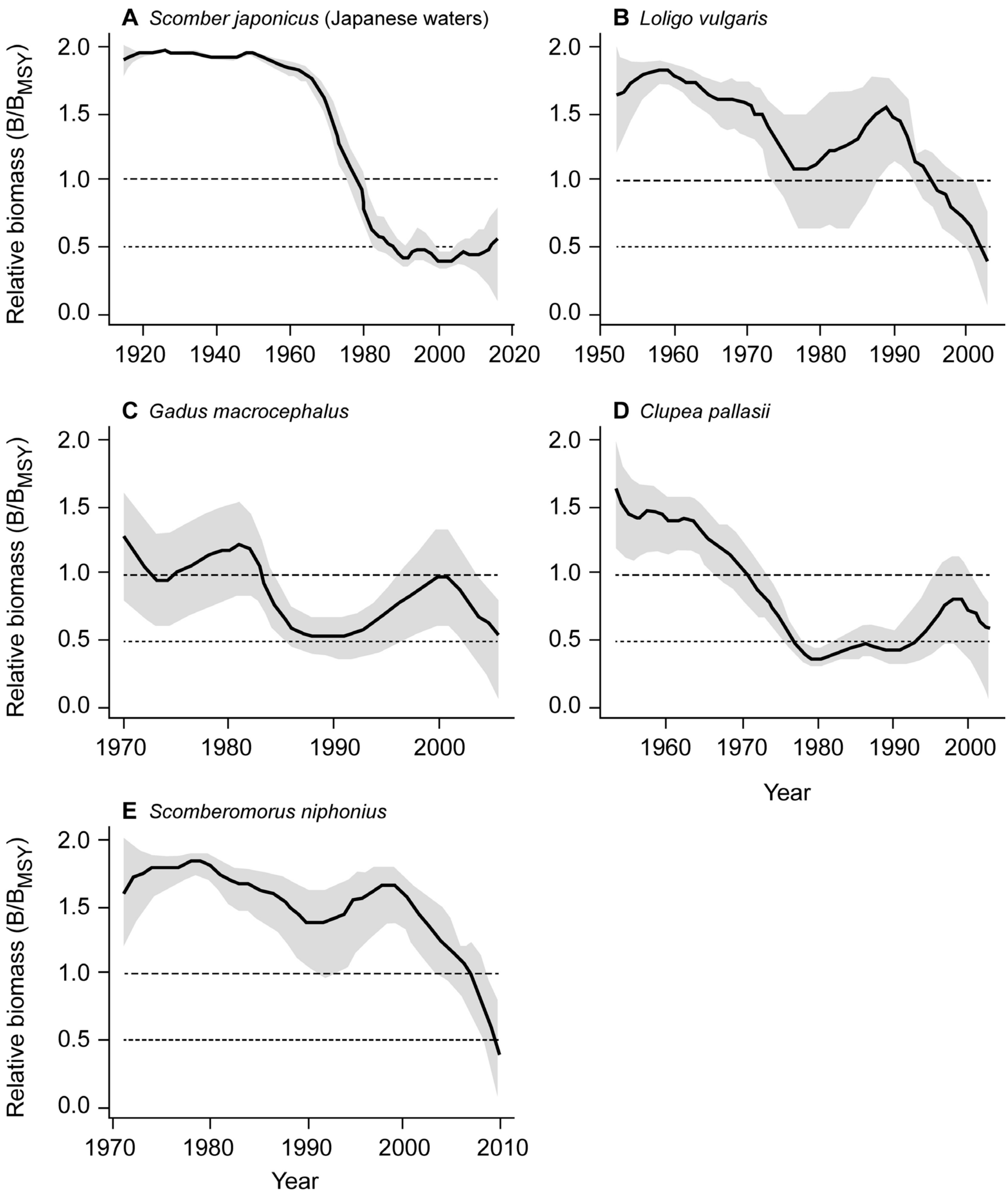


FIGURE 2 | Trend of relative biomass (B/B_{MSY}) generated using the CMSY method for 5 stocks without CPUE data, with the gray areas referring to the 95% confidence intervals. Panels **(A–E)** thus illustrate assessments with a minimum of data.

exploited populations in China, South Korea and Japan, led to a consistent signal being obtained, suggesting that all 15 populations studied here were depleted by similarly intensive fishing activities. We also find that the results overall match what is known of the exploitation of the populations in question.

Thus, in China, chub mackerel *Scomber japonicus* is an important commercial species, reported as suffering from a high exploitation rate since the early 1970s (Cheng and Lin, 2004). Also, following on the decline of resources exploited by the bottom trawl fishery, the exploitation of pelagic Japanese scad *Decapterus maruadsi* has intensified (Zheng et al., 2003), while so-iuy mullet *Planiliza haematocheila* and gray mullet *Mugil cephalus,* two important species of the Mugilidae family, have biomasses reported to have declined in 2000s (Shi et al., 2010).

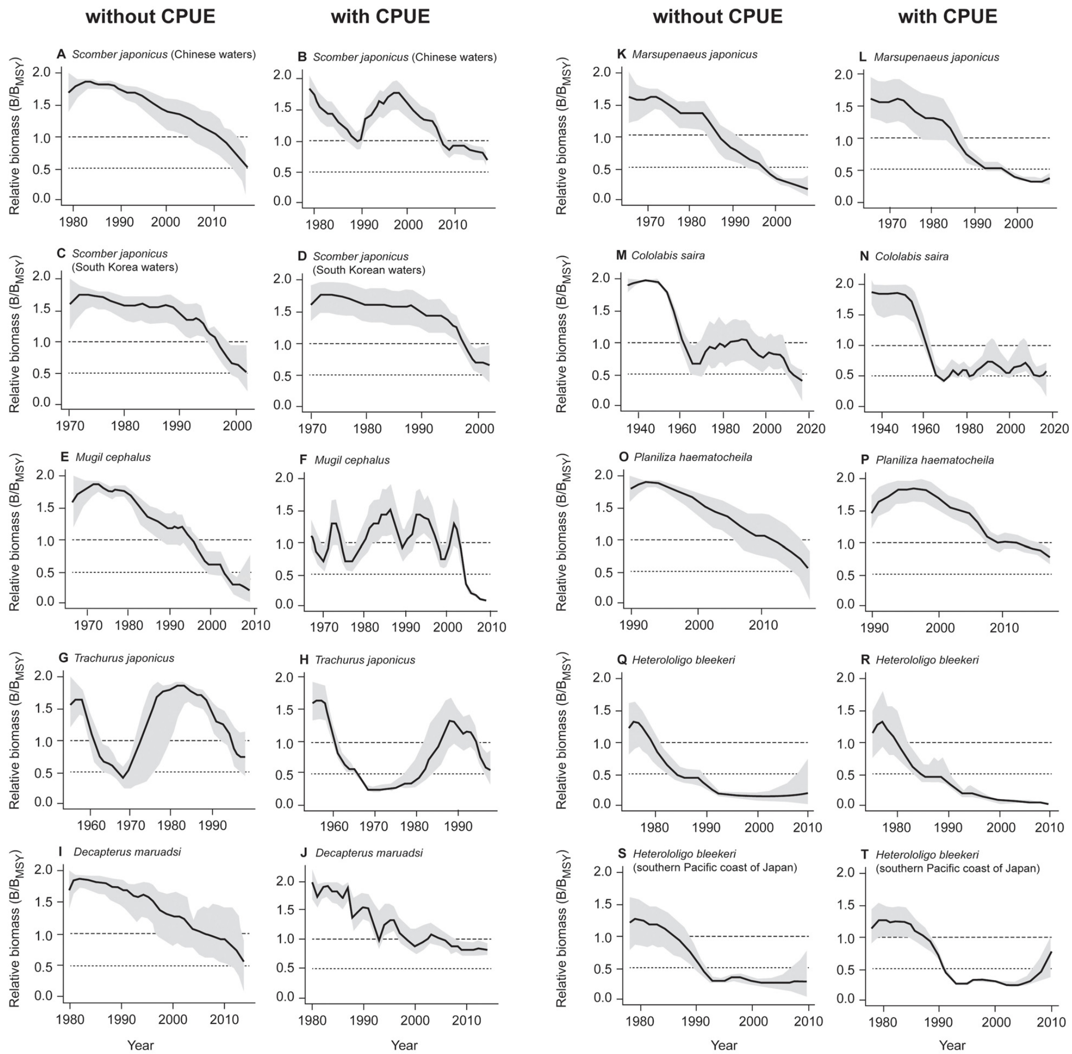


FIGURE 3 | Comparison of relative biomass trends estimated using the CMSY method (without CPUE, left) and BSM (with CPUE, right) for 10 stocks, with the gray areas representing the 95% confidence intervals. Note the match between the pairs of panels, from **(A)** vs. **(B)** to **(S)** vs. **(T)**.

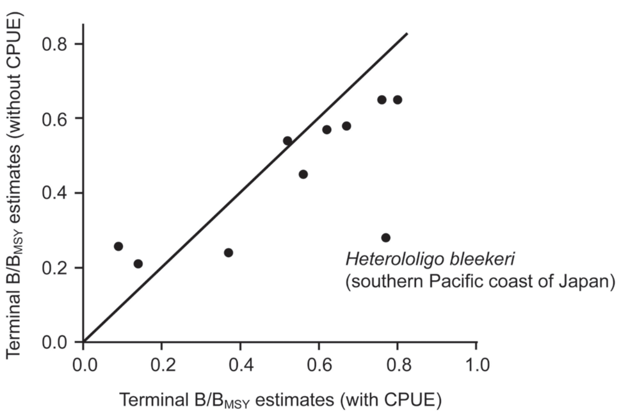


FIGURE 4 | Terminal B/B_{MSY} estimates of 10 stocks without (CMSY) and with (BSM) CPUE data added to the analysis.

TABLE 5 | Definition of fish stock status, based on B/B_{MSY} in the final year of a time series*.

B/B_{MSY}	Stock status
≥1	Healthy
0.8–1.0	Slightly overfished
0.5–0.8	Overfished
0.2–0.5	Grossly overfished
<0.2	Collapsed

*From Palomares et al. (2018).

Similarly, in Japan, spear squid *Heterololigo bleekeri*, widely distributed in coastal waters, have been overexploited to near collapse (Tian, 2009), while the recent decline of kuruma prawn *Marsupenaeus japonicus* catches suggest a much decreased stock size (Hamasaki and Kitada, 2013). Also, pelagic trawling surveys showed that the biomass of Pacific saury *Cololabis saira* around

TABLE 6 | Estimates of r, k, MSY, relative biomass and status as obtained by CMSY and/or BSM method for 15 stocks (the results in bold are based on the BSM method, i.e., catch and abundance data.

Scientific name (common name)	Fishing ground	*r*	*k* (10^3 t)	*MSY* (10^3 t/year)	B_{end}/k	B/B_{MSY}	Status
Clupea pallasii (Pacific herring)	Yellow Sea-East China Sea-East/Japan Sea	0.39	3473	341	0.30	0.59	Overfished
Cololabis saira (Pacific saury)	Japanese waters	**0.40**	**2766**	**280**	**0.29**	**0.58**	Overfished
Decapterus maruadsi (Japanese scad)	Chinese waters	**1.32**	**1662**	**546**	**0.42**	**0.83**	Slightly overfished
Gadus macrocephalus (Pacific cod)	Southern East/Japan Sea	0.28	17.1	1.21	0.27	0.54	Overfished
Heterololigo bleekeri (spear squid)	Southern Japan Sea	**0.46**	**48.8**	**5.62**	**0.06**	**0.13**	Collapsed
Heterololigo bleekeri (spear squid)	Southern Pacific coast	**0.70**	**7.32**	**1.28**	**0.38**	**0.77**	Overfished
Loligo vulgaris (European squid)	Yellow Sea-East China Sea-East/Japan Sea	0.56	2132	298	0.20	0.40	Grossly overfished
Marsupenaeus japonicus (kuruma prawn)	East China Sea	**0.39**	**8.50**	**0.82**	**0.19**	**0.37**	Grossly overfished
Mugil cephalus (flathead gray mullet)	Taiwan Strait	**0.49**	**1192**	**145**	**0.04**	**0.09**	Collapsed
Planiliza haematocheila (so-iuy mullet)	Chinese waters	**0.82**	**647**	**132**	**0.39**	**0.78**	Overfished
Scomber japonicus (chub mackerel)	Chinese waters	**0.58**	**2639**	**383**	**0.35**	**0.70**	Overfished
Scomber japonicus (chub mackerel)	Japanese waters	0.31	11632	912	0.25	0.51	Overfished
Scomber japonicus (chub mackerel)	South Korean waters	**0.46**	**1308**	**150**	**0.32**	**0.64**	Overfished
Scomberomorus niphonius (Japanese Spanish mackerel)	South Korean waters	0.57	168	23.8	0.19	0.38	Grossly overfished
Trachurus japonicus (Japanese jack mackerel)	South Korean waters	**0.56**	**133**	**18.8**	**0.26**	**0.52**	Overfished

Those not in bold are based on the catch data by CMSY).

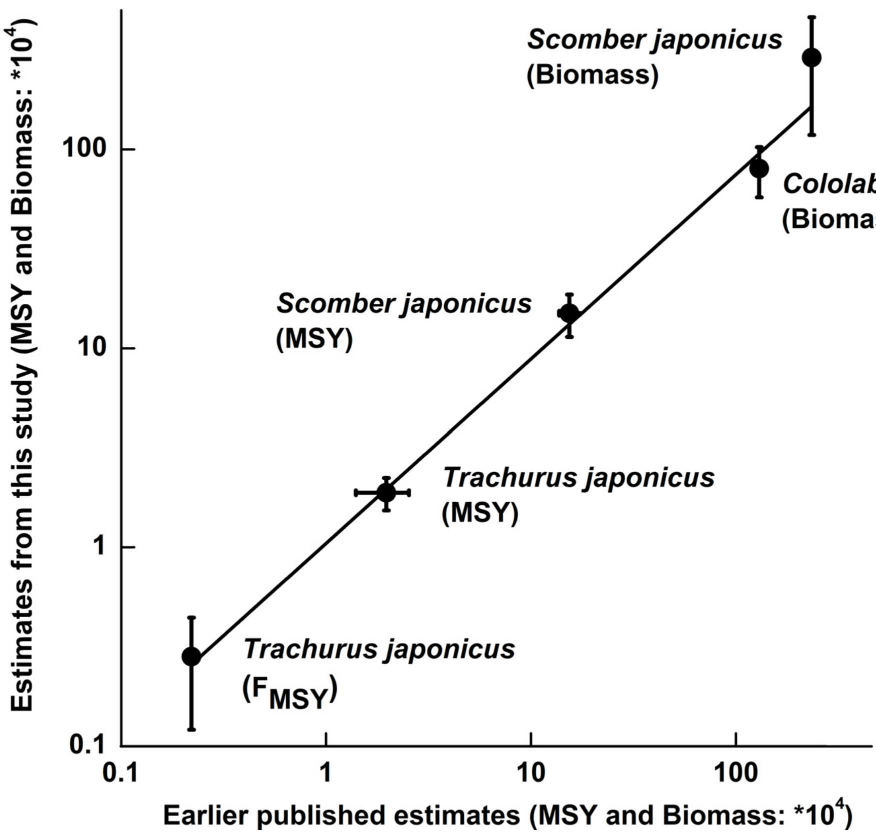


FIGURE 5 | Plot of estimates obtained with the CMSY and BSM methods vs. the corresponding values estimated using other models [*T. japonicus* from Zhang and Lee (2001); *S. japonicus* from Choi et al. (2004) and Yatsu (2019); *Cololabis saira* from Yatsu (2019)]. The vertical bars refer to the confidence intervals of the CMSY and BSM results, while the two horizontal bars express ranges whose mid-ranges were used as point estimates.

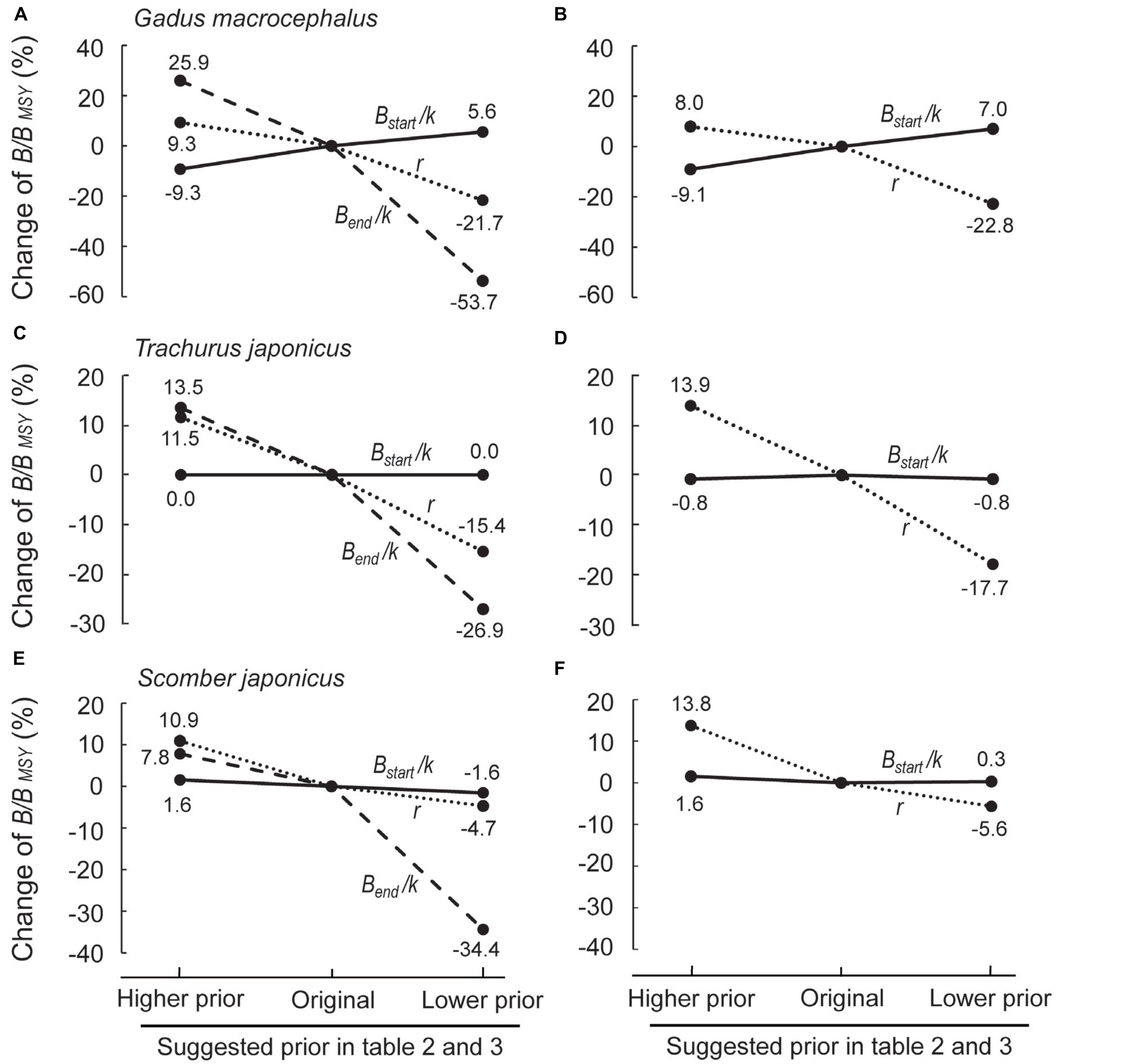


FIGURE 6 | Sensitivity of B/B_{MSY} to changes of the priors (r, B_{start}/k and B_{end}/k) in Pacific cod (*Gadus macrocephalus*), Japanese jack mackerel (*Trachurus japonicus*) and chub mackerel (*Scomber japonicus*). **(A,C,E)** Effects of changing any of the 3 prior ranges (r, B_{start}/k and B_{end}/k); **(B,D,F)** effect of changing r and B_{start}/k, while setting B_{end}/k as "Not Available"; this produces virtually the same results as in **(A,C,E)** (see text).

the Japanese Archipelago decreased from 5.0 million tons in 2003 to 1.8 million tons in 2016 (Yatsu, 2019), while the biomass of *Scomber japonicus* decreased from a high level during the 1970s to the end of the 1990s, then remained at a low level thereafter (Yatsu, 2019).

Finally, in South Korean waters, detailed stock assessments using the same catch and CPUE series as analyzed here, led to estimates of MSY in *Scomber japonicus* of 1.71×10^5 t for the Schaefer model and 1.37×10^5 t for the Fox model (Choi et al., 2004), which neatly bracket our estimates of 1.50×10^5 t, as estimated by BSM method (**Table 6** and **Figure 5**). Similarity, the results of Japanese jack mackerel *Trachurus japonicus* produced by the BSM method also fits well with that generated by a more data-demanding stock assessment model (Zhang and Lee, 2001).

Thus, the results from **Figure 3** are confirmed by the stock assessment literature from China, Japan and South Korea. Also, except for spear squid *Heterololigo bleekeri* in the southern Pacific coast of Japan, while the biomass trajectories in the left panels of **Figure 3**, as obtained without CPUE data, differ somewhat from those in the right panels, which also have narrower confidence intervals, they do not differ systematically in the feature that is most important to fisheries managers, i.e., in their estimates of terminal B/B_{MSY} (see also **Figure 4**).

This, we assume, is basically due to the fact that variations in catches, especially in fully exploited stocks, generally reflect the variations of the underlying biomasses (Kleisner et al., 2013; Pauly et al., 2013). This means that, while it is preferable to use CPUE data in conjunction with the CMSY method, their absence can be compensated, at least in part, by applying priors derived from expert knowledge on the status of fisheries. For the stock of spear squid *Heterololigo bleekeri* in the southern Pacific coast of Japan, its catch and CPUE time series trends diverged after 2005 (Tian et al., 2013; see also **Supplementary Table S2**), which resulted in mismatch results estimated by CMSY and BSM methods (**Figures 3**, **4**).

CMSY and BSM methods rely largely on reliable catch time series. Problematic catch data, such as reflecting regime shifts or pertaining to a species of which a large fraction is discarded, would lead to biased parameter estimates, thus should not be assessed using CMSY and BSM methods. Meanwhile, the result of sensitivity analysis revealed that B_{end}/k has the biggest effect on the outcome of B/B_{MSY}. When a biased estimate of B_{end}/k is used in the assessment, the methods might perform poorly.

In our contribution, we applied CMSY and BSM methods to 15 stocks, most of which were not assessed previously, especially for stocks in Chinese coastal waters. Our results provide preliminary fisheries reference points for these stocks, which can be used in fisheries management. Our results demonstrate that generally, the CMSY and BSM is adequate for assessing stocks in China and other countries where fisheries management has been hampered by a lack of suitable methods and/or detailed data.

CONCLUSION

The problem of overexploitation of fisheries has been well documented globally. This makes stock assessment methods relying mainly on catch data (such as the CMSY and BSM methods), more reliable than if stocks were lightly fished, as for overexploited fisheries, variations in catches generally reflect the variations of the underlying biomasses.

However, if the CMSY and BSM methods are to be widely used, reliable and long catch time series must be available; such time series are generally lacking from Chinese waters. Notably, China's official fishery statistics, i.e., *Chinese Fishery Statistical Yearbook*, lists catches for only a few major commercial species. Thus, a massive improvement of China's catch statistics will be required, to allow assessing and monitoring the success of management efforts.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

CL and WX was responsible for the data collection, formal analysis, and writing original draft. DP was responsible for the conceptualization, methodology, reviewing, and editing the manuscript. All authors contributed to the manuscript and approved the submitted version.

FUNDING

CL and WX acknowledge financial support from the Creative Team Project of the Laboratory for Marine Ecology and Environmental Science, Qingdao National Laboratory for Marine Science and Technology (LMEES-CTSP-2018-1), National Natural Science Foundation of China (No. 31872568), NSFC-Shandong Joint Fund for Marine Ecology and Environmental Sciences (U1606404), Open Fund of CAS Key Laboratory of Marine Ecology and Environmental Sciences, Institute of Oceanology, Chinese Academy of Sciences (KLMEES202004), and Qingdao Postdoctoral Applied Research Project. DP acknowledges support from the Sea Around Us, funded by the Oak Foundation, the Marisla Foundation, the Paul M. Angell Family Foundation, the David and Lucile Packard Foundation, the Minderoo Foundation, and the Bloomberg Philanthropies through RARE.

ACKNOWLEDGMENTS

We thank Dr. M. L. Palomares and Dr. R. Froese for their comments on our results. We are also grateful to Evelyn Liu for redrawing our figures.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00623/full#supplementary-material

REFERENCES

Anticamara, J. A., Watson, R., Gelchu, A., and Pauly, D. (2011). Global fishing effort (1950-2010): trends, gaps, and implications. *Fish. Res.* 107, 131–136. doi: 10.1016/j.fishres.2010.10.016

Asada, Y. (1973). License limitation regulations: the Japanese system. *J. Fish. Board Can.* 30, 2085–2095. doi: 10.1139/f73-335

Cheng, J., and Lin, L. (2004). Study on the biological characteristics ans status of commom mackerel (*Scomber japonicus* Houttuyn) fishery in the East China Sea region. *Mar. Fish.* 26, 73–78.

Choi, Y. M., Zhang, C. I., Lee, J. B., Kim, J. Y., and Cha, H. K. (2004). Stock assessment and management implications of chub mackerel, *Scomber japonicus* in Korean waters. *J. Korean. Soc. Fish. Res.* 6, 90–100.

Chung, S., Kim, S., and Kang, S. (2013). Ecological relationship between environmental factors and Pacific cod (*Gadus macrocephalus*) catch in the southern East/Japan Sea. *Anim. Cells Syst.* 17, 374–382. doi: 10.1080/19768354.2013.853693

Engelhard, G. H. (2016). "On the need to study fishing power change: challenges and perspectives," in *Perspectives on Oceans Past*, eds K. Schwerdtner-Maáñez and B. Poulsen (Dordrecht: Springer), 89–101. doi: 10.1007/978-94-017-7496-3_6

FAO (2018). *The State of World Fisheries and Aquaculture 2018-Meeting the Sustainable Development Goals*. Rome: FAO.

Fisheries and Fishery Administration of the Ministry of Agriculture [FFAMA] (1979–2017). *China Fishery Statistical Yearbook*. Beijing: Agricultural Press of China.

Froese, R., Demirel, N., Coro, G., Kleisner, K. M., and Winker, H. (2017). Estimating fisheries reference points from catch and resilience. *Fish Fish.* 18, 506–526. doi: 10.1111/faf.12190

Froese, R., Zeller, D., Kleisner, K., and Pauly, D. (2012). What catch data can tell us about the status of global fisheries. *Mar. Biol.* 159, 1283–1292. doi: 10.1007/s00227-012-1909-6

Geng, Z., Zhu, J., Xia, M., and Li, Y. (2018). Research progress in fishery stock assessment using data-poor/limited methods. *Trans. Oceanol. Limnol.* 5, 130–137.

Gong, Y., Jeong, H. D., Suh, Y. S., Park, J. H., Seong, K. T., Kim, S. W., et al. (2007). Fluctuations of pelagic fish populations in relation to the climate shifts in the Far-East regions. *J. Ecol. Environ.* 30, 23–38. doi: 10.5141/jefb.2007.30.1.023

Hamasaki, K., and Kitada, S. (2013). Catch fluctuation of Kuruma prawn, *Penaeus japonicus* in Japan relative to ocean climate variability and a stock enhancement program. *Rev. Fish. Sci.* 21, 454–468. doi: 10.1080/10641262.2013.800781

Kang, B., Liu, M., Huang, X., Li, J., Yan, Y., Han, C., et al. (2018). Fisheries in Chinese seas: what can we learn from controversial official fisheries statistics? *Rev. Fish Biol. Fish.* 28, 503–519. doi: 10.1007/s11160-018-9518-1

Kang, J. S. (2006). Analysis on the development trends of capture fisheries in North-East Asia and the policy and management implications for regional cooperation. *Ocean Coast. Manag.* 49, 42–67. doi: 10.1016/j.ocecoaman.2005.10.002

Kim, S. (2010). Fisheries development in northeastern Asia in conjunction with changes in climate and social systems. *Mar. Policy* 34, 803–809. doi: 10.1016/j.marpol.2010.01.028

Kleisner, K., Zeller, D., Froese, R., and Pauly, D. (2013). Using global catch data for inferences on the world's marine fisheries. *Fish Fish.* 14, 293–311. doi: 10.1111/j.1467-2979.2012.00469.x

Lam, V. W., and Pauly, D. (2019). Status of fisheries in 13 Asian large marine ecosystems. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 163, 57–64. doi: 10.1016/j.dsr2.2018.09.002

Lan, K., Lee, M., Zhang, C. I., Wang, P., Wu, L., and Lee, K. (2014). Effects of climate variability and climate change on the fishing conditions for grey mullet (*Mugil cephalus* L.) in the Taiwan Strait. *Clim. Change* 127, 577–578. doi: 10.1007/s10584-014-1208-y

Lee, K. N., Gates, J. M., and Lee, J. B. (2006). Recent developments in Korean fisheries management. *Ocean Coast. Manag.* 49, 355–366. doi: 10.1016/j.ocecoaman.2006.03.002

Lee, S., Kim, B., and Chang, D. (2011). Long-term variation in catch of Spanish mackerel (*Scomberomorus niphonius*) related to environmental change in Korean waters. *J. Kor. Soc. Fish. Tech.* 47, 99–107. doi: 10.3796/KSFT.2011.47.2.099

Liang, C., and Pauly, D. (2017a). Fisheries impacts on China's coastal ecosystems: unmasking a pervasive 'fishing down'effect. *PLoS One* 12:e0173296. doi: 10.1371/journal.pone.0173296

Liang, C., and Pauly, D. (2017b). Growth and mortality of exploited fishes in China's coastal seas and their uses for yield-per-recruit analyses. *J. Appl. Ichthyol.* 33, 746–756. doi: 10.1111/jai.13379

Liu, S., Liu, Y., Fu, C., Yan, L., Xu, L., Wan, R., et al. (2019). Using novel spawning ground indices to analyze the effects of climate change on Pacific saury abundance. *J. Mar. Syst.* 191, 13–23. doi: 10.1016/j.jmarsys.2018.12.007

Liu, Z., Yuan, X., Yang, L., Yan, L., and Cheng, J. (2019). Stock assessment and management strategies for small yellow croaker in the East China Sea based on data-limited assessment models. *J. Fish. Sci. China* 26, 621–635.

Ma, S., Cheng, J., Li, J., Liu, Y., Wan, R., and Tian, Y. (2019). Interannual to decadal variability in the catches of small pelagic fishes from China Seas and its responses to climatic regime shifts. *Deep Sea Res. Part II* 159, 112–129. doi: 10.1016/j.dsr2.2018.10.005

Matsuda, H., Makino, M., Tomiyama, M., Gelcich, S., and Castilla, J. C. (2010). Fishery management in Japan. *Ecol. Res.* 25, 899–907.

Myers, R. A., Barrowman, N. J., Hutchings, J. A., and Rosenberg, A. A. (1995). Population dynamics of exploited fish stocks at low population levels. *Science* 269, 1106–1108. doi: 10.1126/science.269.5227.1106

Palomares, M. L. D., Froese, R., Derrick, B., Nöel, S.-L., Tsui, G., Woroniak, J., et al. (2018). "A preliminary global assessment of the status of exploited marine fish and invertebrate populations," *A Report Prepared By The Sea Around US For OCEANA* (Washington, DC: OCEANA).

Palomares, M. L. D., and Pauly, D. (2019). On the creeping increase of vessels' fishing power. *Ecol. Soc.* 24:31.

Pauly, D., Hilborn, R., and Branch, T. A. (2013). Does catch reflect abundance? Yes, it is a crucial signal. *Nature* 494, 303–306. doi: 10.1038/494303a

Pauly, D., and Zeller, D. (2016). Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nat. Commun.* 7:10244.

Pauly, D., and Zeller, D. (2019). Agreeing with FAO: comments on SOFIA 2018. *Mar. Policy* 100, 332–333. doi: 10.1016/j.marpol.2018.12.009

Schaefer, M. B. (1954). Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Inter Am. Trop. Tuna Comm. Bull.* 1, 23–56.

Schaefer, M. B. (1957). A study of the dynamics of the fishery for yellowfin tuna in the eastern tropical Pacific Ocean. *Inter Am. Trop. Tuna Comm. Bull.* 2, 243–285.

Shen, G., and Heino, M. (2014). An overview of marine fisheries management in China. *Mar. Policy* 44, 265–272. doi: 10.1016/j.marpol.2013.09.012

Shi, Z. H., Peng, S. M., and Hou, J. L. (2010). The prospects of resources exploitation and ecological culture of Mugilidae in China. *Prog. Fish. Sci.* 31, 120–125.

Tanoue, W. (2015). *Japan's Total Aowable Catch Systems In Fishery Resource Management*. Washington, DC: University of Washington.

Tian, Y. (2009). Interannual-interdecadal variations of spear squid *Loligo bleekeri* abundance in the southwestern Japan Sea during 1975-2006: impact of the trawl fishing and recommendations for management under the different climate regimes. *Fish. Res.* 100, 78–85. doi: 10.1016/j.fishres.2009.06.005

Tian, Y., Nashida, K., and Sakaji, H. (2013). Synchrony in the abundance trend of spear squid *Loligo bleekeri* in the Japan Sea and the Pacific Ocean with special reference to the latitudinal differences in response to the climate regime shift. *ICES J. Mar. Sci.* 70, 968–979. doi: 10.1093/icesjms/fst015

Watson, R., Cheung, W. W. L., Anticamara, J., Sumaila, U. R., Zeller, D., and Pauly, D. (2013). Global marine yield halved as fishing intensity redoubles. *Fish Fish.* 14, 493–503. doi: 10.1111/j.1467-2979.2012.00483.x

Yatsu, A. (2019). Review of population dynamics and management of small pelagic fishes around the Japanese Archipelago. *Fish Fish.* 85, 611–639. doi: 10.1007/s12562-019-01305-3

Zhang, C. I., and Lee, J. B. (2001). Stock assessment and management implications of horse mackerel (*Trachurus japonicus*) in Korean waters, based on the relationships between recruitment and the ocean environment. *Prog. Oceanogr.* 49, 513–537. doi: 10.1016/s0079-6611(01)00038-6

Zhang, K., Liao, B., Xu, Y., Zhang, J., Sun, M., Qiu, Y., et al. (2017). Assessment for allowable catch of fishery resources in the South China Sea based on statistical data. *Haiyang XueBao* 39, 25–33.

Zheng, Y. J., Chen, X. Z., Cheng, J. H., Wang, Y. L., Shen, X. Q., et al. (2003). *Biological Resources and Environment of the East China Sea Continental Shelf*. Shanghai: Shanghai Science and Technology Press.

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Marine Science

ORIGINAL RESEARCH
published: 30 July 2020
doi: 10.3389/fmars.2020.00618

Evaluating Stock Status of 16 Commercial Fish Species in the Coastal and Offshore Waters of Taiwan Using the CMSY and BSM Methods

Peilong Ju[1], Yongjun Tian[1,2,3], Mingru Chen[4,5,6]*, Shengyun Yang[4], Yang Liu[1,2], Qinwang Xing[1] and Peng Sun[1]**

[1] Laboratory of Fisheries Oceanography, Fisheries College, Ocean University of China, Qingdao, China, [2] Institute for Advanced Ocean Study, Ocean University of China, Qingdao, China, [3] Laboratory for Marine Fisheries Science and Food Production Processes, Pilot National Laboratory for Marine Science and Technology, Qingdao, China, [4] State Key Laboratory of Marine Environmental Science, College of Ocean and Earth Sciences, Xiamen University, Xiamen, China, [5] Xiamen City Key Laboratory of Urban Sea Ecological Conservation and Restoration, Xiamen University, Xiamen, China, [6] China-ASEAN College of Marine Sciences, Xiamen University Malaysia, Sepang, Malaysia

OPEN ACCESS

Edited by:
Cui Liang,
Institute of Oceanology, Chinese Academy of Sciences, China

Reviewed by:
Hui Zhang,
Institute of Oceanology, Chinese Academy of Sciences, China
Fabian Zimmermann,
Norwegian Institute of Marine Research (IMR), Norway

***Correspondence:**
Yongjun Tian
yjtian@ouc.edu.cn
Mingru Chen
mrchen@xmu.edu.cn
Peng Sun
sunpeng@ouc.edu.cn

Specialty section:
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

Received: 31 January 2020
Accepted: 06 July 2020
Published: 30 July 2020

Citation:
Ju P, Tian Y, Chen M, Yang S, Liu Y, Xing Q and Sun P (2020) Evaluating Stock Status of 16 Commercial Fish Species in the Coastal and Offshore Waters of Taiwan Using the CMSY and BSM Methods. Front. Mar. Sci. 7:618. doi: 10.3389/fmars.2020.00618

The waters around Taiwan are impacted by the Kuroshio and coastal currents, resulting in a high productivity and a high diversity of marine life. As a consequence, there are a multitude of fisheries around Taiwan, conducted by a fleet that has grown enormously in the last four decades. Here, we investigate the effect of the resulting fishing pressure on 16 commercial fish stocks including demersal and pelagic species in the coastal and offshore waters of Taiwan using the Monte Carlo Catch-Maximum Sustainable Yield (CMSY) and Bayesian Schaefer Model (BSM) methods. Both of these methods required principally catch time series, with the BSM methods also requiring catch-per-unit-of-effort data. The results show that of the 16 assessed stocks, 10 stocks have collapsed, 2 are severely overfished, 2 are overfished, 1 is slightly overfished, and only 1 stock remains in a healthy status; these troubling results are attributed to excessive fishing pressure. However, climate-driven environmental variability may be another factor affecting the fishery resources around Taiwan, as evidenced by chub mackerel *Scomber japonicus*, the one stock deemed healthy, which is here attributed to favorable environmental condition. Using the fisheries reference points provided here, rebuilding plans could be provided for the other 15 species; however, such plans are not likely to be successful without reducing the size of the Taiwanese fishing fleet.

Keywords: Chinese coastal fisheries, Taiwan waters, CMSY and BSM, commercial fish, stock assessment

INTRODUCTION

Fisheries are not only an important food source for humans, but also provide livelihood for local communities (Rice and Garcia, 2011; Liao et al., 2019). However, one-third of globally assessed stocks are overfished (FAO, 2018), while in Asia, almost half of the exploited stocks are overexploited or have collapsed (Lam and Pauly, 2019). By this measure, it can be suggested that the unsustainable exploitation of stocks in Asia is more serious.

The waters around Taiwan are very productive and support of high biodiversity (Hobday and Pecl, 2014), notably due to the combined effects of the Kuroshio Current, the South China Sea

Warm Current, and the China Coastal Current (Ho et al., 2016; Ju et al., 2019; Liao et al., 2019; **Figure 1**), and this is reflected in nearly 2,600 species of fish and 500 species of crustaceans being reported from Taiwan's waters (Ji et al., 2014; see also www.fishbase.org and www.sealifebase.org).

Correspondingly, a wide variety of fishing gears are used to exploit this biodiversity, notably purse seines, bottom and pelagic trawls, longlines, gill and set nets, and so on (Fisheries Agency, 1949–2019). However, because of overexploitation (Chen et al., 2018; Liao et al., 2019), fisheries catches, after a long period of increase since the 1950s, peaked in 1980 and then gradually decreased (**Figure 2**). While the status of coastal and offshore fisheries in Taiwan waters is widely perceived as being highly problematic (Liu, 2013; Liao et al., 2019), only a few of the fish stocks have been assessed (Chen, 2006; Shao, 2011). This contribution assesses 16 of the coastal and offshore exploited fish stocks in the waters around Taiwan, such as to provide reference points for the management of their fisheries.

Palomares et al. (2018) listed three reasons for exploited fish stock to remain unassessed in developing countries and regions: lack of expertise, scarcity of data, and absence of stock assessment methods suitable for use in data-sparse situations. These deficiencies have recently been mitigated, at least in part, through the recent development of easy-to-learn computer-intensive stock assessment methods relying primarily on time series of catch data. Among these, the Monte Carlo Catch-Maximum Sustainable Yield (CMSY) method of Froese et al. (2017) figures prominently as a straightforward approach for estimating fisheries reference points from the time series of catch data and ancillary information, or "prior."

Here, we use the CMSY method, and a related method, a Bayesian state-space implementation of the Schaefer model

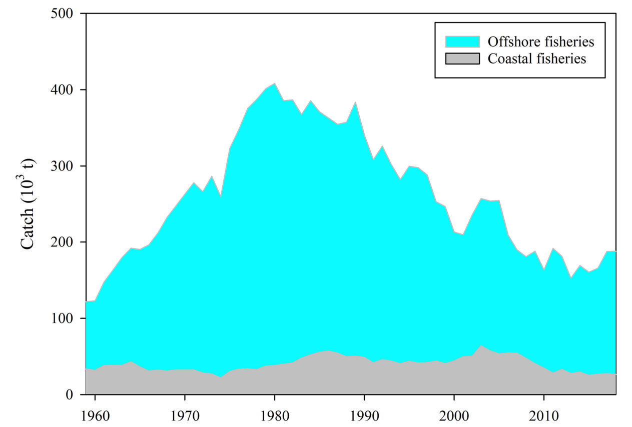


FIGURE 2 | Catches of Taiwan coastal and offshore marine capture fisheries from 1959 to 2018. Data source: Fisheries Agency (1949–2019).

(BSM; Froese et al., 2017), to estimate biomass (B) and the current status of 16 commercial fish species in the coastal and offshore waters of Taiwan. Also, key fisheries reference points such as intrinsic rate of population increase (r), carrying capacity (k), maximum sustainable yield (MSY), and the terminal ratio B/B_{MSY} are estimated.

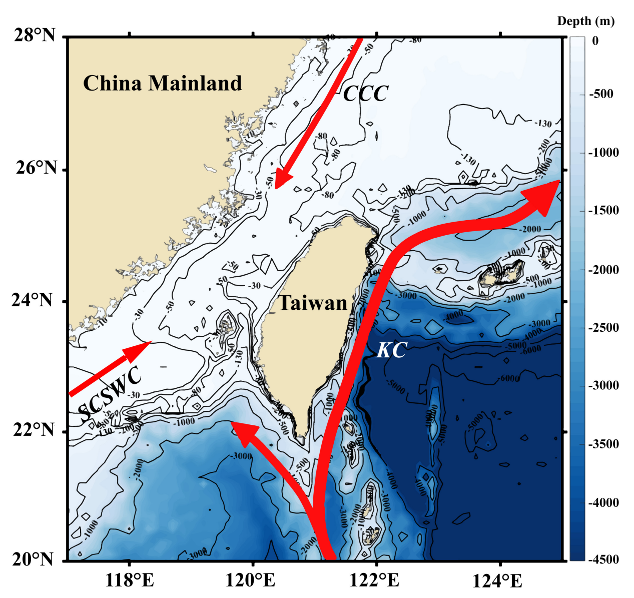


FIGURE 1 | Map of the coastal and offshore waters of Taiwan. CCC, China Coastal Current; SCSWC, South China Sea Warm Current; KC, Kuroshio Current.

MATERIALS AND METHODS

Fisheries Data

Catch data of the 16 commercial fish species in Taiwan waters (**Supplementary Table S1**) and the number of fishing vessels were collected from Fisheries Statistical Yearbook Taiwan, Kinmen and Matsu areas (Fisheries Agency, 1949–2019). The catch-per-unit-of-effort (CPUE) data were defined by catch/the number of fishing vessels. The basic fisheries data available for this study are summarized in **Table 1**. The species therein include top predators, benthopelagic fishes, small pelagic fishes, and demersal fishes (**Table 1**). The species were selected if they were separately listed as a commercial species in the Fisheries Statistical Yearbook, and their catch time series covered at least 20 years. In addition, management regulations may introduce biases in stock assessments by affecting trends in catch. However, major managements for Taiwan coastal and offshore fisheries (**Supplementary Table S2**) have little effect on the regulations of these 16 assessed species. Therefore, biases by managements can be ignored for 16 assessed species.

CMSY and BSM Methods

General Description

The CMSY method was first proposed as a Monte-Carlo method by Martell and Froese (2013), who were inspired by stock reduction analysis (Kimura and Tagart, 1982; Kimura et al., 1984); it was then updated to overcome some shortcomings (Froese et al., 2017). CMSY is used to estimate biomass, exploitation rate (F/F_{MSY}), relative stock size (B/B_{MSY}), and fisheries reference points (MSY, r, k) from time series of catch, resilience, and

TABLE 1 | Basic data information on key species in the coastal and offshore waters of Taiwan, with "resilience" levels from FishBase.

Scientific name (common name)	Ecological group	Catch and CPUE	Resilience (*r*)	Prior *r* range	B_{start}/k	B_{end}/k
Scomberomorus guttatus (Indo-Pac. king mackerel)	Top predator	1989–2017	Medium	0.37–0.85[1]	0.2–0.4	–
Scomberomorus commerson (narrow-barred Spanish mackerel)	Top predator	1989–2017	Medium	0.37–0.85[1]	–	–
Scomberomorus niphonius (Japanese Spanish mackerel)	Top predator	1950–2017	Medium	0.37–0.85[1]	–	–
Muraenesox cinereus (daggertooth pike conger)	Top predator	1970–2017	Medium	0.37–0.85[1]	0.4–0.6	–
Clupanodon thrissa (Chinese gizzard shad)	Small pelagic	1993–2017	High	0.79–1.79[1]	0.2–0.4	–
Scomber japonicus (chub mackerel)	Small pelagic	1980–2017	Medium	0.32–0.73[1]	0.01–0.2	0.2–0.6
Trachurus japonicus (Japanese jack mackerel)	Small pelagic	1995–2017	Medium	0.49–1.12[1]	0.1–0.2	0.3–0.4
Decapterus maruadsi (Japanese scad)	Small pelagic	1989–2017	High	0.6–1.5[2]	0.01–0.2	0.2–0.4
Mene maculate (moonfish)	Small pelagic	1950–2016	High	0.6–1.5[2]	–	0.4–0.8
Atrobucca nibe (blackmouth croaker)	Demersal	1950–2017	Medium	0.2–0.8[2]	–	–
Acanthopagrus schlegelii (blackhead seabream)	Demersal	1989–2017	Medium	0.2–0.8[2]	–	0.01–0.2
Priacanthus macracanthus (red bigeye)	Demersal	1974–2017	Medium	0.21–0.48[1]	0.6–0.8	–
Psenopsis anomala (Pacific rudderfish)	Benthopelagic	1950–2017	Medium	0.32–0.73[1]	–	–
Pampus argenteus (silver pomfret)	Benthopelagic	1990–2017	Medium	0.37–0.85[1]	0.4–0.6	–
Pennahia argentata (silver croaker)	Benthopelagic	1970–2017	High	0.37–0.85[1]	0.47–0.9	–
Parastromateus niger (black pomfret)	Benthopelagic	1966–2017	Medium	0.37–0.85[1]	0.01–0.2	–

[1] FishBase (www.fishbase.org). [2] Froese et al. (2017).

qualitative stock status information at the beginning and the end of the time series (see Froese et al., 2017, for a complete description). The predictions of the CMSY method can be strengthened by the BSM method when relative abundance data (i.e., CPUE data) are available in addition to catch data. The basic biomass dynamics of the CMSY and BSM methods followed Eq. 1:

$$B_{t+1} = B_t + r\left(1 - \frac{B_t}{k}\right)B_t - C_t \quad (1)$$

where B_t and B_{t+1} are the biomass in year t and the subsequent year, respectively; r is the intrinsic rate of population increase; k is the carrying capacity (here taken as the unexploited stock size); and C_t is the catch in year t.

A linear decline of surplus production is incorporated in Eq. 2 when stock size is strongly depleted, that is, its biomass falls less than 0.25 k:

$$B_{t+1} = B_t + 4\frac{B_t}{k}r\left(1 - \frac{B_t}{k}\right)B_t - C_t \left| \frac{B_t}{k} < 0.25 \right. \quad (2)$$

Determining the Boundaries of the *r*-*k* Space

To determine prior k ranges for the selected species under assessment, the proxies of resilience and the corresponding r ranges are provided in **Table 1**, based on Froese et al. (2017) and based on FishBase (Froese and Pauly, 2019[1]), respectively. The prior ranges for k were derived based on three empirical rules in Froese et al. (2017), represented here by Eq. 3 for stocks with low prior biomass at the end of the available catch time series, and Eq. 4 for stocks with high prior biomass at the end of the time series:

$$k_{\text{low}} = \frac{\max(C)}{r_{\text{high}}}, \; k_{\text{high}} = \frac{4\max(C)}{r_{\text{low}}} \quad (3)$$

$$k_{\text{low}} = \frac{2\max(C)}{r_{\text{high}}}, \; k_{\text{high}} = \frac{12\max(C)}{r_{\text{low}}} \quad (4)$$

[1] www.fishbase.org

where k_{low} and k_{high} are the lower and upper bounds of the prior range of k, $\max(C)$ is the maximum catch in the time series, and r_{low} and r_{high} are the lower and upper bounds of r range to be explored by the Monte-Carlo routine of CMSY.

The prior ranges of r values were obtained from the "resilience" that FishBase estimates for each fish species, and which are available as follows: high = > r = 0.6–1.5; medium = >r = 0.2–0.8; low = >r = 0.05–0.5, and very low = >r = 0.015–0.1 year^{-1}. Note that in general, species that can get large and have a high potential longevity have a low to very resilience, and conversely for small, short-lived species.

Setting Prior Biomass Range

The B_{start}/k (prior biomass at the beginning of the time series) and B_{end}/k (prior biomass at the end of the time series) for the 16 stocks under assessment are given in **Table 1**. These priors were not set by us, but instead were estimated based on the default rules described in the **Supplementary Material** of Froese et al. (2017).

Stock Status Definitions

The definitions of stock status used here, as defined by Palomares et al. (2018) based on B/B_{MSY} at the end of the biomass trajectory, are summarized in **Table 2**.

TABLE 2 | Definition of stock status (Palomares et al., 2018) based on B/B_{MSY} in the end of time series.

B/B_{MSY}	Stock status
≥1	Healthy
0.8–1.0	Slightly overfished
0.5–0.8	Overfished
0.2–0.5	Severely overfished
<0.2	Collapsed

TABLE 3 | Fisheries reference points (*r*, *k*, and MSY), relevant biomass (B_{end}/k and B/B_{MSY}) and stock status of 16 commercially exploited stocks estimated from BSM method.

Species	r (year^{-1})	k (10^3 t)	MSY 10^3 year^{-1}	B_{end}/k	B/B_{MSY}	Stock status
Scomberomorus guttatus	0.67 (0.53–0.83)	6.68 (5.36–8.34)	1.11 (0.98–1.26)	0.03 (0.02–0.06)	0.07 (0.04–0.11)	Collapsed
Scomberomorus commerson	0.71 (0.57–0.88)	22.5 (18.1–28)	3.98 (3.48–4.57)	0.04 (0.03–0.06)	0.09 (0.06–0.13)	Collapsed
Scomberomorus niphonius	0.88 (0.79–0.99)	45.7 (41–50.9)	10.1 (9.68–10.5)	0.01 (0.01–0.02)	0.03 (0.02–0.04)	Collapsed
Muraenesox cinereus	0.62 (0.50–0.77)	50.10 (40–62.6)	7.78 (6.73–9)	0.01 (0.01–0.02)	0.02 (0.02–0.03)	Collapsed
Clupanodon thrissa	1.21 (0.95–1.54)	0.11 (0.09–0.14)	0.03 (0.03–0.04)	0.15 (0.06–0.31)	0.30 (0.11–0.63)	Severely overfished
Scomber japonicus	0.68 (0.55–0.83)	338 (269–426)	57.1 (48.4–67.5)	0.57 (0.42–0.70)	1.13 (0.83–1.4)	Healthy
Trachurus japonicus	0.97 (0.82–1.14)	33.3 (26.7–41.4)	8.04 (6.77–9.55)	0.36 (0.28–0.46)	0.73 (0.55–0.92)	Overfished
Decapterus maruadsi	0.96 (0.84–1.1)	40.5 (32.9–49.9)	9.72 (7.99–11.8)	0.32 (0.19–0.45)	0.65 (0.37–0.91)	Overfished
Mene maculata	0.85 (0.73–0.98)	28.20 (23.2–34.2)	5.97 (4.97–7.19)	0.49 (0.38–0.69)	0.98 (0.71–1.39)	Slightly overfished
Atrobucca nibe	0.32 (0.21–0.49)	90.2 (69.7–117)	7.19 (4.75–10.9)	0.03 (0.02–0.04)	0.05 (0.03–0.08)	Collapsed
Acanthopagrus schlegelii	0.52 (0.36–0.75)	3.62 (2.72–4.82)	0.47 (0.36–0.65)	0.22 (0.18–0.28)	0.45 (0.36–0.56)	Severely overfished
Priacanthus macracanthus	0.33 (0.25–0.44)	63.1 (56.8–92.8)	5.27 (4.88–7.51)	0.02 (0.02–0.03)	0.05 (0.03–0.07)	Collapsed
Psenopsis anomala	0.50 (0.38–0.64)	37.9 (30.2–47.7)	4.69 (3.81–5.78)	0.03 (0.02–0.05)	0.06 (0.04–0.09)	Collapsed
Pampus argenteus	0.66 (0.50–0.89)	20.4 (15.8–26.3)	3.39 (2.67–4.3)	0.03 (0.02–0.04)	0.05 (0.03–0.08)	Collapsed
Pennahia argentata	0.61 (0.49–0.76)	51.6 (42.1–63.3)	7.87 (6.83–9.08)	0.04 (0.03–0.05)	0.08 (0.06–0.10)	Collapsed
Parastromateus niger	0.59 (0.47–0.74)	33.6 (26.7–42.1)	4.95 (3.98–6.16)	0.01 (0.01–0.02)	0.02 (0.02–0.03)	Collapsed

The number between brackets: 95% confidence intervals; r, maximum intrinsic growth rate of population (resilience); k, carrying capacity; MSY, maximum sustainable yield.

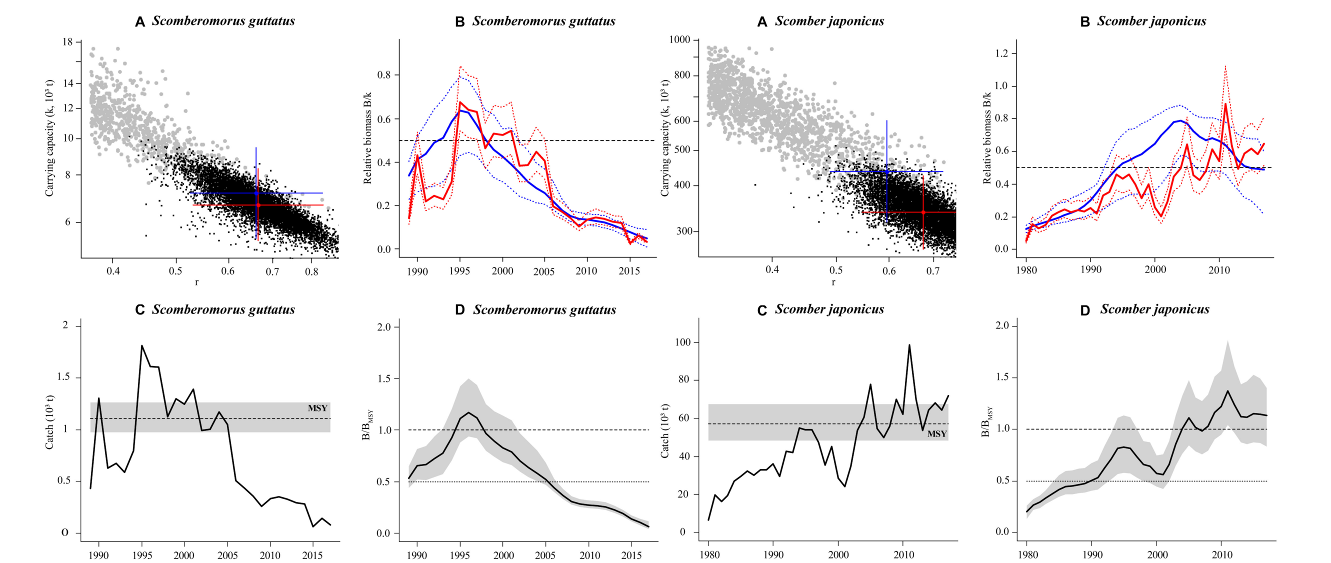


FIGURE 3 | Results of BSM outputs for the collapsed stock Indo-Pacific king mackerel *Scomberomorus guttatus* (left four panels) and the healthy stock chub mackerel *Scomber japonicus* (right four panels). Panel **(A)** shows the viable *r-k* pairs found by CMSY method (gray dots) and BSM method (black dots), and the blue cross is the most probable *r-k* pair with its 95% confidence interval (CI) found by CMSY, whereas red cross indicates the most probable *r-k* pair and its 95% CI found by BSM. Panel **(B)** shows the biomass trajectories (lines) with the 2.5th and 97.5th percentiles (dotted lines) estimated by CMSY (blue) and BSM (red). Panel **(C)** shows catch relative to the BSM estimate of MSY, with indication of 95% CI in gray. Panel **(D)** shows the development of relative total biomass (B/B_{MSY}), with CI (gray area) indicating uncertainty.

RESULTS

Table 3 presents the fisheries reference points (*r*, *k*, and MSY), relevant biomass (B_{end}/k and B/B_{MSY}), and stock status of 16 commercial fish stocks.

Figure 3 illustrates two examples, Indo-Pacific king mackerel (*Scomberomorus guttatus*), which documents a collapsed stock, and chub mackerel (*Scomber japonicus*), which documents a healthy stock. **Figure 3A** shows the most probable *r-k* pair and its 95% confidence interval as identified by the CMSY method (blue cross) and by the BSM method (red cross), which incorporated CPUE data. **Figure 3B** shows the similar trends of biomass trajectories estimated by CMSY (blue) and BSM (red). These similar values and trends from the two methods indicate that the results are more credible. Finally, **Figures 3C,D** show the trajectory of relative biomass (B/B_{MSY}) and estimated MSY levels.

Supplementary Figure S1 similar to **Figure 3** are presented for the other 15 of our stocks in the **Supplementary Material**. Jointly, **Figure 3** and **Supplementary Figure S1** show that, of our 16 stocks, 10 stocks have collapsed, 2 are severely overfished, 2 stocks overfished, 1 is slightly overfished, and only 1 remains healthy (**Table 3**).

DISCUSSION

CMSY and BSM are now well-established methods for the assessment of data-poor stocks, as they rely mainly only a time series of catch and ancillary qualitative information to quantify the biomass and related information on the stocks under investigation (Froese et al., 2017, 2018). However, for this study, parameters estimated from stock assessment may have some uncertainty due to the inherent limitations in catch (CPUE) data, although these data are from official statistics. The limitations of these input data were qualitatively described below. First, a fraction of catch as discards may be not recorded in official statistics. Second, some pelagic species are straddling stocks distributed across more than one exclusive economic zone, whereas catch data for these species are only collected in Taiwanese Exclusive Economic Zone and may therefore not fully reflect changes in stock size. Finally, catch and fishing effort data may be partly manufactured.

The stocks assessed by the BSM method as "collapsed" include four top predators (*S. guttatus*, *Scomberomorus commerson*, *Scomberomorus niphonius*, *Muraenesox cinereus*), four benthopelagic species (*Psenopsis anomala*, *Pampus argenteus*, *Pennahia argentata*, *Parastromateus niger*), and two demersal species (*Atrobucca nibe*, *Priacanthus macracanthus*). Their demise can be attributed to the ever-increasing fishing pressure exerted by a fishing fleet which grew, in the past 40 years, 3.14-folds in terms of vessel number and 35.2 times in term of cumulative engine power (Liu, 2013). Meanwhile, coastal and offshore catches have decreased from 408,000 t in 1980 to 198,000 t in 2018 (Fisheries Agency, 1949–2019; **Figure 2**). Among the other stocks affected were *P. anomala* (Du et al., 2010), *P. argentata* (Ju et al., 2016), *P. macracanthus* (Ju et al., 2016), and *P. niger* (Tao et al., 2012), occurring in the western Taiwan waters (Taiwan Strait), and which became overfished by the 2000s. These fish species belong to Taiwan's most important economic species.

Three species of small pelagic fish (Japanese jack mackerel *Trachurus japonicus*, Japanese scad *Decapterus maruadsi*, and Chinese gizzard shad *Clupanodon thrissa*) and blackhead seabream (*Acanthopagrus schlegelii*) are also overfished and/or severely overfished. Although climate-driven environmental variability can affect the population fluctuations of small pelagic fishes (Yu et al., 2018; Kanamori et al., 2019; Oozeki et al., 2019; Yatsu, 2019), (over-)exploitation also plays the important role in the fluctuations (Saraux et al., 2019) or even leads to population collapses (Essington et al., 2015). Indeed, the biomass of *T. japonicus* in Kuroshio Current systems has decreased sharply in the recent decades (Oozeki et al., 2019), mainly due to high exploitation.

Moonfish (*Mene maculata*), a subtropical species abundant in the eastern and southwestern Taiwan waters (Hwang et al., 2002), is "slightly overfished" as assessed in this study (**Table 3**). The stock status is supported by the study of Hwang et al. (2002), which reported that the stock in Taiwan waters suffered from an exploitation, which lead to a decreasing catch in the 1990s.

Chub mackerel (*S. japonicus*) is the only stock that our study found to be "healthy" (**Table 3**). This is confirmed by the report by Ju (2018) that the biomass of chub mackerel is increasing in the southern Taiwan Strait and that this species is recovering from depletion in the Pacific coast of northeastern Japan (Ichinokawa et al., 2015; Li et al., 2018; Oozeki et al., 2019; Yatsu, 2019). However, this positive development appears to be due to favorable environmental conditions (Hiyama et al., 2002; Li et al., 2014; Yasuda et al., 2014; Yu et al., 2018; Kanamori et al., 2019), enabling the stock to resist a threefold increase of fishing effort in the past 40 years (Liu, 2013).

Thus, with 15 of 16 major fish stocks being overexploited or collapsed, it can be inferred that the various management measures for the management of Taiwan's coastal and offshore fisheries at least in part for these 16 species fisheries and which include imposing total allowable catches, individual quota, area closures, fishing capacity limitations, size, gear, and season limitations (Huang and Chuang, 2010; Chen, 2012; Huang et al., 2016) are still insufficient, as assessed by the catches of coastal and offshore fisheries still decreasing (Fisheries Agency, 1949–2019).

Effective fisheries management is the main driver for recovery of fish stocks (Zimmermann and Werner, 2019; Hilborn et al., 2020). Therefore, we believe that the overall size of Taiwan's fishing fleet, generated by continuous growth in the last four decades, is the major reason why the technical measures listed above are not bearing fruit as expected.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because Our manuscript was based on official statistics of Taiwan, and no live vertebrates or higher invertebrates were involved, thus we believe an ethical review process was not required for our study.

AUTHOR CONTRIBUTIONS

PJ, YT, MC, QX and PS collected and analyzed data, provided ideas and drafted this manuscript. YT, SY, YL, and PS edited the manuscript. All authors contributed to the article and approved the submitted version.

FUNDING

PJ, YT, YL, and PS were partially supported by National Key Research and Development Project (No. 2018YFD0900902) and National Natural Science Foundation of China (Nos. 41930534 and 41861134037). MC and SY were in part funded by the National Key R&D Program of China (No. 2018YFC1406301), the Natural Science Foundation of Fujian Province, China (No. 2018J01066), and Xiamen University Malaysia Research Fund (No. XMUMRF/2020-C5/ICAM/0007).

ACKNOWLEDGMENTS

The authors thank Dr. Daniel Pauly for editing the manuscript. They also thank Dr. Maria Lourdes Palomares for the constructive comments on these results. We would like to thank Jiamei Xiao for helping collect data.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00618/full#supplementary-material

REFERENCES

Chen, C.-S. (2012). Management of the precious coral fishery in Taiwan: progress and perspectives. *Mar. Policy* 36, 623–629. doi: 10.1016/j.marpol.2011.10.016

Chen, J. L. (2006). *A Study on The Planning and Management of Fishery Resource Conservation Areas in Taiwan*. Keelung: National Taiwan Ocean University.

Chen, J. L., Lin, Y. S., and Chuang, C. T. (2018). Improving the management of Taiwanese fishery resource conservation zones based on public perceptions and willingness to pay for ecosystem services. *J. Coast. Conserv.* 22, 385–398. doi: 10.1007/s11852-017-0586-5

Du, J., Lu, Z., Chen, M., Yang, S., and Chen, X. (2010). Changes in ecological parameters and resources of Japanese butterfish, *Psenopsis anomala*, in the middle and northern Taiwan Strait. *J. Oceanogr. Taiwan Strait* 29, 234–240.

Essington, T. E., Moriarty, P. E., Froehlich, H. E., Hodgson, E. E., Koehn, L. E., Oken, K. L., et al. (2015). Fishing amplifies forage fish population collapses. *Proc. Natl. Acad. Sci. U.S.A.* 112, 6648–6652. doi: 10.1073/pnas

FAO (2018). *The State off Word Fisheries and Aquaculture 2018-Meeting the Sustainable Development Goals*. Rome: Food and Agriculture Organization.

Fisheries Agency (1949–2019). *Fisheries Statistical Yearbook 1950–2018, Taiwan, Kinmen and Matsu Area*. Taipei: Fisheries Agency.

Froese, R., Demirel, N., Coro, G., Kleisner, K. M., and Winker, H. (2017). Estimating fisheries reference points from catch and resilience. *Fish Fish.* 18, 506–526. doi: 10.1111/faf.12190

Froese, R., and Pauly, D. (2019). *FishBase. World Wide Web Electronic Publication*. Available online at: http://www.fishbase.org, version (accessed December, 2019).

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A. C., Dimarchopoulou, D., et al. (2018). Status and rebuilding of European fisheries. *Mar. Policy* 93, 159–170. doi: 10.1016/j.marpol.2018.04.018

Hilborn, R., Amoroso, R. O., Anderson, C. M., Baum, J. K., Branch, T. A., Costello, C., et al. (2020). Effective fisheries management instrumental in improving fish stock status. *PNAS* 117, 2218–2224. doi: 10.1073/pnas.1909726116

Hiyama, Y., Yoda, M., and Ohshimo, S. (2002). Stock size fluctuations in chub mackerel (*Scomber japonicus*) in the East China Sea and the Japan/East Sea. *Fish. Oceanogr.* 11, 347–353. doi: 10.1046/j.1365-2419.2002.00217.x

Ho, C. H., Lu, H. J., He, J. S., Lan, K.-W., and Chen, J. L. (2016). Changes in patterns of seasonality shown by migratory fish under global warming: evidence from catch data of Taiwan's coastal fisheries. *Sustainability* 8, 273. doi: 10.3390/su8030273

Hobday, A. J., and Pecl, G. T. (2014). Identification of global marine hotspots: sentinels for change and vanguards for adaptation action. *Rev. Fish Biol. Fish.* 24, 415–425. doi: 10.1007/s11160-013-9326-6

Huang, H.-W., and Chuang, C.-T. (2010). Fishing capacity management in Taiwan: experiences and prospects. *Mar. Policy* 34, 70–76. doi: 10.1016/j.marpol.2009.04.014

Huang, H.-W., Wang, S.-B., Wang, S.-P., Lu, H.-J., Chen, C.-S., Liao, C.-H., et al. (2016). *Status and Challenges for Taiwan Marine Fisheries Resources, the 4th Taiwan and Ocean Conference*. Taipei: National Taiwan Ocean University & Taiwan Research Foundation.

Hwang, S. Y., Chen, C. T., and Liu, K. M. (2002). Age and growth of the Moon fish, *Mene maculata*, before and after heavy exploitation in Southwestern Taiwan waters. *J. Fish. Soc. Taiwan* 29, 299–311.

Ichinokawa, M., Okamura, H., Watanabe, C., Kawabata, A., and Oozeki, Y. (2015). Effective time closures: quantifying the conservation benefits of input control for the Pacific chub mackerel fishery. *Ecol. Appl.* 25, 1566–1584. doi: 10.1890/14-1216.1

Ji, W. W., Ruan, W., Fang, H., Wang, Q., and Lu, Y. N. (2014). Review on the development of fisheries in Taiwan. *Fish. Inform. Strat.* 29, 300–306.

Ju, P., Cheung, W. W. L., Lu, Z., Yang, S., Guo, Z., Chen, M., et al. (2019). Age, growth, and abundance fluctuation of Jordan's damsel *Teixeirichthys Jordani* (Actinopterygii: Perciformes: Pomacentridae) in the southern Taiwan Strait. *Acta Ichthyol. Piscat.* 49, 243–250. doi: 10.3750/AIEP/02571

Ju, P. L. (2018). *Study on Fishery Ecosystem in the Southern Taiwan Strait based on Ecopath with Ecosim*. Ph.D. thesis, Xiamen University, Xiamen.

Ju, P. L., Yang, L., Lu, Z. B., Yang, S. Y., Du, J. G., Zhong, H. Q., et al. (2016). Age, growth, mortality and population structure of silver croaker *Pennahia argentata* (Houttuyn, 1782) and red bigeye *Priacanthus macracanthus* Cuvier, 1829 in the north-central Taiwan Strait. *J. Appl. Ichthyol.* 32, 652–660. doi: 10.1111/jai.13053

Kanamori, Y., Takasuka, A., Nishijima, S., and Okamura, H. (2019). Climate change shifts the spawning ground northward and extends the spawning period of chub mackerel in the western North Pacific. *Mar. Ecol. Prog. Ser.* 624, 155–166. doi: 10.3354/meps13037

Kimura, D., Balsiger, J., and Ito, D. (1984). Generalized stock reduction analysis. *Can. J. Fish. Aquat. Sci.* 41, 1325–1333. doi: 10.1139/f84-162

Kimura, D., and Tagart, J. (1982). Stock reduction analysis, another solution to the catch equations. *Can. J. Fish. Aquat. Sci.* 39, 1467–1472. doi: 10.1139/f82-198

Lam, V. W., and Pauly, D. (2019). Status of fisheries in 13 Asian large marine ecosystems. *Deep Sea Res. II.* 163, 57–64. doi: 10.1016/j.dsr2.2018.09.002

Li, G., Chen, X., Lei, L., and Guan, W. (2014). Distribution of hotspots of chub mackerel based on remote-sensing data in coastal waters of China. *Int. J. Remote Sens.* 35, 1–23. doi: 10.1080/01431161.2014.916057

Li, Y., Pan, L., Guan, W., and Jiao, J. (2018). Simulation study of individual-based on interannual fluctuation of chub mackerel's (*Scomber japonicus*) recruitment in the East China Sea. *Haiyang Xuebao* 40, 87–95.

Liao, C. P., Huang, H. W., and Lu, H. J. (2019). Fishermen's perceptions of coastal fisheries management regulations: key factors to rebuilding coastal fishery resources in Taiwan. *Ocean Coast. Manage.* 172, 1–13. doi: 10.1016/j.ocecoaman.2019.01.015

Liu, W. H. (2013). Managing the offshore and coastal fisheries in Taiwan to achieve sustainable development using policy indicators. *Mar. Pol.* 39, 162–171. doi: 10.1016/j.marpol.2012.11.001

Martell, S., and Froese, R. (2013). A simple method for estimating MSY from catch and resilience. *Fish Fish.* 14, 504–514. doi: 10.1111/j.1467-2979.2012.00485.x

Oozeki, Y., Carranza, M. Ñ, Takasuka, A., Dejo, P. A., Kuroda, H., Malagas, J. T., et al. (2019). Synchronous multi-species alternations between the northern Humboldt and Kuroshio Current systems. *Deep Sea Res. II* 159, 11–21. doi: 10.1016/j.dsr2.2018.11.018

Palomares, M. L. D., Froese, R., Derrick, B., Nöel, S.-L., Tsui, G., Woroniak, J., et al. (2018). *A Preliminary Global Assessment of the Status of Exploited Marine Fish and Invertebrate Populations. A Report Prepared by the Sea Around Us for OCEANA*. Vancouver: The University of British Columbia.

Rice, J. C., and Garcia, S. M. (2011). Fisheries, food security, climate change and biodiversity: characteristics of the sector and perspectives of emerging issues. *ICES J. Mar. Sci.* 68, 1343–1353. doi: 10.1093/icesjms/fsr041

Saraux, C., Beveren, E. V., Brosset, P., Queiros, Q., Bourdeix, J., Dutto, G., et al. (2019). Small pelagic fish dynamics: a review of mechanisms in the Gulf of Lions. *Deep Sea Res. II* 159, 52–61. doi: 10.1016/j.dsr2.2018.02.010

Shao, K. T. (2011). *Investigation and Planning of Fishery Resources Conservation Zones and Rare Species*. Taipei: Fishery Agency.

Tao, Y., Mingru, C., Jianguo, D., Zhenbin, L., and Shengyun, Y. (2012). Age and growth changes and population dynamics of the black pomfret (*Parastromateus niger*) and the frigate tuna (*Auxis thazard thazard*), in the Taiwan Strait. *Lat. Am. J. Aquat. Res.* 40, 649–656. doi: 10.3856/vol40-issue3-fulltext-13

Yasuda, T., Yukami, R., and Ohshimo, S. (2014). Fishing ground hotspots reveal long-term variation in chub mackerel *Scomber japonicus* habitat in the East China Sea. *Mar. Ecol. Prog. Ser.* 501, 239–250. doi: 10.3354/meps10679

Yatsu, A. (2019). Review of population dynamics and management of small pelagic fishes around the Japanese Archipelago. *Fish. Sci.* 85, 611–639. doi: 10.1007/s12562-019-01305-3

Yu, W., Guo, A., Zhang, Y., Chen, X., Qian, W., and Li, Y. (2018). Climate-induced habitat suitability variations of chub mackerel *Scomber japonicus* in the East China Sea. *Fish. Res.* 207, 63–73. doi: 10.1016/j.fishres.2018.06.007

Zimmermann, F., and Werner, K. M. (2019). Improved management is the main driver behind recovery of Northeast Atlantic fish stocks. *Front. Ecol. Environ.* 17, 93–99. doi: 10.1002/fee.2002

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Marine Science

ORIGINAL RESEARCH
published: 31 July 2020
doi: 10.3389/fmars.2020.00616

Assessment of 12 Fish Species in the Northwest Pacific Using the CMSY and BSM Methods

Yibang Wang[1,2,3], Yuanchao Wang[1,2,4], Cui Liang[1,2,5], Hui Zhang[1,2,4,5]* and Weiwei Xian[1,2,4,5]*

[1] CAS Key Laboratory of Marine Ecology and Environmental Sciences, Institute of Oceanology, Chinese Academy of Sciences, Qingdao, China, [2] Laboratory for Marine Ecology and Environmental Science, Qingdao National Laboratory for Marine Science and Technology, Qingdao, China, [3] Qingdao University of Science and Technology, Qingdao, China, [4] University of Chinese Academy of Sciences, Beijing, China, [5] Center for Ocean Mega-Science, Chinese Academy of Sciences, Qingdao, China

OPEN ACCESS

Edited by:
Athanassios C. Tsikliras,
Aristotle University of Thessaloniki,
Greece

Reviewed by:
Gianpaolo Coro,
Istituto di Scienza e Tecnologie dell'Informazione "Alessandro Faedo" (ISTI), Italy
Donna Dimarchopoulou,
Aristotle University of Thessaloniki,
Greece

***Correspondence:**
Hui Zhang
zhanghui@qdio.ac.cn
Weiwei Xian
wwxian@qdio.ac.cn

Specialty section:
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

Received: 04 February 2020
Accepted: 06 July 2020
Published: 31 July 2020

Citation:
Wang Y, Wang Y, Liang C, Zhang H and Xian W (2020) Assessment of 12 Fish Species in the Northwest Pacific Using the CMSY and BSM Methods. Front. Mar. Sci. 7:616. doi: 10.3389/fmars.2020.00616

We assessed 12 marine fish species in the Northwestern Pacific exploited by Japanese fisheries, using published catch time series, CPUE data and the CMSY and BSM methods. The results showed that one stock was severely depleted, three stocks were outside of safe biological limits, three stocks were fully/overfished, three stocks were recovering, while the other two stocks were in good condition. These results match those of previous research on the status of fish species in the Northwestern Pacific, where overfishing is becoming increasingly apparent. We used the CMSY/BSM assessments as a basis for suggestions to assist in the management and rebuilding of fishery resources in this area.

Keywords: east coast of Japan, overfishing, stock assessment, CMSY/BSM methods, data-sparse stock

INTRODUCTION

Concern about overfishing is a global issue, but the successful management of well-assessed fisheries has effectively reduced the impact of fishing in developed regions and countries such as Europe and the United States, respectively (Hilborn and Ovando, 2014; Froese et al., 2018). However, for other regions, e.g., in East Asia, not enough is known about the status of fisheries, which hinders predictions on the future sustainability of global fisheries (Ichinokawa et al., 2017).

Japan is one of the most important fishing countries in the world, with the fifth largest catch; according to the Food and Agriculture Organization (FAO), Japan accounts for 5% of the world marine catch (FAO, 2016). In 1997, the Japanese Fisheries Agency introduced fisheries management, combining total allowable catch (TAC) with traditional effort limitations (Makino, 2011). Every year since 1998, the Fisheries Research Agency of Japan (FRA) has been assessing 84 stocks of 52 important fish species, including the species studied here, i.e., *Clidoderma asperrimum*, *Engraulis japonicus*, *Etrumeus teres*, *Theragra chalcogramma*, *Glossanodon semifasciatus*, *Laemonema longipes*, *Lophius litulon*, *Sardinops melanostictus*, *Scomber australasicus*, *Sebastolobus macrochir*, *Tanakius kitaharae,* and *Trachurus japonicus* (Ichinokawa et al., 2017). Thus, the data used in our research are considered reliable and the evaluation results can be compared with their reports.

Catch-MSY was proposed as a new method to estimate the maximum sustainable yield (MSY) and related indicators (notably carrying capacity k, and intrinsic rate of population growth r, or 'resilience') using only catch data and a Monte-Carlo approach (Martell and Froese, 2013). Froese et al. (2017) improved on this method, now called CMSY, to address its shortcomings, including the selection of the optimal combination of r and k, and the provision of default priors for relative stock size at the first and end year of the catch data time series. It also addressed the issue of 'depensation' i.e., the reduction of r that often occurs at very low stock sizes, and added a routine for a Bayesian state-space implementation of the Schaefer model (BSM), which allowed incorporating time series of relative biomass (e.g., CPUE data) into the analyses to reduce the uncertainty of the estimates of MSY and related statistics.

In this study we applied the CMSY and BSM methods (Froese et al., 2017) to 12 species caught by Japanese fishing vessels in the northwestern Pacific, to assess the status of their fisheries.

MATERIALS AND METHODS

Data Sources

The data source and main sources of available information on the 12 fish stocks investigated here are summarized in **Table 1**. The data were released by the Fisheries Agency of Japan in 2018[1].

Declaration Statement

Our manuscript was based on survey cruise data, and no live vertebrates or higher invertebrates were involved; thus we believe that an ethical review process was not required for our study.

General Description of the CMSY and BSM Methods

The CMSY catch-only approach, applying advanced Monte-Carlo filtering, can be used to produce proxies for MSY, biomass that can produce MSY (B_{msy}), fishing pressure that can produce MSY (F_{msy}). Also, CMSY estimates biomass and related fishery reference points such as relative stock size (B/B_{msy}) and exploitation (F/F_{msy}), based on a catch time series and a measure of the productivity or 'resilience' of the species. Furthermore, a Bayesian state-space Schaefer surplus production model (BSM) is included in the CMSY software and produces refined stock status estimates, which requires catch and effort or an index of biomass or relative abundance (e.g., catch per unit of effort) as input (Froese et al., 2017, 2018).

It is the goal for CMSY to combine information on the stock's productivity and exploitation history with data from surveys and official catch reports. CMSY can also account for gaps (or absence) in abundance information, which is the main advantage compared to other models (Froese et al., 2018).

A time series of catch can be regarded as the product of the available biomass times its productivity; thus, if two of the three variables are known (that is, catch, biomass and productivity) the third variable can be estimated (Froese et al., 2017). Given a prior range of unexploited biomass (assumed to represent carrying capacity, or k) and a prior range of r, the CMSY method uses Monte-Carlo approach to detect viable or 'feasible' r–k pairs. A pair of r-k values is considered 'feasible' if the biomass trajectory that can be computed from it is compatible with the observed catch time series, if the predicted biomasses do not become negative and remain compatible with the prior estimates of the relative biomass range at the beginning and end of the respective time series. Under these conditions, a feasible set of r–k pairs would normally generate a relatively small triangular cloud in log space, from which a single r-k pair can be selected as optimal (Froese et al., 2017). For validation, the predictions of the CMSY method were compared with simulated data with known parameters and biomass data (Froese et al., 2017).

Here, we give the basic equations on the CMSY approach, while further details on the CMSY estimation framework and concepts are given in the detailed CMSY documentation by Froese et al. (2017).

The basic biomass dynamics are described by Equation (1):

$$B_{t+1} = B_t + r(1 - B_t/k)B_t - C_t \quad (1)$$

where B_{t+1} is the exploited biomass in the subsequent year $t + 1$, B_t is the current biomass, r is the intrinsic rate of population increase, k is the carrying capacity (assumed equivalent to the unexploited population size) and C_t is the catch in year t.

When the biomass of a stock is severely depleted, and falls below 0.25 k, Equation (1) is changed to Equation (2):

$$B_{t+1} = B_t + (4rB_t/k)(1 - B_t/k)B_t - C_t | B_t/k < 0.25 \quad (2)$$

where the term $4B_t/k$ assumes a linear decline of recruitment at less than half of the biomass capable of producing MSY.

Determining the Boundaries of the r-k Space

To determine priors r for the 12 species being evaluated, the resilience levels provided by FishBase (Froese and Pauly, 2019) were converted to r-ranges (**Table 2**).

The prior ranges of k were then estimated based on three hypotheses: (1) the size of the unexploited population k is greater than the maximum catch in the time series, thus the lower limit of k is determined by this maximum catch; (2) MSY is expressed as a fraction of the available biomass, and the size of this fraction depends on the productivity of the population. Thus, dividing the maximum catch by the upper and lower limits of r should provide reasonable limits for the upper and lower values of k; (3) the maximum catch will constitute a greater proportion of k in severely depleted stocks than in stocks that are lightly depleted.

These considerations are summarized in Equations (3) and (4). Given known values of k, the appropriate range of the catch/productivity ratio was empirically determined using simulation data (Froese et al., 2017).

$$k_{low} = \max(C)/r_{high};\ k_{high} = 4\max(C)/r_{low} \quad (3)$$

where k_{low} and k_{high} are the lower and upper bounds of the prior range of k, $max(C)$ is the maximum catch in the time series, and r_{low} and r_{high} are the lower and upper boundaries of the range of r values that the CMSY method will explore.

$$k_{low} = 2\max(C)/r_{high};\ k_{high} = 12\max(C)/r_{low} \quad (4)$$

where the variables and parameters are defined as in Equation (3) (Froese et al., 2017).

[1] https://www.jfa.maff.go.jp/e/index.html

TABLE 1 | Summary of data available for the stock assessments presented here.

Scientific name (Common name)	Region	Catch	Additional data	Method
Clidoderma asperrimum (roughscale sole)	Northeast Japan Sea	1972–2017	CPUE (1972–2017)	BSM and CMSY
Engraulis japonicus (Japanese anchovy)	East coast of Japan	1989–2017	SSB (1989–2017)	BSM and CMSY
Etrumeus teres (Pacific round herring)	Southeast Japan Sea	1985–2017	SSB (1985–2017)	BSM and CMSY
Gadus chalcogrammus (walleye epollock)	Northeast Japan Sea	1981–2017	SSB (1981–2017)	BSM and CMSY
Glossanodon semifasciatus (deep-sea smelt)	East coast of Japan	1980–2016	CPUE (1980–2016)	BSM and CMSY
Laemonema longipes (longfin codling)	Northeast Japan Sea	1989–2017	None	CMSY
Lophius litulon (yellow goosefish)	East coast of Japan	1991–2017	CPUE (1991–2017)	BSM and CMSY
Sardinops melanostictus (South American pilchard)	East coast of Japan	1975–2017	CPUE (1975–2017)	BSM and CMSY
Scomber australasicus (blue mackerel)	East coast of Japan	1982–2017	SSB (1982–2017)	BSM and CMSY
Sebastolobus macrochir (broadbanded thornyhead)	Northeast Japan Sea	1972–2017	CPUE (1972–2017)	BSM and CMSY
Tanakius kitaharae (willowy flounder)	East coast of Japan	1973–2017	None	CMSY
Trachurus japonicus (Japanese jack mackerel)	East coast of Japan	1982–2017	CPUE (1982–2017)	BSM and CMSY

All data originated from Catch and CPUE from Fisheries Agency of Japan.

TABLE 2 | Ranges suggested by FishBase (Froese and Pauly, 2019) for population growth rate (year^{-1}).

Resilience (*r*)	Prior *r* range	Range assumed for the stocks in Table 1
High	0.6–1.5	*E. japonicus*; *G. semifasciatus*
Medium	0.2–0.8	*C. asperrimum*; *E. teres*; *S. melanostictus*; *S. australasicus*; *T. japonicus*
Low	0.05–0.5	*G. chalcogrammus*; *L. longipes*; *L. litulon*; *S. macrochir*; *T. kitaharae*
Very low	0.015–0.1	—

Setting Prior Biomass Ranges

To provide a prior estimate of relative biomass at the beginning and end of the time series and for the (optional) intermediate years, several possible biomass ranges were selected, based on the assumed depletion level; see **Tables 3**, **4** and Froese et al. (2017).

Table 3 presents the recommended B_{start}/k range for the 12 stocks evaluated. Studies have shown that global fishing efforts, expressed in terms of total engine power and the number of catch days (kilowatt days) in a year, remained roughly unchanged from 1950 to 1970 and then steadily increased to the present (Anticamara et al., 2011).

Thus, we set B_{start}/k of *C. asperrimum* (Hattori et al., 2008), *G. chalcogramma* (Nishimura et al., 2002), *G. semifasciatus* (Nashida et al., 2007), and *S. australasicus* (Fisheries Agency of Japan, 2018) as low (B_{start}/k = 0.4–0.8), and *E. japonicus* (Wada, 1997), *E. teres* (Nyuji and Takasuka, 2017), *L. longipes* (Fisheries Agency of Japan, 2018), *L. litulon* (Fisheries Agency of Japan, 2018), *S. melanostictus* (Watanabe et al., 1995), *S. macrochir* (Noranarttragoon et al., 2011), and *T. japonicus* (Fisheries Agency of Japan, 2018) as very low (B_{start}/k = 0.6–1).

The B_{start}/k for *T. kitaharae* was set at medium depletion (0.2–0.6; **Table 3**) to force its biomass at the start of the assessment period to be 'medium' (Fisheries Agency of Japan, 2018).

TABLE 3 | Suggested fractions B_{start}/k for the period before catch data became available*.

Depletion	Suggested prior	Range assumed for the stocks in Table 1
Very low	0.6–1	*E. japonicus*; *E. teres*; *L. longipes*; *L. litulon*; *S. melanostictus*; *S. macrochir*; *T. japonicus*
Low	0.4–0.8	*C. opilio*; *C. asperrimum*; *G. semifasciatus*; *G. chalcogrammus*; *P. olivaceus*; *S. australasicus;*
Medium	0.2–0.6	*T. kitaharae*
Strong	0.01–0.4	—
Very strong	0.01–0.2	—

*See **Supplementary Material** to Froese et al. (2017).*

TABLE 4 | Suggested ranges of the fraction B_{end}/k for the period prior to catches being available*.

Depletion	Suggestion	Assumed level of final depletion for the stocks in Table 1
Low	0.4–0.8	—
Medium	0.2–0.6	*E. teres*; *L. longipes*; *G. chalcogrammus*; *T. kitaharae*; *L. litulon*; *S. macrochir*
Strong	0.01–0.4	*G. semifasciatus*; *S. melanostictus*; *S. australasicus*; *T. japonicus*
Very strong	0.01–0.2	*C. asperrimum*; *E. japonicus*

*See **Supplementary Material** to Froese et al. (2017).*

Table 4 presents the recommended B_{end}/k range for the 12 stocks evaluated. Considering the results in published research papers for each of the species, we chose a 'very strong' depletion at the end of the time series (i.e., B_{end}/k = 0.01–0.2), for *C. asperrimum* (Hattori et al., 2008) and *E. japonicus* (Fisheries Agency of Japan, 2018). For the other species, we found sources suggesting 'strong' depletions (B_{end}/k = 0.01–0.4): *G. semifasciatus* (Nashida et al., 2007), *S. melanostictus* (Fisheries Agency of Japan, 2018), *S. australasicus* (Fisheries Agency of Japan, 2018), and *T. japonicus* (Fisheries Agency of Japan, 2018) (**Table 4**).

RESULTS

All 12 stocks were analyzed using the CMSY method. The BSM method was applied to 10 stocks with CPUE data (**Table 1**).

The blue mackerel (*Scomber australasicus*) is a widely distributed and commercially exploited species in Japanese coastal waters and we used it to illustrate the CMSY and BSM outputs (**Figure 1**). The results of the other species are presented in **Supplementary Materials**.

Figures 2, **3** visually summarize our results regarding the development of relative biomass, while **Tables 5**, **6** provide numerical information.

The figures of relative biomass (B/B_{msy}) clearly show that, in this area, 4 species were severely depleted and/or outside of safe biological limits in the last years with available data (2016–2017) (**Figures 2**, **3**). The figures of fishing pressure (F/F_{msy}) clearly present that 5 species were overexploited in the last years with available data (2016–2017) (**Figures 4**, **5**).

The fishing pressure (F/F_{msy}) – stock state (B/B_{msy}) plot clearly shows that, in the northwest Pacific, more than half of the species assessed are overexploited and/or outside of safe biological limits in the last years with available data (2016–2017) (**Figure 6**).

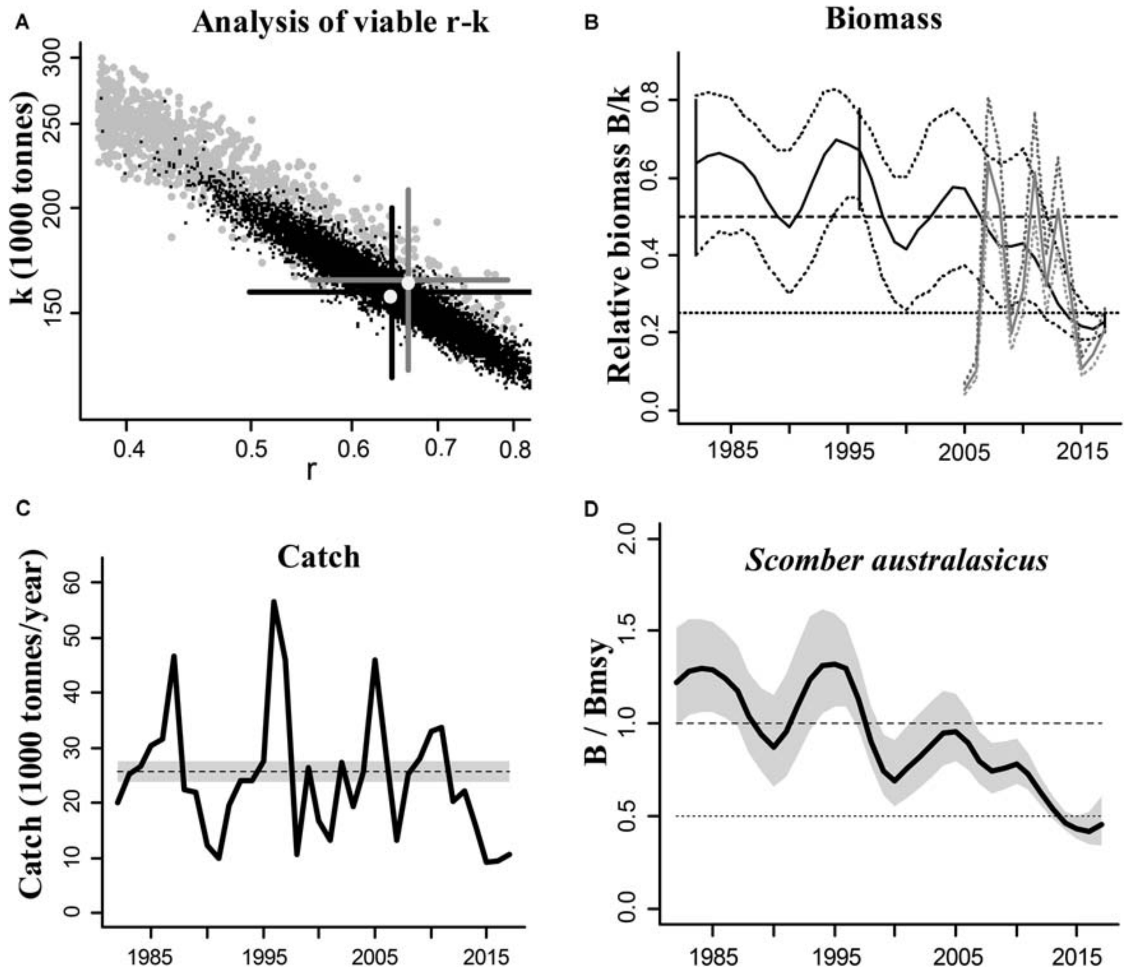


FIGURE 1 | Results of the CMSY and BSM analyses for the blue mackerel (*Scomber australasicus*) in the Northwestern Pacific (east coastal of Japan). **(A)** feasible r–k pairs found by CMSY (gray points) and BSM methods (black points). The optimal r–k pair estimated by CMSY and its approximate 95% confidence interval (CI) are represented by a gray cross, and the optimal r–k pair estimated by BSM and its approximate CI are represented by a black cross. In this example the estimates of the two methods are similar, which suggests that the results are reliable; **(B)** biomass trajectory estimated by CMSY (black line) and available abundance data scaled to the BSM estimate of k (gray line), along with the 2.5th and 97.5th percentiles. The vertical lines show the prior ranges for relative biomass. The dashed horizontal line indicates B_{msy} = 0.5 k, while the dotted horizontal line indicates half B_{msy} as the limit below which recruitment may be impaired; **(C)** catches relative to the BSM estimate of MSY and its CI; **(D)** estimated relative biomass trajectory (B/B_{msy}), with the gray area indicating uncertainty.

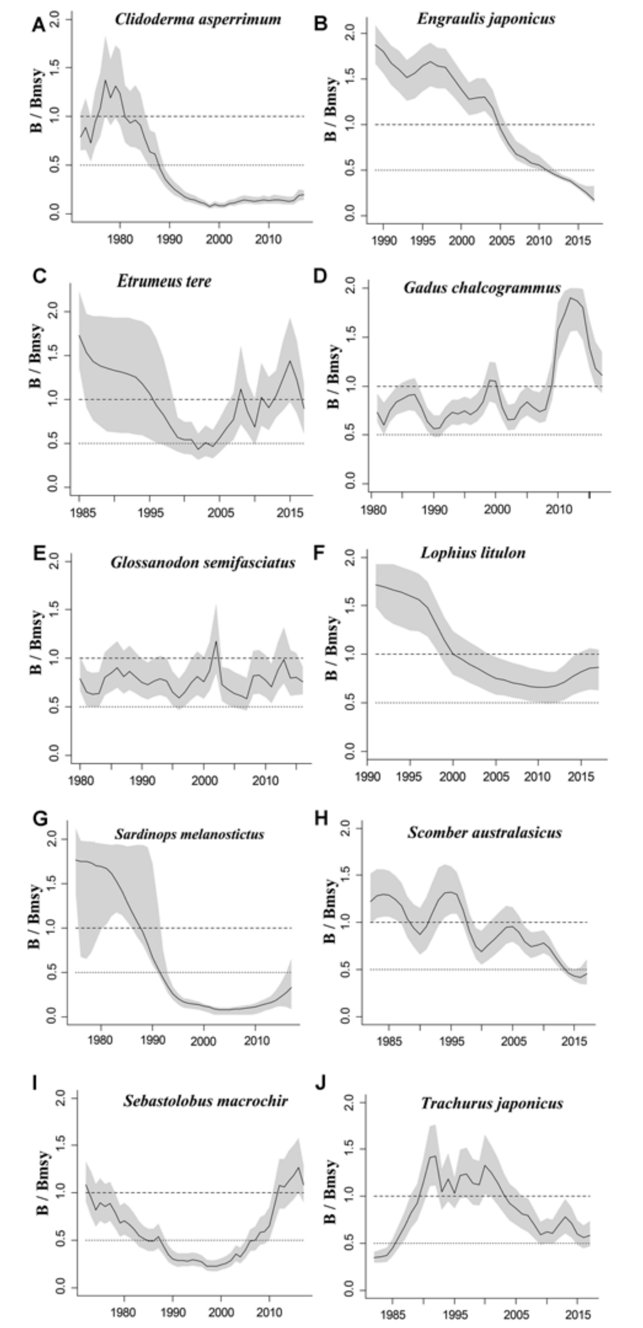


FIGURE 2 | Relative biomass (B/B_{msy}) trajectories generated by CMSY and BSM for 10 stocks with CPUE data.

Thus, stocks of the 12 species can be defined according to the B/B_{msy} of the last year of a time series (**Table 5**). **Table 6** summarizes *r*, *k*, *MSY*, F/F_{msy} and relative biomass, and provides estimates for the 12 species, as obtained by the CMSY and/or the BSM methods. Among the 12 stocks, 5 (42%) were subject to ongoing overfishing ($F/F_{msy} > 1$) and 4 stocks (33%) were outside of safe biological limits ($B/B_{msy} < 0.5$) or severely depleted ($B/B_{msy} < 0.2$) (**Table 6**). Three stocks (25%) were in critical condition, defined by being outside of safe biological limits. Altogether, 7 stocks (58%) were subject to unsustainable exploitation ($F/F_{msy} > 1$ or $B/B_{msy} < 0.2$). In contrast, only 4 stocks (33%) could be considered as being well managed and in good condition according to the analysis, i.e., recovering or being healthy and having a biomass above the one that can produce MSY (**Table 6**).

DISCUSSION

The results of our application of the CMSY and BSM methods to 12 fish species caught by Japanese fishing vessels in the northwestern Pacific are discussed below.

Roughscale Sole (*C. asperrimum*)

Roughscale sole (*C. asperrimum*), of the family Pleuronectidae, has a wide range in the northern Pacific, from China, Japan and the Kuril Islands to Canada and California, where the seabed is muddy and sandy (Tokranov and Orlov, 2003; see also Froese and Pauly, 2019). This species is important commercially to the offshore trawl fishery off northeastern Japan. Although trawling catches off the northeastern coast peaked at 6,329 tonnes in 1978 (Hattori et al., 2008), they declined sharply in 1990–2000 and catches were below 300 tonnes in 2010. Since 2003, fisheries managers in northeastern Japan have implemented a large-scale restoration program for benthic fish stocks, mainly through the protection of spawning populations via the designation of fisheries restricted areas for a certain period of time (Abe et al., 2013). The estimate of $B_{end}/k = 0.1$ indicated that the resource status of this species was highly depleted in 2017, while $B/B_{msy} = 0.2$ indicated that this species was severely depleted. The relative biomass reached its peak in 1978 and then declined sharply (**Figure 2A**), consistent with the results of Abe et al. (2013). There are only a few papers on the assessment of the roughscale sole at present (Abe et al., 2013), although they mainly focus on morphological and habitat characteristics. Thus, it is important to use CMSY and BSM, aiming to assess the current stock status and exploitation level and provide theoretical basis for fishery managers.

Japanese Anchovy (*E. japonicus*)

Japanese anchovy is mainly distributed in the western Pacific, including the south Sakhalin Islands, the Sea of Japan and the Pacific coast of Japan, and south to Guangdong and Taiwan (Froese and Pauly, 2019). Japanese anchovy is one of the most important fish species in Japan. It is thought to consist of three major stocks: (i) Pacific fish found mainly along the southern Pacific coast of Honshu and Shikoku; (ii) in the Tsushima Warm Current, mainly in the Sea of Japan and the East China Sea; and (iii) in the Seto Inland Sea (Zenitani and Kimura, 2007). Here, we considered Japanese anchovy is the first stock. Japanese anchovy began to be fished in the late 1980s. In 1989, the annual landings of the species amounted to 40,000 tonnes, and in 1995 they increased dramatically to 489,000 tonnes (Wada, 1997). In our research, the estimate $B_{end}/k = 0.09$ suggested that the resource

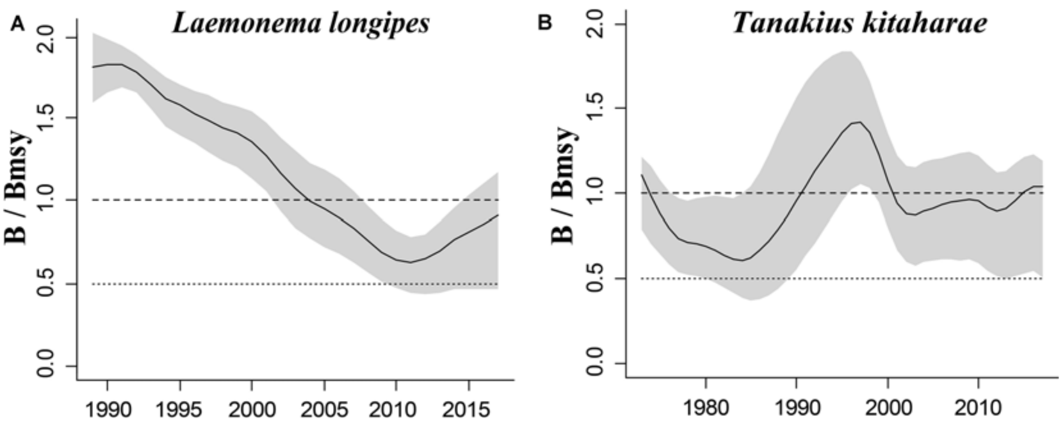


FIGURE 3 | Relative biomass (B/B_{msy}) trajectories generated by CMSY for 2 stocks without CPUE data.

TABLE 5 | Definition of fish stock status, based on B/B_{msy} and F/F_{msy} in the final year of a time series*.

B/B_{msy}	F/F_{msy}	Stock status
≥1	<1	Healthy stocks
0.5–1	<1	Recovering stocks
0.5–1	>1	Fully/overfished stocks
0.2–0.5	>1	Stocks outside of safe biological limits
<0.2	>1	Severely depleted stocks

*From Froese et al. (2016) and Froese et al. (2018), see also Garcia et al. (2018).

status of this species was strongly depleted in 2017, while the B/B_{msy} = 0.18 indicated that the stock is grossly overfished. The relative biomass of Japanese anchovy was on a declining trend from 1989 to 2017 (**Figure 2B**) and, even though the resilience of the species is relatively high, its biomass remained at an extremely low level owing to overfishing. Our results are in line with those of a report released by the fisheries agency in 2018 (Fisheries Agency of Japan, 2018). Yatsu (2019) reported the stock assessment of Japanese anchovy with data from 1905 to 2015 in the northwestern Pacific, suggesting that it is overfished, which is consistent with our result (**Table 7**).

Pacific Round Herring (*E. teres*)

The taxonomic status of Pacific round herring, here referred to as '*Etrumeus teres*' is currently unsettled, as it appears that the previously wide-ranging species referred to as *Etrumeus teres* as has been split into an Atlantic species, *E. sadina*, and a Pacific species, *E. micropus* (see Froese and Pauly, 2019). Pending a taxonomic revision of the genus *Etrumeus*, we continue to use *E. teres*. Pacific round herring is a coastal fish that is important in the seine net and other fisheries along the coasts of Japan. The total catch of Pacific round herring, mainly along the southern coast of Japan, has trended to increase 5000–55,000 tonnes since 1985 and remained above 37,000 tonnes from 2012 to 2015 (Nyuji and Takasuka, 2017). Indeed, round herring exhibits a relatively stable population dynamics over a long period of time (Oozeki et al., 2007). In this study, the parameter B_{end}/k = 0.45 indicated that the depletion of this species was moderate level in 2017, while the parameter B/B_{msy} = 0.90 indicated that the biomass of this

TABLE 6 | Estimates of *r*, *k*, *MSY*, relative biomass and status as obtained by CMSY and/or BSM method for 12 stocks exploited by Japanese fleets.

Scientific names	r (year^{-1})	k (10^3 t)	MSY (10^3 t/year)	B_{end}/k	B/B_{msy}	F/F_{msy}	Status
C. asperrimum	**0.61**	**14.7**	**2.26**	**0.1**	**0.2**	0.926	Outside of safe biological limits
E. japonicus	**1.04**	**1007**	**263**	**0.09**	**0.18**	3.4	Severely depleted stocks
E. teres	**0.48**	**200**	**24**	**0.45**	**0.90**	1.52	Fully/overfished stocks
G. chalcogrammus	**0.47**	**1928**	**227**	**0.56**	**1.11**	0.367	Healthy stocks
G. semifasciatus	**1.03**	**1.56**	**0.4**	**0.38**	**0.76**	0.595	Recovering stocks
L. longipes	0.34	343	29.4	0.46	0.91	0.438	Recovering stocks
L. litulon	**0.23**	**5.52**	**0.32**	**0.43**	**0.87**	1.81	Fully/overfished stocks
S. melanostictus	**0.64**	**12517**	**1999**	**0.16**	**0.33**	1.06	Outside of safe biological limits
S. australasicus	**0.66**	**164**	**27.2**	**0.23**	**0.46**	0.995	Outside of safe biological limits
S. macrochir	**0.26**	**3551**	**233**	**0.54**	**1.08**	0.639	Healthy stocks
T. kitaharae	0.28	1.58	0.11	0.52	1.04	1.09	Fully/overfished stocks
T. japonicus	**0.507**	**363**	**46**	**0.29**	**0.588**	0.888	Recovering stocks

The results in bold are based on the BSM method, i.e., catch and abundance data. Those not in bold are based on the catch data by CMSY.

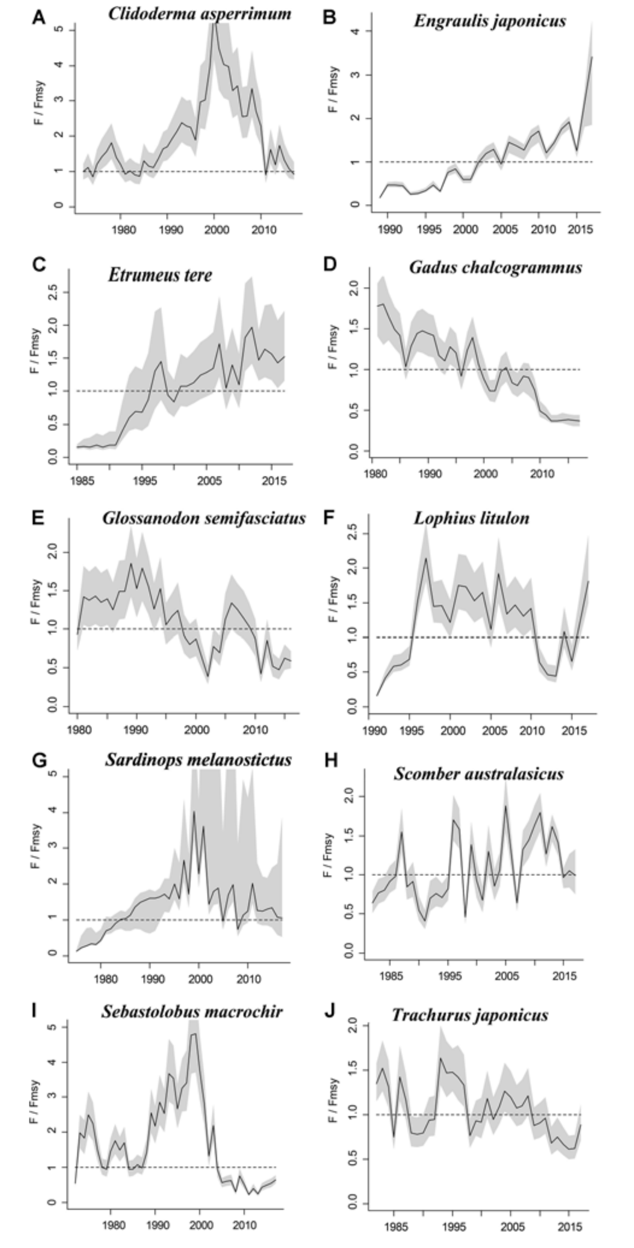


FIGURE 4 | Exploitation level (F/F_{msy}) trajectories generated by CMSY and BSM for 10 stocks with CPUE data.

species was at a nearly healthy level in 2017. The biomass of the species began to decline in 1985 and was at its lowest in 2002 before recovering gradually (**Figure 2C**). This result is consistent with a study by Oozeki et al. (2007). Suzuki et al. (2018) used a generalized additive mixed model (GAMM) to analyze the data of Pacific round herring from 1997 to 2013, however, they did not give the stock assessment clearly (**Table 7**).

Alaska Pollock (*G. chalcogrammus*)

Widely distributed in the northern Pacific (Froese and Pauly, 2019), Alaska pollock is an important commercial species in Japan (Nakatani, 1988). In Hokkaido and northern Honshu, catches of this species are obtained by trawling; from 1975 to the end of the 1980s, these catches remained at a high level, from 200,000 to 300,000 tonnes. However, after peaking at 290,000 tonnes in 1981, catches dropped below 200,000 tonnes. In the late 1990s, catches increased to 250,000 tonnes (Nishimura et al., 2002). The parameter B/B_{msy} = 1.11 indicated that the biomass of this species was at a healthy level in 2017. There are few studies on the stock assessment of Alaska pollock in the northwestern Pacific Ocean. Holsman et al. (2016) used multi-species statistical catch at age models (MSCAA) to assess the stock in the eastern Bering Sea with data from 1979 to 2012. They reported a fishing mortality of less than 0.2, suggesting this stock was healthy (Holsman et al., 2016), which is consistent with our result in **Figure 4D** and **Table 7**.

Deep-sea Smelt (*G. semifasciatus*)

Deep-sea smelt is distributed in the northwestern Pacific, especially in southern Japan. It is found on the shelf edge and in the upper bathyal, where the seabed is sandy and muddy (Froese and Pauly, 2019). It is one of the most important benthic fish in the waters off the central and southern Pacific coasts of Japan. In 2004, Japanese boats caught just under 1,000 tonnes of this fish. Total catches in Pacific waters are at low levels (half of their 1996 peak) with a slight downward trend (Nashida et al., 2007). In this study, B_{end}/k = 0.38 indicated that the resource depletion of this species was strong in 2016; however, the B/B_{msy} and F/F_{msy} indicated that it was recovering in 2016. Moreover, its relative biomass (B/B_{msy}) fluctuated between 0.5 and 1.0 (**Figure 2E**). Our assessment is consistent with the results published by the Fisheries Agency of Japan (2018). Beyond that, there is no report on the stock assessment of deep-sea smelt until now.

Longfin Codling (*L. longipes*)

Longfin codling is distributed in the northern Pacific, from central Japan to Okhotsk and to the Aleutian Islands and Bering Sea, and the species is found on the continental slope (Froese and Pauly, 2019). Catches were low in the 1980s and the species was used as an alternative to Alaska pollock in the 1990s, when it was caught as a primary target. The catch hovered between 22,000 and 38,000 tonnes from 1992 to 1999, reached a record high of 48,000 tonnes in 2000, dropped in 2011 owing to the earthquake and recovered in 2012. However, after 2016, it decreased again (Fisheries Agency of Japan, 2018). According to the CMSY analysis, the species was recovering in 2017 (**Table 6**). The relative biomass trends of longfin codling are similar to those of the Fisheries Agency of Japan (2018) (**Figure 3A**). Currently, the research on the stock assessment of longfin codling is still not well developed, so it is useful and informative to apply various assessment models to assess its current status.

Yellow Goosefish (*L. litulon*)

Yellow goosefish is mainly distributed in the northwestern Pacific, including Japan and Korea, and in the Yellow and East China Seas (Froese and Pauly, 2019). In Japan, its catch was small compared with that of other commercially exploited fish (Yoneda et al., 2001). After 1991, the catch started to increase,

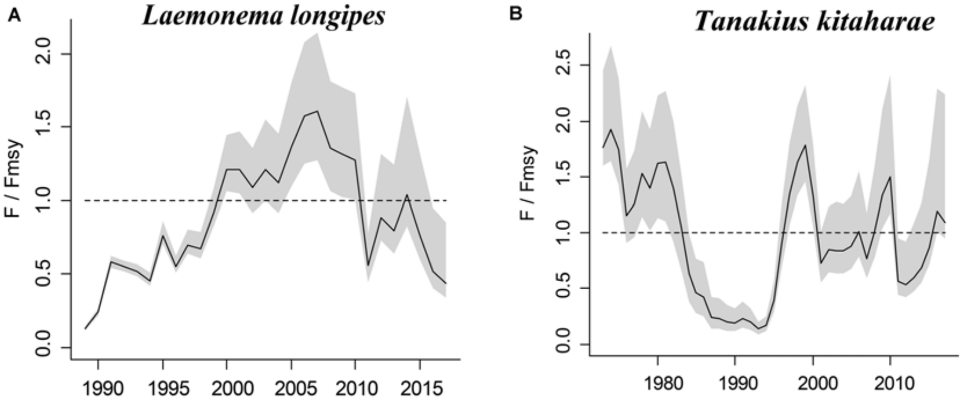


FIGURE 5 | Exploitation level (F/F_{msy}) trajectories generated by CMSY for 2 stocks without CPUE data.

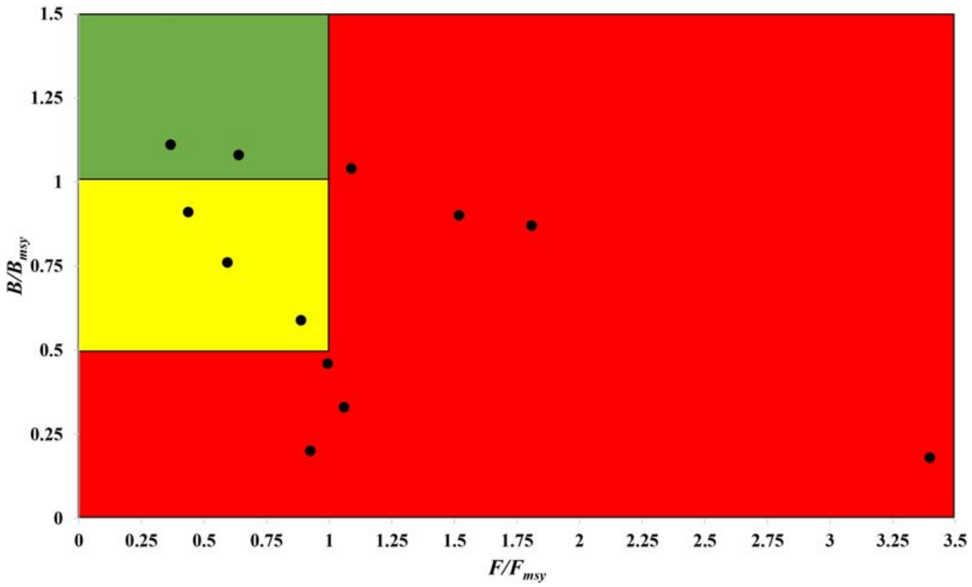


FIGURE 6 | Presentation of 12 stocks in the northwest Pacific in a pressure (F/F_{msy}) – status (B/B_{msy}) plot, for the last years with available data (2016–2017). Red area: stocks that are being overfished or are outside of safe biological limits; yellow area: recovering stocks; green area: stocks subject to sustainable fishing pressure and of a healthy stock biomass that can produce high yields close to MSY.

but it dropped in 2011 because of an earthquake (Fisheries Agency of Japan, 2018); relative biomass decreased in a similar manner (**Figure 2F**). According to the CMSY analysis, the species was overfished in the last year with available data (2017) (**Table 6**). There was no research to report the assessment of yellow goosefish in the same waters. But in China's coastal seas, Zhai and Pauly (2019) reported low current biomass of the yellow goosefish in 2019 using the CMSY method, owing to the high fishing mortality exerted on the stock.

South American Pilchard (*S. melanostictus*)

South American pilchard, or 'Pacific sardine,' is widely distributed in the Indo-Pacific, from southern Africa to the eastern Pacific. Three lineages were confirmed through cluster and parsimony analyses of haplotypic divergences: southern Africa (*S. ocellatus*) and Australia (*S. neopilchardus*); Chile (*S. sagax*) and California (*S. caeruleus*); and Japan (*S. melanostictus*) (Froese and Pauly, 2019). The lineage relating to Japan (*S. melanostictus*) is discussed here. The catch of South American pilchard began to decline after 1989, peaking at 5.43 million tonnes in 1988; dropping from 1989 to 2.49 million tonnes in 1992 (Watanabe et al., 1995); and remaining low at around 100,000 tonnes from 2002 to 2009. Since then, with the decrease in fishing pressure from 2010 to 2014, caused by the 2011 earthquake, the stocks increased to more than 1 million tonnes in 2014 (Fisheries Agency of Japan, 2018). The parameter $B_{end}/k = 0.16$ indicated that the biomass of this species was depleted in 2017, and the estimate of $B/B_{msy} = 0.33$ indicated that the species had been outside of safe biological limits. Our results for the relative biomass of the species (**Figure 2G**) are consistent with data released by the Fisheries Agency of Japan (2018). Moreover, the assessment of south American pilchard was reported in 2009. The authors used cohort analysis to assess the stock status with data from 1953 to 2006 and their results suggested that the collapse of the south American pilchard stock in the 1990s was caused by fishing mortality (Ohshimo et al., 2009). This is consistent with our results, which could be confirmed by **Figures 2G**, **4G**.

Blue Mackerel (*S. australasicus*)

Blue mackerel lives in the coastal waters of the western Pacific, Australia and New Zealand, the northwestern and eastern Pacific, the northern and southern Indian Ocean to the Red Sea, and the northeastern Pacific near Hawaii and Mexico (Froese and Pauly, 2019). The catch of blue mackerel in Japan before 1981 was much lower than in recent years. The biomass of blue mackerel was over 100,000 tonnes in 1995. In 2006, it reached a record high, but, after 2011, it showed a decreasing trend (Fisheries Agency of Japan, 2018). Our result suggested that the biomass of this species was at an extremely low level ($B_{end}/k = 0.23$) and that it was being outside of safe biological limits in 2017 ($B/B_{msy} = 0.46$). Fluctuations in the relative biomass of blue mackerel (**Figure 2H**) were consistent with those reported by the Fisheries Agency of Japan (2018). On the contrary, Zhang and Chen (2020) reported a healthy stock status for the blue mackerel in the Pacific Ocean by using virtual population analysis and yield per recruit with data from 1995 to 2015 (**Table 7**). One of the reasons is that the study area of the assessment is different, i.e., Zhang and Chen (2020) evaluate the whole Pacific Ocean, while this study evaluates Japan's coastal area.

Broadbanded Thornyhead (*S. macrochir*)

Broadbanded thornyhead is widely distributed in the northern Pacific, from Sagami Bay, Japan, to the southern Kuril Islands and off Sakhalin, Russia (Froese and Pauly, 2019). It is a high-value fishery and a key target for small and medium trawl fisheries along Japan's Pacific coast north of Honshu, whose catches began to decline in 1975 (Noranarttragoon et al., 2011). Catches of the species fell from 1,292 tonnes in 1983 to 274 tonnes in 1992, owing to a strong biomass decline (Koya et al., 1995); the catch in 2014 was about one-sixth of what it had been in the late 1970s (Sakaguchi et al., 2014). As the Japanese government began to implement a resource recovery plan in 2001, the biomass of broadbanded thornyhead began to increase (Fisheries Agency of Japan, 2018). Correspondingly, the changes in the relative biomass of this species in this study (**Figure 2I**) were related to the measures taken by the Japanese government. Thus, the resource status of this species could be considered healthy (**Table 6**). Currently, there is no report on the stock assessment of broadbanded thornyhead.

Willowy Flounder (*T. kitaharae*)

Willowy flounder is mainly distributed in the northwestern Pacific and inhabits muddy seabeds (Froese and Pauly, 2019). Its catch reached more than 210 tonnes in the early 1970s but declined to a low level from 1980 to 1990. Catch began to increase sharply in the mid-1990s, reaching more than 240 tonnes in

TABLE 7 | Comparison of fishery resource assessment studies for twelve fish species.

Scientific names	Assessment Method	Assessment Time	Assessment Result	Comparison with this study	Region	References
C. asperrimum	None	None	None	None	None	None
E. japonicus	Virtual population analysis (VPA)	1905–2015	Overfished	Consistent	Northwestern Pacific Ocean	Yatsu, 2019
E. teres	Generalized additive mixed model (GAMM)	1997–2013	None	None	East China and Japan Seas	Suzuki et al., 2018
G. chalcogrammus	Multi-species statistical catch at age models (MSCAA)	1979–2012	Healthy	Consistent	Eastern Bering Sea (United States).	Holsman et al., 2016
G. semifasciatus	None	None	None	None	None	None
L. longipes	None	None	None	None	None	None
L. litulon	CMSY and BSM	2013–2014	Overfished	Consistent	Bohai and yellow seas	Zhai and Pauly, 2019
S. melanostictus	Cohort analysis	1953–2006	Overfished	Consistent	The Sea of Japan and East China Sea	Ohshimo et al., 2009
S. australasicus	Virtual population analysis (VPA) Yield per recruit (YPR)	1995–2015	Healthy	Inconsistent	Pacific Ocean	Zhang and Chen, 2020
S. macrochir	None	None	None	None	None	None
T. kitaharae	None	None	None	None	None	None
T. japonicus	Cohort analysis	1965–1995	Overfished	Consistent	Korea and adjacent waters	Zhang and Lee, 2001

1998–1999, a record high. Since then, catches have declined, falling below 100 tonnes in 2001, then again increasing to 144 tonnes in 2009 and 160 tonnes in 2010. After 2011, the impact of earthquakes decreased, and catches of 139 tonnes were made in 2016 and of 127 tonnes in 2017 (Fisheries Agency of Japan, 2018), with a similar trend in the relative biomass of willowy flounder (**Figure 3B**). In 2017, the relative (B/B_{msy} = 1.04) and end biomass (B_{end}/k) of willowy flounder was relatively high, suggesting that it was fully/overfished. There is no research that can be compared with our assessment at present.

Japanese Jack Mackerel (*T. japonicus*)

Japanese jack mackerel is widely distributed in the northern Pacific (Froese and Pauly, 2019). Its resources increased in the 1980s, rising from 140,000 to a high level of 160,000 tonnes in the mid-1990s, but declined from 1997 to below 100,000 tonnes after 2006. The biomass of the stocks in 2017 was 43,000 tonnes (Fisheries Agency of Japan, 2018). In this study, the parameters B_{end}/k = 0.29 and B/B_{msy} = 0.588 suggested that the biomass was relatively low (**Figure 2J**), and that the species was recovering, which is consistent with the assessment given by the Fisheries Agency of Japan (2018), based on the Acceptable biological catch (ABC) estimation. In addition, Japanese jack mackerel was assessed in Korea and adjacent waters with data from 1965 to 1995, based on Schaefer (1954) and Fox (1970) production models and Biomass-based cohort analysis (**Table 7**). The main findings were that biomass (B) was 50% lower than $B_{30\%}$ in 1995 and the fishing mortality (F) was high in 1993 (Zhang and Lee, 2001), which are similar with our results (see in **Figures 2J**, **4J**).

CONCLUSION

CMSY is a Monte-Carlo method that estimates fisheries reference points (MSY, F_{msy}, B_{msy}) as well as relative stock size (B/B_{msy}) and exploitation (F/F_{msy}). The Bayesian state-space implementation of the Schaefer surplus production model (BSM) is the advanced part of the CMSY package. Compared to other implementations of surplus production models, the main advantage of BSM is that it focuses on informative priors and it accepts fragmented abundance data. However, the CMSY and BSM methods do not consider other factors, such as environmental shifts or the interaction among stocks. Thus, it would be advisable to use the CMSY and BSM methods along with other models or multispecies approaches to evaluate the stocks more accurately and in a more holistic way.

The Japanese fisheries have great potential for rapid recovery and biomasses can be rebuilt by adjusting the fishing intensity to appropriate levels. We expect that assessments using the CMSY and BSM methods will contribute to improvements in the management of Japan's fisheries and management systems. Also, they should help us gain a more detailed understanding of the state of global fisheries stocks.

During the 1990s and early 2000s, overfishing prevented the recovery of the Japanese Pacific stocks of *Clidoderma asperrimum*, *Engraulis japonicus*, *Etrumeus teres*, *Lophius litulon*, *Sardinops melanostictus*, *Scomber australasicus,* and *Tanakius kitaharae*. However, these stocks have been recovering since 2010, owing to the reduction of fishing pressure and the subsequent biomass increase. In the face of global climate change and international fishing pressure, the following three recommendations for management in Japan are proposed: (1) fishery scientists need to collect more accurate biological and environmental data, so that managers could benefit from more informative assessments of the status of ocean species; (2) it is important to incorporate environmental factors in stock assessments, especially for ocean stocks, which are sensitive to changes in environmental conditions; (3) it is crucial to establish an international framework for stock assessment and management with China, Korea, and Russia. These policies are expected to contribute to the sustainable management of fisheries in the future.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

YbW analyzed the data and completed the first draft. YcW and CL provided the guidance on data analysis and structure of our contribution, which was revised by HZ and WX. All authors contributed to the article and approved the submitted version.

FUNDING

The present work was supported by Creative Team Project of the Laboratory for Marine Ecology and Environmental Science, Qingdao National Laboratory for Marine Science and Technology (LMEES-CTSP-2018-1), the National Key Research and Development Project of China (2019YFD0902101), the National Natural Science Foundation of China (Nos. 41976094 and 31872568), the Natural Science Foundation of China–Shandong Joint Fund for Marine Ecology and Environmental Sciences (U1606404), the Key Deployment Project of Center for Ocean Mega-Science, Chinese Academy of Sciences (COMS2019Q14), and the Youth Innovation Promotion Association CAS.

ACKNOWLEDGMENTS

We are grateful for advice from Rainer Froese on the use of the CMSY method, and to Daniel Pauly for his editing the final draft of this contribution. Also, we appreciate the financial support of National Natural Science Foundation of China and Chinese Academy of Sciences. We thank Liwen Bianji, of Edanz Editing China (www.liwenbianji.cn/ac), for editing the first English-language draft of our manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00616/full#supplementary-material

REFERENCES

Abe, T., Wada, T., Aritaki, M., Sato, N., and Minami, T. (2013). Morphological and habitat characteristics of settling and newly settled roughscale Sole *Clidoderma asperrimum* collected in the coastal waters of northeastern Japan. *Fish. Sci.* 79, 767–777. doi: 10.1007/s12562-013-0649-y

Anticamara, J. A., Watson, R., Gelchu, A., and Pauly, D. (2011). Global fishing effort (1950–2010): trends, gaps, and implications. *Fish. Res.* 107, 131–136. doi: 10.1016/j.fishres.2010.10.016

FAO (2016). *The State of World. Fisheries and Aquaculture*. Rome: FAO.

Fisheries Agency of Japan (2018). *Resource Assessment for the Pacific Anchovy in the Year 2018*. Tokyo: FAJ.

Fox, W. W. Jr. (1970). An exponential surplus yield model for optimizing exploited fish populations. *Trans. Am. Fish. Soc.* 99, 80–88. doi: 10.1577/1548-8659(1970)99<80:AESMFO>2.0.CO;2

Froese, R., Demirel, N., Coro, G., Kleisner, K. M., and Winker, H. (2017). Estimating fisheries reference points from catch and resilience. *Fish Fish.* 18, 506–526. doi: 10.1111/faf.12190

Froese, R., Garilao, C., Winker, H., Coro, G., Demirel, N., Tsikliras, A., et al. (2016). *Exploitation and Status of European Stocks*. Available online at: http://oceanrep.geomar.de/34476/ (accessed February, 2020).

Froese, R., and Pauly, D. (eds) (2019). *FishBase. World Wide Web Electronic Publication*. Available online at: https://www.fishbase.de/ (accessed February, 2020).

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A. C., Dimarchopoulou, D., et al. (2018). Status and rebuilding of European fisheries. *Mar. Policy* 93, 159–170. doi: 10.1016/j.marpol.2018.04.018

Garcia, S. M., Ye, Y., Rice, J., and Charles, A. (eds) (2018). *Rebuilding of Marine Fisheries. Part 1: Global Review. FAO Fisheries and Aquaculture Technical Paper No. 630/1*. Rome: FAO, 294.

Hattori, T., Ueda, Y., Narimatsu, Y., and Ito, M. (2008). Distributional changes of roughscale sole (*Clidoderma asperrimum*) off the Pacific coast of northern Honshu, Japan. *Bull. Jpn. Soc. Fish. Oceanogr.* 72, 14–21.

Hilborn, R., and Ovando, D. (2014). Reflections on the success of traditional fisheries management. *ICES J. Mar. Sci.* 71, 1040–1046. doi: 10.1093/icesjms/fsu034

Holsman, K. K., Ianelli, J., Aydin, K., Punt, A. E., and Moffitt, E. A. (2016). A comparison of fisheries biological reference points estimated from temperature-specific multi-species and single-species climate-enhanced stock assessment models. *Deep Sea Res. II Top. Stud. Oceanogr.* 134, 360–378. doi: 10.1016/j.dsr2.2015.08.001

Ichinokawa, M., Okamura, H., and Kurota, H. (2017). The status of Japanese fisheries relative to fisheries around the world. *ICES J. Mar. Sci.* 74, 1277–1287. doi: 10.1093/icesjms/fsx002

Koya, Y., Hamatsu, T., and Matsubara, T. (1995). Annual reproductive cycle and spawning charateristics of the female kichiji rockfish *Sebastolobus macrochir*. *Fish. Sci.* 61, 203–208. doi: 10.2331/fishsci.61.203

Makino, M. (2011). *Fisheries Management in Japan: Its Institutional Features and Case Studies*. Dordrecht: Springer.

Martell, S., and Froese, R. (2013). A simple method for estimating MSY from catch and resilience. *Fish Fish.* 14, 504–514. doi: 10.1111/j.1467-2979.2012.00485.x

Nakatani, T. (1988). Studies on the early life history of walleye pollock *Theragra chalcogramma* in Funka Bay and vicinity, Hokkaido. *Mem. Fac. Fish. Hokkaido Univ.* 35, 1–46.

Nashida, K., Sakaji, H., and Honda, H. (2007). Spawning seasons of adult and growth of 0-year-old deepsea smelt *Glossanodon semifasciatus* in Tosa Bay, Pacific coast of Shikoku. *Bull. Jpn. Soc. Fish. Oceanogr.* 71, 270–278.

Nishimura, A., Hamatsu, T., Yabuki, K., and Shida, O. (2002). Recruitment fluctuation and biological responses of walleye pollock in the Pacific coast of Hokkaido. *Fish. Sci.* 68, 206–209. doi: 10.2331/fishsci.68.sup1_206

Noranarttragoon, P., Ueda, Y., Hattori, T., and Matsuishi, T. (2011). Value-per-recruit analysis of bighand thornyhead *Sebastolobus macrochir* caught off the Pacific coast of northern Honshu, Japan. *Fish. Sci.* 77, 497–502. doi: 10.1007/s12562-011-0368-1

Nyuji, M., and Takasuka, A. (2017). Spawning cycle and fecundity of a multiple spawner round herring *Etrumeus teres* off southern Japan: oocyte growth and maturation analysis. *J. Sea Res.* 122, 11–18. doi: 10.1016/j.seares.2017.02.009

Ohshimo, S., Tanaka, H., and Hiyama, Y. (2009). Long-term stock assessment and growth changes of the Japanese sardine (Sardinops melanostictus) in the Sea of Japan and East China Sea from 1953 to 2006. *Fish. Oceanogr.* 18, 346–358. doi: 10.1111/j.1365-2419.2009.00516.x

Oozeki, Y., Takasuka, A., Kubota, H., and Barange, M. (2007). Characterizing spawning habitats of Japanese sardine, *Sardinops melanostictus*, Japanese anchovy, *Engraulis japonicus*, and Pacific round herring, *Etrumeus teres*, in the Northwestern Pacific. *Calif. Coop Ocean. Fish. Invest.* 48:191.

Sakaguchi, S. O., Takishita, K., Goto, T., Shibata, H., Kojima, S., Fujikura, K., et al. (2014). Analyses of age and population genetic structure of the broadbanded thornyhead *Sebastolobus macrochir* in North Japan suggest its broad dispersion and migration before settlement. *J. Oceanogr.* 70, 457–462. doi: 10.1007/s10872-014-0240-x

Schaefer, M. B. (1954). Some aspects of the dynamics of populations important to the management of commercial marine fisheries. *Bull. Math. Biol.* 53, 253–279. doi: 10.1016/S0092-8240(05)80049-7

Suzuki, K. K., Yasuda, T., Kurota, H., Yoda, M., Hayashi, A., Muko, S., et al. (2018). Spatiotemporal variations in the distribution of round herring eggs in the East China and Japan Seas during 1997–2013. *J. Sea Res.* 142, 1–10. doi: 10.1016/j.seares.2018.09.003

Tokranov, A. M., and Orlov, A. M. (2003). On the distribution and biology of roughscale sole *Clidoderma asperrimum* (Temminck et Schlegel, 1846) in the Pacific waters off the northern Kuril Islands and southeastern Kamchatka. *Bull. Sea Fish. Inst.* 159, 67–80.

Wada, T. (1997). "Review of the small pelagic resources and their fisheries in Japan," in *Proceedings of the First Session APFIC Working Party on Marine Fisheries, Small Pelagic Resources and Their Fisheries in the Asia–Pacific Region*, (Bangkok: FAO Regional Office for Asia and Pacific), 227–243.

Watanabe, Y., Zenitani, H., and Kimura, R. (1995). Population decline off the Japanese sardine *Sardinops melanosticus* owing to recruitment failures. *Can. J. Fish. Aquat. Sci.* 52, 1609–1616. doi: 10.1139/f95-154

Yatsu, A. (2019). Review of population dynamics and management of small pelagic fishes around the Japanese Archipelago. *Fish. Sci.* 85, 611–639. doi: 10.1007/s12562-019-01305-3

Yoneda, M., Tokimura, M., Fujita, H., Takeshita, N., Takeshita, K., Matsuura, S., et al. (2001). Reproductive cycle, fecundity, and seasonal distribution of the anglerfish *Lophius litulon* in the East China and Yellow seas. *Fish. Bull.* 99, 356–356.

Zenitani, H., and Kimura, R. (2007). Elemental analysis of otoliths of Japanese anchovy: trial to discriminate between Seto Inland Sea and Pacific stock. *Fish. Sci.* 73, 1–8. doi: 10.1111/j.1444-2906.2007.01295.x

Zhai, L., and Pauly, D. (2019). Yield-per-recruit, utility-per-recruit, and relative biomass of 21 exploited fish species in China's Coastal Seas. *Front. Mar. Sci.* 6:724. doi: 10.3389/fmars.2019.00724

Zhang, C., and Chen, X. (2020). Management and assessment of spotted mackerel (*Scomber australasicus*) biomass in the Pacific Ocean. *J. Fish. China* 44, 206–212. doi: 10.11964/jfc.20171211117

Zhang, C. I., and Lee, J. B. (2001). Stock assessment and management implications of horse mackerel (Trachurus japonicus) in Korean waters, based on the relationships between recruitment and the ocean environment. *Prog. Oceanogr.* 49, 513–537. doi: 10.1016/s0079-6611(01)00038-6

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Marine Science

ORIGINAL RESEARCH
published: 21 August 2020
doi: 10.3389/fmars.2020.00640

Stock Status Assessments for 12 Exploited Fishery Species in the Tsushima Warm Current Region, Southwest Japan and East China, Using the CMSY and BSM Methods

Yuanchao Wang[1,2,3], *Cui Liang*[1,2,4]*, *Yibang Wang*[1,5], *Weiwei Xian*[1,2,3,4]* and *Maria Lourdes Palomares*[6]

[1] Key Laboratory of Marine Ecology and Environmental Sciences, Institute of Oceanology, Chinese Academy of Sciences, Qingdao, China, [2] Laboratory for Marine Ecology and Environmental Science, Qingdao National Laboratory for Marine Science and Technology, Qingdao, China, [3] University of Chinese Academy of Sciences, Beijing, China, [4] Center for Ocean Mega-Science, Chinese Academy of Sciences, Qingdao, China, [5] Qingdao University of Science and Technology, Qingdao, China, [6] Sea Around Us, Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, BC, Canada

OPEN ACCESS

Edited by:
Violin Stoyanov Raykov,
Institute of Oceanology (BAS),
Bulgaria

Reviewed by:
Gorka Merino,
Technology Center Expert in Marine and Food Innovation (AZTI), Spain
Ertug Duzgunes,
Karadeniz Technical University, Turkey

***Correspondence:**
Cui Liang
liangc@qdio.ac.cn;
cui-liang@hotmail.com
Weiwei Xian
wwxian@qdio.ac.cn

Specialty section:
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

Received: 04 February 2020
Accepted: 13 July 2020
Published: 21 August 2020

Citation:
Wang Y, Liang C, Wang Y, Xian W and Palomares ML (2020) Stock Status Assessments for 12 Exploited Fishery Species in the Tsushima Warm Current Region, Southwest Japan and East China, Using the CMSY and BSM Methods. Front. Mar. Sci. 7:640. doi: 10.3389/fmars.2020.00640

This contribution presented stock assessments for 10 fish and 2 squid populations exploited by Chinese, South Korean, and Japanese fishing fleets in the Tsushima Warm Current region, i.e., Southwest Japan and East China. The methods used were a Monte Carlo method (CMSY) and a Bayesian state-space implementation of the Schaefer model (BSM), based on published time series of catch and abundance data (SSB and CPUE). Results showed that 2 fish stocks, Japanese jack mackerel (*Trachurus japonicus*) and yellowback sea-bream (*Dentex hypselosomus*), had a healthy status, while daggertooth pike conger (*Muraenesox cinereus*) appeared to have collapsed. The other 9 stocks showed varying degrees of overfishing. The cooperation of several countries would be required to recover the fishery resources in the Tsushima Warm Current region.

Keywords: CMSY, BSM, fishery status, reference points, stock assessments

INTRODUCTION

The capture production (FAO catalog: Fish, crustaceans, molluscs, etc.) in the Northwest Pacific Ocean (No. 61 fishing area, FAO) accounted for 20.2% of the world total marine capture in 2017 (FAO, 2019). The management of exploited fishery stocks in this region requires a knowledge of stock status and relevant reference points that can be used in formulating fishery management policies. However, this kind of information is usually deficient or inadequate, especially for data-limited stocks (Froese et al., 2012). In recent years, in order to resolve this dilemma, there have been attempts targeting research effort on data-limited stocks to support newly released fishery management policies (DAFF, 2007; MSA, 2007; MFNZ, 2008; CFP, 2013).

In response to severe depletions of fishery resources, neighboring countries of the Northwest Pacific Ocean, such as Japan, South Korea, and China, have intervened with a series of fishery management strategies. In Japan, a total allowable catch (TAC) system was introduced by the

Fisheries Agency of Japan (FAJ) in 1997, in addition to existing management strategies, to deal with overfishing problems. The FAJ raised the Resource Recovery Plan system in 2001, which is mainly based on the co-management concept (Makino, 2018; Yatsu, 2019). In 2018, the FAJ started to adopt the MSY as an explicit fishery target for efficient managements. In South Korea, to promote the recovery of overexploited stocks, a buyback program was initiated in 1994 and a fish stock rebuilding plan was instituted in 2004. "Jayul Community Fisheries Management" was a program carried out in 2001 to increase accountabilities and instill "a sense of ownership" among local stakeholders. Lee and Rahimi Midani (2014) suggested that the fishery productivity had increased in the coastal area of South Korea, but more vessels needed to be removed. In China, most fisheries are multi-species, and there are certain difficulties in determining the sustainable total catch. Overall, input control and technical measures are the common and main strategies of these countries. These measures have achieved certain effects on fishery managements. However, the problem is that the prerequisite, namely, fishery stock status, is often neglected in the implementation of these managements.

There are 2 main kinds of models for assessments of fishery stock status: one is the age-structured models when age and/or length data are available, and the other is surplus production models when only catch and/or abundance data are available. Ecosystem-based fishery strategy is identified as a key to improve fishery managements, and there is a demand for all exploited fishery stock assessments, including the data-limited stocks. However, efficient and compatible methods, particularly for the data-limited stocks, are always necessary and deficient.

A Monte Carlo-type method (CMSY) and a Bayesian state-space implementation of the Schaefer model (BSM) were developed for data-limited fishery stock assessments (Froese et al., 2017). CMSY can be used to perform assessments based on the time series of catch and resilience data. It is a notable improvement over the Catch-MSY method of Martell and Froese (2013) with the inclusion of decrease for the reproduction when a stock is severely depleted. It is an advanced implementation of a surplus production model. Froese et al. (2018) provided CMSY estimates for 397 European stocks and results showed that 69% of the 397 stocks were in the state of overfishing, while sustainably exploited stocks in the Mediterranean were no more than 20%. Palomares et al. (2018) implied that 73.4% of 1,320 assessed stocks were under the MSY level in biomass all over the world. The BSM method was developed for cases in which abundance data are available in addition to time series of catch (Froese et al., 2017), such as catch per unit effort (CPUE) and spawning stock biomass (SSB). The main advantages of the BSM method are the highly flexible and steerable priors, and the data mining possibilities from uncompleted abundance data.

In this contribution, the CMSY and BSM methods were used to assess the status and essential reference points for 12 fishery stocks distributed in the Tsushima Warm Current region of the Northwest Pacific Ocean, and 9 stocks among them were evaluated by the BSM method with time series of catch and the relevant abundance data (SSB or CPUE). The other 3 stocks, for which only catch data were available, were assessed by the CMSY method. Based on these results, the relative stock status and essential reference points were given and the application of CMSY and BSM methods was discussed, as required for management of the fisheries and further research.

MATERIALS AND METHODS

Study Area

The Tsushima Warm Current is one of the complex current system in the Northwest Pacific Ocean, supporting the main fisheries of neighboring countries. Its main marginal seas include the East China Sea, Yellow Sea, and the Sea of Japan. A whole life history stage of a target fishery stock would be affected by surrounding countries. The 12 stocks in question accounted for about 19.48% of the total capture production in the Northwest Pacific Ocean in 2017 (FAO, 2019). In recent decades, the severe depletions of fishery resources and the substantial environmental fluctuations suggest that the ecosystem structure is underlying rapid change. The annual average sea surface temperature (SST) around Japan has increased by +1.11°C over the last 100 years, and increasing blooms of harmful algae and jellyfish are prominent and common problems in the coastal area of surrounding countries (Yatsu, 2019). These urgent situations have attracted global attention.

Dataset

The datasets for the 12 stocks in question were obtained from the FAJ and Japan Fisheries Research and Education Agency[1] (abbreviated as FAJ) as is shown in the **Supplementary Material** (time series of catch and standard CPUE and SSB in **Supplementary Table S1**; the distribution areas, spawning, and fishing grounds of these stocks are shown in **Supplementary Figure S1**). The basic information for each stock is shown in **Table 1**, and their relative priors for CMSY and BSM are shown in **Table 2**. Black scraper (*Thamnaconus modestus*), daggertooth pike conger (*Muraenesox cinereus*), and swordtip squid (*Uroteuthis edulis*) had only time series of catch, while the other 9 stocks had both catch and relative abundance data. The prior ranges for intrinsic rate of population increase (r) were obtained from FishBase (Froese et al., 2000; Froese and Pauly, 2019), where they were referred to as "resilience" (Musick, 1999). The priors of relative biomass for the first year (B_{start}), the intermediate year (B_{int}), and the end year of the time series of catch (B_{end}) were based on the relative FAJ reports of these stocks. The CMSY and BSM methods were implemented in R language (R Core Team, 2013) and relative R code can be found from http://oeanrep.geomar.de/33076/.

CMSY Method

The CMSY method filters the suitable r–k pairs using a Monte Carlo approach with the priors of the intrinsic rate of population increase (r), unexploited population size or carrying capacity (k),

[1] http://abchan.fra.go.jp/

TABLE 1 | Basic information of the 12 fishery stocks in question.

Common name (Scientific name)	Time series of catch	Additional data	Data sources
South American pilchard (*Sardinops melanostictus*)	1960–2017	SSB	Yasuda et al., 2019
Japanese jack mackerel (*Trachurus japonicus*)	1973–2017	SSB	Yoda et al., 2019
Chub mackerel (*Scomber japonicus*)	1973–2017	SSB	Kuroda et al., 2019a
Blue mackerel (*Scomber australasicus*)	1992–2017	SSB	Kuroda et al., 2019b
Japanese flying squid (*Todarodes pacificus*)	1979–2017	SSB	Kaga et al., 2019
Red-eye round herring (*Etrumeus micropus*)	1975–2017	SSB	Suzuki et al., 2019
Japanese anchovy (*Engraulis japonicus*)	1977–2016	SSB	Hayashi et al., 2019
Yellowback sea-bream (*Dentex hypselosomus*)	1966–2017	SSB	Kawauchi et al., 2019
Japanese Spanish mackerel (*Scomberomorus niphonius*)	1984–2017	CPUE	Motomitsu and Yoda, 2019
Black scraper (*Thamnaconus modestus*)	1977–2016	NA	Sakai et al., 2019
Daggertooth pike conger (*Muraenesox cinereus*)	1980–2017	NA	Aonuma et al., 2019
Swordtip squid (*Uroteuthis edulis*)	1988–2017	NA	Yoda and Takahashi, 2019

All data sources were collected from Fisheries Agency of Japan and Japan Fisheries Research and Education Agency.

TABLE 2 | Prior ranges used for CMSY and BSM; the resilience ranges were from FishBase (Froese and Pauly, 2019).

Scientific name	Resilience	*r* ranges	B_{start} ranges	B_{int} ranges	B_{end} ranges
S. melanostictus	Medium	NA	0.01–0.4	0.4–0.8 (1990)	0.2–0.6
T. japonicus	Medium	0.41–0.74	0.4–0.8	0.5–0.9 (1990)	0.2–0.6
S. japonicus	Medium	0.32–0.73	0.4–0.8	0.3–0.9 (1996)	0.01–0.4
S. australasicus	Medium	0.41–0.78	0.4–0.8	0.2–0.4 (2012)	0.2–0.4
T. pacificus	High	0.74–1.68	0.8–0.9	0.2–0.6 (1996)	0.01–0.2
E. micropus	Medium	NA	0.4–0.8	0.01–0.2 (2002)	0.01–0.4
E. japonicus	High	NA	0.4–0.8	0.2–0.6 (1998)	0.01–0.4
D. hypselosomus	Medium	NA	0.4–0.8	0.01–0.4 (1986)	0.2–0.6
S. niphonius	Medium	NA	0.4–0.8	0.01–0.2 (1997)	0.2–0.4
T. modestus	Medium	NA	0.4–0.8	0.01–0.4 (1994)	0.01–0.3
M. cinereus	Medium	NA	0.2–0.6	0.01–0.4 (2013)	0.01–0.1
U. edulis	High	NA	0.2–0.6	0.01–0.4 (2013)	0.01–0.3

*The priors of B_{start}, B_{int}, and B_{end} are based on relevant stock assessment reports from the Fisheries Agency of Japan and Japan Fisheries Research and Education Agency (see **Table 1**).*

and the relative biomass for the first year of the time series of catch (B_{start}) (**Table 2**). The range of the prior k is calculated in the R code by Eqs 1 and 2, i.e.,

$$k_{\text{low}} = \frac{\max(C)}{r_{\text{high}}} \text{ and } k_{\text{high}} = \frac{4\max(C)}{r_{\text{low}}} \left| endb_{\text{mean}} \leq 0.5 \right. \quad (1)$$

$$k_{\text{low}} = \frac{2\max(C)}{r_{\text{high}}} \text{ and } k_{\text{high}} = \frac{12\max(C)}{r_{\text{low}}} \left| endb_{\text{mean}} > 0.5 \right. \quad (2)$$

where k_{low} and k_{high} are the lower and higher boundary priors for k, respectively, $\max(C)$ is the maximum catch value of the time series of catch, r_{low} and r_{high} are the lower and higher boundary priors of r, and $endb_{\text{mean}}$ is the mean of relative prior biomass range for the end of the time series.

In the filter process, a pair of r–k values are randomly selected in prior ranges of r and k, and then a biomass (B_t) is selected from the B_{start} ranges for the start year of time series of catch. If B_t/k is greater than 0.25, this randomly selected r–k–B_{start} combination will be used to calculate the predicted biomass in subsequent years according to Eq. 3 (Schaefer, 1954, 1957), i.e.,

$$B_{t+1} = B_t + r\left(1 - \frac{B_t}{k}\right)B_t - C_t \quad (3)$$

where B_{t+1} is the predicted biomass in the subsequent year $t + 1$, and C_t is the catch in the year of t.

If B_t/k is smaller than 0.25, Eq. 4 will be used to calculate the relevant biomass in the subsequent years:

$$B_{t+1} = B_t + 4\frac{B_t}{k}r\left(1 - \frac{B_t}{k}\right)B_t - C_t \quad (4)$$

where the term $4\frac{B_t}{k}$ assumes a linear decline of recruitment below half of the biomass that is capable of producing MSY to account for "depensation", i.e., to simulate the reduction of productivity that tends to occur at very low stock sizes (Hutchings, 2000).

These randomly selected r–k pairs will be accepted if they meet all the following three conditions: (1) the predicted biomass is not smaller than 0.01 k; (2) the predicted biomass falls inside the prior biomass range of the intermediate year (B_{int}); and (3) the predicted biomass falls inside the prior biomass range of the final year (B_{end}). The process will be terminated once 1,000 suitable r–k pairs are found. These suitable r–k pairs will form a triangle pattern with a thin tip as is shown in the **Supplementary Figure S2**. In contrast to the Catch-MSY method, the best r–k pair of the CMSY method is chosen not in the center, but in the tip region of the triangle (Froese et al., 2017).

BSM Method

The Bayesian state-space implementation of the Schaefer model (i.e., the BSM method) provides more precise estimates of r, k, and MSY (Millar and Meyer, 1999; Froese et al., 2017) for stocks for which additional abundance data, such as (at least 2 estimates of) relative biomass or CPUE, are available. This method is included in the CMSY R code.

In the BSM method, the prior ranges of r and k are converted to prior density distributions. Meanwhile, a new prior, the catchability coefficient q, is added to establish the relationship between the biomass trajectory that is inferred from r–k pairs and the abundance (or relative biomass) data that are available externally. Herein, r is log-normally distributed based on a chi-square test of the density of the suitable r values resulting from CMSY analysis of simulated data against several standard distributions, while k and q are assumed to have log-normal distributions (Froese et al., 2017).

The abundance index, catchability coefficient q, is obtained from Eq. 5, i.e.,

$$CPUE_t = qB_t \tag{5}$$

where $CPUE_t$ is the catch per unit effort in the year t and q is the catchability coefficient.

The basic dynamics of the corresponding Schaefer production model for abundance can therefore be expressed in the form of Eq. 6, i.e.,

$$CPUE_{t+1} = CPUE_t + r\left(1 - \frac{CPUE_t}{qk}\right)CPUE_t - qC_t \tag{6}$$

whose parameters are defined in Eqs 3 and 5.

In this method, the prior q is calculated by the several settings and based on the Schaefer equilibrium equation. q at the MSY level of biomass,

$$q = \frac{0.25rCPUE}{C} \tag{7}$$

q at half MSY level of biomass,

$$q = \frac{0.75rCPUE}{C} \tag{8}$$

The low and high q priors are calculated by the following equations:

$$q_{\text{low}} = \frac{0.25r_{\text{pgm}}CPUE_{\text{mean}}}{C_{\text{mean}}}|endb_{\text{mean}} \geq 0.5 \quad \text{or} \tag{9}$$

$$q_{\text{low}} = \frac{0.5r_{\text{pgm}}CPUE_{\text{mean}}}{C_{\text{mean}}}|endb_{\text{mean}} < 0.5$$

where q_{low} is the lower prior for the catchability coefficient q, r_{pgm} is the geometric mean of the r prior range, $CPUE_{\text{mean}}$ and C_{mean} are the mean of the CPUE and catch, respectively, taken over the last 5 years for species with medium and high resilience or over the last 10 years for species with low or very low resilience, $endb_{\text{mean}}$ is defined in Eqs 1 and 2.

$$q_{\text{high}} = \frac{0.5r_{\text{high}}CPUE_{\text{mean}}}{C_{\text{mean}}}|endb_{\text{mean}} \geq 0.5 \quad \text{or}$$

$$q_{\text{high}} = \frac{r_{\text{high}}CPUE_{\text{mean}}}{C_{\text{mean}}}|endb_{\text{mean}} < 0.5 \tag{10}$$

where q_{high} is the upper prior for the catchability coefficient q, r_{high} is the upper prior range for r, and other parameters are defined in Eq. 9.

The JAGS software (Plummer, 2003) is used for sampling the probability distributions of the parameters with the Markov Chain Monte Carlo method (Froese et al., 2017).

RESULTS

In this contribution, we applied the CMSY and BSM methods to 12 fishery stocks distributed in the Tsushima Warm Current region. The main results of CMSY and BSM are shown in **Table 3**, including assessments for r (0.37–1.05 year^{-1}), k (7.75–6723 tonnes), relative biomass of the end year of time series of catch B_{end}/k (0.0333–0.578), related fishery reference points, i.e., MSY (0.985–1049 tonnes·year^{-1}), B_{MSY} (3.87–3362 tonnes), B/B_{MSY} (0.0666–1.16), and exploitation rates (0.00362–1.35). The estimates of relative biomass B/k trajectories depicted the fluctuations of population sizes for 12 stocks and a significant decline of relative biomass in 1990s was observed in **Figure 1**. **Figure 2** shows the B/B_{MSY} and F/F_{MSY} curves for each stock.

Among the 12 stocks, the B/B_{MSY} estimates of Japanese jack mackerel (*T. japonicus*) and yellowback sea-bream (*D. hypselosomus*) were both above 1.0, which meant that they had a healthy status according to the criteria in Palomares et al. (2018). The B/B_{MSY} of daggertooth pike conger (*M. cinereus*) was 0.067 in the last year, which corresponded to a collapsed status. The other 9 stocks exhibited different degrees of overfishing. The B_{MSY} of *T. japonicus* was above 500,000 tonnes, and the stocks with B_{MSY} > 1,000,000 tonnes included chub mackerel (*S. japonicus*) (overfished), South American pilchard (*S. melanostictus*) (grossly overfished), and back scraper (*T. modestus*) (grossly overfished). These stocks with large capacities were long-term targets of fishing activities and in different degrees of overfishing.

The biomass levels estimated from the BSM method were depicted and compared with re-estimated biomass "true values" collected from FAJ reports (**Figure 3**), which implied a relative larger uncertainty of the BSM method estimated for South American pilchard (*S. melanostictus*). For the diagnostic tests of BSM fits, predicted versus observed catch and abundance data are provided in **Supplementary Figures S3A–I**, which showed that the autocorrelations of residuals of the abundance data of South American pilchard (*S. melanostictus*) and Japanese anchovy (*E. japonicus*) were both deemed not negligible.

TABLE 3 | Results of the CMSY and BSM analyses with 95% confidence interval in relative brackets (*k*, MSY, and B_{MSY} in tonnes).

Scientific name	*r*	*k*	MSY	B_{MSY}	B/B_{MSY}	$F/(r/2)$	F/F_{MSY}	Stock status
S. melanostictus	0.624	6723	1049	3362	0.464	0.111	0.12	Grossly overfished
	(0.384–1.01)	(4807–9403)	(870–1264)	(2403–4702)	(0.333–1.16)		(0.0481–0.167)	
T. japonicus	0.693	1072	186	536	1.16	0.647	0.647	Healthy
	(0.574–0.838)	(894–1285)	(167–206)	(447–642)	(0.92–1.37)		(0.548–0.813)	
S. japonicus	0.581	2334	339	1167	0.651	0.974	0.974	Overfished
	(0.471–0.716)	(1936–2814)	(309–372)	(968–1407)	(0.501–0.822)		(0.772–1.27)	
S. australasicus	0.73	321	58.6	161	0.794	0.902	0.902	Overfished
	(0.61–0.873)	(272–380)	(54.5–63.1)	(136–190)	(0.626–0.94)		(0.762–1.14)	
T. pacificus	1.05	851	223	425	0.414	0.584	0.706	Grossly overfished
	(0.891–1.23)	(726–997)	(208–239)	(363–498)	(0.303–0.508)		(0.574–0.964)	
E. micropus	0.609	274	41.7	137	0.904	0.95	0.95	Slightly overfished
	(0.476–0.779)	(220–341)	(38.2–45.5)	(110–170)	(0.744–1.06)		(0.81–1.16)	
E. japonicus	0.946	364	86	182	0.443	1.33	1.51	Grossly overfished
	(0.79–1.13)	(310–426)	(79.3–93.3)	(155–213)	(0.338–0.68)		(0.981–1.97)	
D. hypselosomus	0.508	7.75	0.985	3.87	1.02	0.719	0.719	Healthy
	(0.391–0.661)	(6.06–9.91)	(0.832–1.17)	(3.03–4.96)	(0.754–1.31)		(0.559–0.971)	
S. niphonius	0.429	166	17.8	83	0.56	1.04	1.04	Overfished
	(0.293–0.629)	(129–213)	(14–22.7)	(64.7–106)	(0.355–0.874)		(0.669–1.65)	
T. modestus	0.37	4258	394	2129	0.334	1.35	2.02	Grossly overfished
	(0.267–0.511)	(3146–5763)	(319–486)	(1573–2881)	(0.0561–0.581)		(1.16–12)	
M. cinereus	0.538	30.8	4.14	15.4	0.0666	0.00362	0.0272	Collapsed
	(0.368–0.786)	(14.7–64.3)	(1.83–9.4)	(7.37–32.2)	(0.0234–0.185)		(0.00977–0.0773)	
U. edulis	0.375	329	30.8	164	0.252	0.956	1.9	Grossly overfished
	(0.27–0.522)	(197–549)	(16.7–57.1)	(98.3–275)	(0.0329–0.573)		(0.835–14.5)	

DISCUSSION

South American Pilchard (*Sardinops melanostictus*)

The South American pilchard (*S. melanostictus*), also known as Pacific sardine, is a pelagic–neritic fish species belonging to the Clupeidae family (Froese and Pauly, 2019). The stock around Japan is one of the three lineages of this species, as established by cluster and parsimony analyses of haplotypic divergences (Grant et al., 1998). The ratio B_{end}/k and B/B_{MSY} value suggested that this stock was grossly overfished in 2017. The biomass trajectory of this stock was consistent with the results of Yasuda et al. (2019), and the biomass size was increasing in recent years (**Figure 2**). The low fishing pressure (F/F_{MSY} = 0.12) may not change the natural law of climate effects on this stock. The biomass fluctuation of this stock may be related to climate change, and the stock would change drastically even though a reliable and constant MSY or F_{MSY} was given and implemented (Katsukawa, 2002).

Figure 3 shows that the biomass level estimated by the BSM method in this study had a larger deviation for this stock, compared with that of FAJ reports. This could be mainly due to the significant correlation between the population dynamics and environmental elements. Nishikawa (2018) presented that water temperature and/or its relevant elements affected the recruitment through larval survival, and lower temperature conditions increased larval survival rate (Takasuka et al., 2007; Nishikawa et al., 2013). What's more, the combination of strong MOI (Monsoon Index) and weak AO (Arctic Oscillation) could improve the supplement of this stock by increasing the biomass of phytoplankton and zooplankton (Ohshimo et al., 2009). Many factors were related to the stock status, such as climate changes, spawning season and location, and fishing activities (Nishikawa, 2018). This implied that the fishery management should not only be based on the results of models; the knowledge of environmental variables and life histories would be necessary for a credible judgment.

Japanese Jack Mackerel (*Trachurus japonicus*)

Japanese jack mackerel (*T. japonicus*) is a pelagic–neritic marine fish. It is distributed in southern Japan, Korean Peninsula, to the East China Sea (Froese and Pauly, 2019; **Supplementary Figure S1**). The biomass of this stock increased from the 1980s to the early 1990s and had been around 400,000 tonnes since 2005 (Yoda et al., 2019). This contribution showed that the relative biomass B/k value (**Figure 1**) of this stock was already declining in the early 1980s. The fishing pressure (F/F_{MSY}) and the stock status (B/B_{MSY}) had been both around the MSY level since 2010. This species is a salinity-sensitive species (Tashiro and Iwatsuki, 1995). Salinity and zooplankton biomass in its habitat were significantly correlated with the recruitment of this species (Zhang and Lee, 2001). The uncertainty of the stock status would be interpreted by integrating the relevant environmental factors.

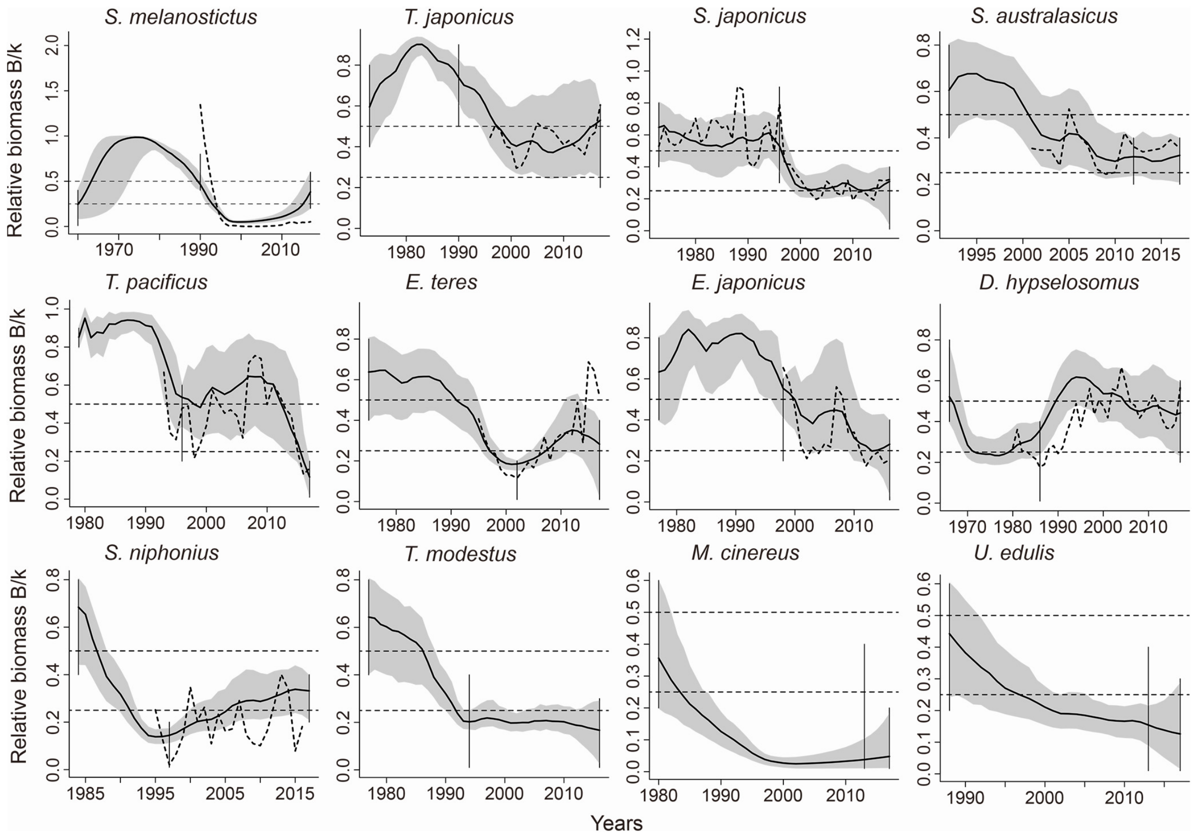


FIGURE 1 | Biomass trajectories (solid line) estimated by CMSY for 12 species in question. The gray areas showed the 95% confidence intervals of the biomass, and the dotted lines showed additional information (CPUE or SSB) when available. The three vertical lines indicated the prior biomass ranges, and two horizontal dotted lines indicated the 2.5th and 97.5th percentiles.

Chub Mackerel (*Scomber japonicus*)

Chub mackerel (*S. japonicus*) is a pelagic–neritic fish ranging from the southern East China Sea to the northern Sea of Japan, and also occurring in the Yellow Sea and Bohai Sea of China (Limbong et al., 1991; Yamada et al., 2007, Yasuda et al., 2014). The fishing effort of the large and medium purse seine fishery in the Tsushima Warm basin was relatively low, but increased along the Pacific Ocean coast of Japan since 2016 (Kuroda et al., 2019a). Hiyama et al. (2002) found that the increase of fishing effort targeting this species at the end of 1990s implied abundance recovery, and it may be related to the SST. The biomass of this stock required to generate the maximum sustainable yield was around 1,170,000 tonnes, higher than the current biomass (760,000 tonnes) estimated here. The gradually increased fishing intensity since 1990 reduced its biomass, and the B/B_{MSY} ration of 0.651 in 2017 suggests that this stock was already overfished.

Blue Mackerel (*Scomber australasicus*)

Blue mackerel (*S. australasicus*) is a pelagic–neritic fish whose adults migrate from the southern East China Sea or the Sea of Japan to the west coast of Kyushu (Kuroda et al., 2019b). The results obtained here suggested that the biomass of this stock was at a high level in the early 1990s, strongly declined around 2000, and increased again after 2010. The terminal B/B_{MSY} (0.794) and F/F_{MSY} (0.902) were close to the level that could produce MSY. However, the biomass level was still relatively low, and hence the stock must still be considered overfished. Sogawa et al. (2019) indicated that several factors (the location, the specific water characteristic, and copepod community) could determine the spawning process, which could be related to the low biomass level.

Japanese Flying Squid (*Todarodes pacificus*)

Japanese flying squid (*T. pacificus*) is a pelagic cephalopod whose recruitment rate has generally been low since 2002 (Kaga et al., 2019). The exploited stock in this contribution is a winter group, and its spawning ground is on the Pacific side of Japan. Ji et al. (2020) studied the effects of global warming on the stock recruitment, which indicated that the increased temperature would increase the survival rate of spawning cohorts in autumn and winter. **Figure 1** shows that there were two periods of decline in its biomass: one was after the early 1990s, and the other was after 2010. The B/B_{MSY} ratio close to 1 from the middle of 1990s to 2010, suggests a healthy stock status in this period. High fishing pressure might be the reason of biomass declining after 2010 and this was consistent with Kaga et al. (2019).

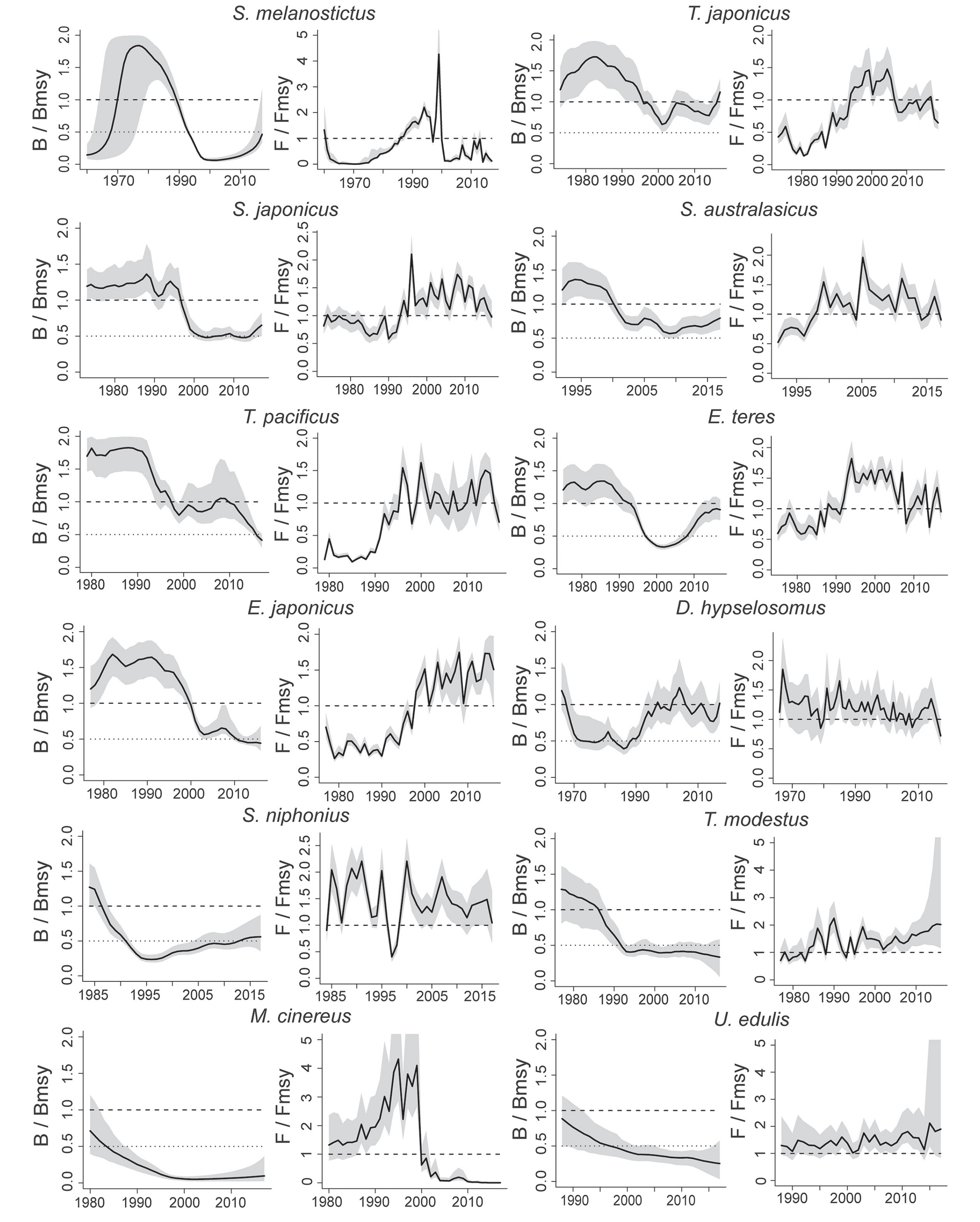


FIGURE 2 | For each stock, the left graph shows the trajectory of relative total biomass (B/B_{MSY}), and the gray area indicated 95% confidence intervals; the right graph shows relative exploitation (F/F_{MSY}), with F_{MSY} corrected for reduced recruitment below $0.5B_{MSY}$.

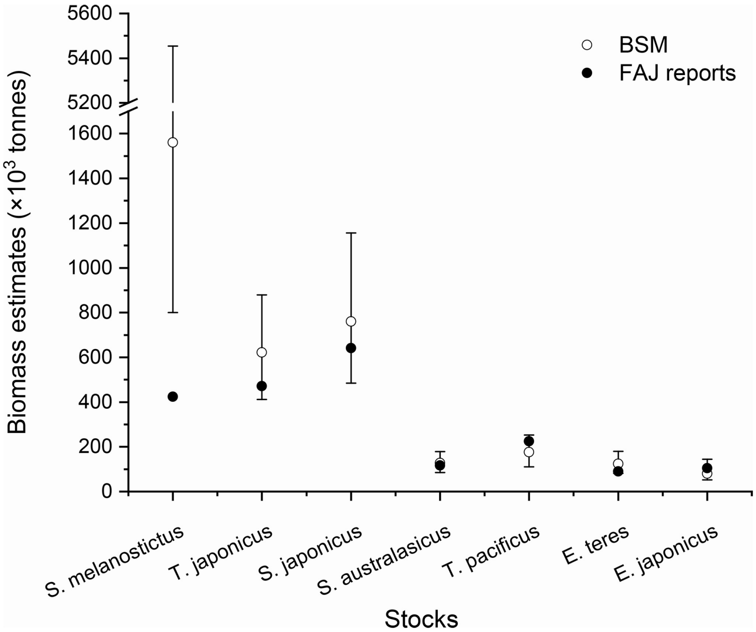


FIGURE 3 | Comparisons of biomass estimates between BSM results (dots with error bars) obtained in this study and FAJ reports. The biomass estimates based on FAJ were re-assessed values treated as "true values". The other five stocks in question (*D. hypselosomus*, *S. niphonius*, *T. modestus*, *M. cinereus*, and *U. edulis*) did not have biomass data in the FAJ reports.

Red-Eye Round Herring (*Etrumeus micropus*)

Red-eye round herring (*E. micropus*) (previously misidentified as *E. teres*, an Atlantic congeneric) is a pelagic–neritic fish distributed mainly in the Tsushima Warm Current basin. **Figure 1** shows that its biomass had been at a very low level since the 1990s, which might result from the high fishing pressure since the early 1990s (**Figure 2**). After 2010, with the decrease of fishing pressure, its biomass showed a recovery trend. The ratio B/B_{MSY} was slightly lower than the MSY level in 2017, indicating that a slight overfishing occurred for this stock.

Japanese Anchovy (*Engraulis japonicus*)

Japanese anchovy (*E. japonicus*) is a pelagic–neritic fish distributed mainly in the coastal areas of Japan, Korea, and China (Iversen et al., 1993; Ohshimo, 1996). The biomass of this stock had been at a low level since the late 1990s (**Figure 1**), owing to a high fishing pressure (**Figure 2**). Its MSY was estimated at 86,000 tonnes (**Table 3**), larger than that for the period of 1987–2000, namely, the low-level biomass period (Wang et al., 2006: MSY = 55,000 tonnes). The relative biomass (B/B_{MSY} = 0.443) in 2017 suggested that the stock was grossly overfished.

Yellowback Sea-Bream (*Dentex hypselosomus*)

Yellowback sea-bream (*D. hypselosomus*) is a marine demersal fish species, distributed in warm water areas with a depth of 100–200 m, and ranging from Honshu in Japan to Hainan Island in Southern China (Kawauchi et al., 2019). Yoda and Yoneda (2009) presented that this species had a very large reproduction potential, which may imply its strong anti-interference ability. Its biomass had increased to an MSY level since the late 1990s due to a decrease of fishing pressure (**Figure 2**). Its estimated relative biomass (B/B_{MSY}) in the final year of the time series represented a healthy status for this stock.

Japanese Spanish Mackerel (*Scomberomorus niphonius*)

Japanese Spanish mackerel (*S. niphonius*) is a marine, pelagic–neritic fish that was mainly caught by large and medium seines in the East China Sea before the mid-1990s. Fixed net catches in the Sea of Japan had increased since 2000, accounting for more than half of Japan's total catch of this species. Its biomass had been recovering from the low levels since 1995 (**Figure 1**). The series of F/F_{MSY} (**Figure 2**) showed that the fishing pressure had been overall higher than required to generate MSY. Yun and Nam (2017) presented the estimation of MSY as 26,761 tonnes of South Korea. The MSY value in this study was 17,800 tonnes, which excluded part of South Korea relative biomass B/B_{MSY} (0.56) of this stock suggested that it was in an overfished state.

Black Scraper (*Thamnaconus modestus*)

Black scraper (*T. modestus*) is a marine, reef-associated fish whose catches by China and South Korea have been at low level since the mid-1990s. However, the long-term fluctuations of this stock render judgment difficult (Sakai et al., 2019). The results of this contribution suggested that the biomass of this stock was declining before the 1990s, and had kept at a low level since then. The fishing pressure had been above the MSY level since the mid-1980s and tended to further increase in recent years. The carrying capacity of this stock was estimated at 4,260,000 tonnes;

however, the ratio B/B_{MSY} (0.334) in 2017 indicated that it was grossly overfished.

Daggertooth Pike Conger (*Muraenesox cinereus*)

Daggertooth pike conger (*M. cinereus*) is a demersal fish whose stock has been at a low level since 2000 (**Figure 1**), due to the high fishing pressure from 1990 to 2000 (**Figure 2**). The ratio B/B_{MSY} (0.067) indicated that the stock was collapsed. The rebuilding of this stock requires the efforts of the surrounding countries that have exploited it.

Swordtip Squid (*Uroteuthis edulis*)

Swordtip squid (*U. edulis*) is a demersal cephalopod whose catch exceeded 35,000 tonnes in 1988, decreased to about 10,000 tonnes after 2001, and was 7,400 tonnes in 2017 (Yoda and Takahashi, 2019). This stock presented a large part of revenue for many fishers especially in the eastern Tsushima Strait (Yoda and Takahashi, 2018). Similar with Japanese flying squid (*T. pacificus*), this stock seemed to benefit from warmer environment (Liao et al., 2018). The results of this study showed that the biomass of this stock had been declining since the beginning of the catch time series, and the fishing pressure increased in recent years (**Figure 2**). The carrying capacity k was 329,000 tonnes, and the ratio B/B_{MSY} (0.252) in 2017 indicated that the stock was grossly overfished.

Data-Limited Stock Assessments

Recruitment is highly variable for most fish stocks (Maunder and Thorson, 2018), which should be integrated into the assessment process to account for the uncertainties in the spawning biomass (Ludwig and Walters, 1981). Haltuch et al. (2019) indicated that assessments including the environmental drivers would be more appropriate for species with short pre-recruit survival windows. In this study, the biomass level of South American pilchard (*S. melanostictus*) from BSM was significantly different from that of the FAJ report. This suggests that the CMSY and BSM method is not appropriate for stocks that are affected by environmental factors that might lead to a regime shift that have the tendency to change a stock's population structure and thus, the evolution of its biomass.

The attempts of ecosystem-based fishery management factors have made significant progress to expand single-species stock assessments with available science and data, and good inclusion of ecosystem interactions could help to avoid the overoptimistic assessments (Marshall et al., 2018). The consequence is that the complexity of stock assessments is continuing to increase, such as much more data sources and more types of stock assessment models. The cost of this trend is the increased technical skill requirements for model selections and assessments of data sources (Dichmont et al., 2016). For some fishery stocks, the reliable information is usually insufficient, such as age and length structures and natural mortality. In contrast, time series of catch and fishing efforts are easier to be collected. Usually, these species are not the main targets of fishery industries, but they are indispensable in the trophic structure of an ecosystem. The assessment methods applied in this study just focus on these data-limited stock assessments. In general, the stock status is always overestimated at very low stock sizes because the decrease of recruitment potential is not included in these production models; the CMSY and BSM methods give the solution as stated in Eq. 4. For the management, the control rules should not be made only based on the results of assessment models, and indexes that are robust to variations in recruitment should be developed (Maunder and Thorson, 2018).

CONCLUSION

In this contribution, the CMSY and BSM were applied in the assessments for 12 fishery stocks exploited in the Tsushima Warm Current region. Most of them were exploited mainly by the fleets of three surrounding countries (Japan, South Korea, and China). Japanese jack mackerel (*T. japonicus*) and yellowback sea-bream (*D. hypselosomus*) had a healthy status, while the stock of daggertooth pike conger (*M. cinereus*) appeared to have collapsed. The other 9 stocks experienced different degrees of overfishing. These results underscored the need for better management of the fishery resources in this area, which requires international cooperation in the formulation and implementation of resources rebuilding in the Tsushima Warm Current area.

It is a trend to all exploited stocks assessments, including the data-limited stocks. The CMSY and BSM method performed good overall in this study and presented reliable results except the South American pilchard (*S. melanostictus*), which indicated that the modeling process should be prudent and experienced. The users should have technical skills and professional trains in order to give sufficient judgments on the model selections and weights of multiple data sources (Dichmont et al., 2016). The management rules need to base on multi-source datasets, not only the results from the efficient modeling, but also variables outside the stock itself. This requires the close cooperations among surrounding countries to piece the information of stocks themselves and bio- and non-bio environs together. Future research could pay attention to the inclusion of time series of variables and more explicit rules and restrictions in determining relative biomass levels.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because our manuscript was based on survey cruise data, and no live vertebrates or cephalopods were involved, thus we believe an ethical review process was not required for our study.

AUTHOR CONTRIBUTIONS

YCW and WX conceived and designed the study. YCW performed data collection and analysis, and wrote the first draft of the manuscript, with the insights from CL, YBW, WX, and MP. All authors contributed to the article and approved the submitted version.

FUNDING

This research was funded by grants for Creative Team Project of the Laboratory for Marine Ecology and Environmental Science, Qingdao National Laboratory for Marine Science and Technology (LMEES-CTSP-2018-1), National Natural Science Foundation of China (31872568 and 41976094), and Natural Science Foundation of China-Shandong Joint Fund for Marine Ecology and Environmental Sciences (U1606404).

ACKNOWLEDGMENTS

We acknowledge Dr. Daniel Pauly from *Sea Around Us*, University of British Columbia, Canada, for his contribution in the stock assessment workshop held in Qingdao, China, and his valuable comments on our first draft.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00640/full#supplementary-material

REFERENCES

Aonuma, Y., Sakai, T., and Kawauchi, Y. (2019). *Stock Assessment and Evaluation for Daggertooth Pike Conger Muraenesox cinereus (fiscal year 2018) in Marine Fisheries Stock Assessment and Evaluation for Japanese waters (fiscal year 2018/2019)*. Kanagawa: Fisheries Agency and Fisheries Research and Education Agency of Japan, 2126–2142.

CFP (2013). Regulation (EU) No 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC. *Off. J. Eur. Union L* 354, 22–61.

DAFF (2007). *Commonwealth Fisheries Harvest Strategy: Policy and Guidelines. Australian Government, Department of Agriculture, Fisheries and Forestry*. Available online at: http://www.agriculture.gov.au/SiteCollectionDocuments/fisheries/domestic/hsp.pdf (accessed December 19, 2014).

Dichmont, C. M., Deng, R. A., Punt, A. E., Brodziak, J., Chang, Y. J., Cope, J. M., et al. (2016). A review of stock assessment packages in the United States. *Fish. Res.* 183, 447–460. doi: 10.1016/j.fishres.2016.07.001

FAO (2019). *FAO yearbook: Fishery and Aquaculture Statistics 2017*. Rome. 524–527.

Froese, R., Demirel, N., Coro, G., Kleisner, K. M., and Winker, H. (2017). Estimating fisheries reference points from catch and resilience. *Fish* 18, 506–526. doi: 10.1111/faf.12190

Froese, R., Palomares, M. L. D., and Pauly, D. (2000). "Estimation of life-history key facts," in *FishBase 2000: Concepts, Design and Data Sources*, eds R. Froese and D. Pauly (Philippines: ICLARM), 167–175.

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A. C., Dimarchopoulou, D., et al. (2018). Status and rebuilding of European fisheries. *Mar. Policy* 93, 159–170. doi: 10.1016/j.marpol.2018.04.018

Froese, R., Zeller, D., Kleisner, K., and Pauly, D. (2012). What catch data can tell us about the status of global fisheries. *Mar. Biol.* 159, 1283–1292. doi: 10.1007/s00227-012-1909-6

Froese, R. and Pauly, D. eds (2019). FishBase. World Wide Web electronic publication.

Grant, W. S., Clark, A. M., and Bowen, B. W. (1998). Why restriction fragment length polymorphism analysis of mitochondrial DNA failed to resolve sardine (Sardinops) biogeography: insights from mitochondrial DNA cytochrome b sequences. *Can. J. Fish. Aquat. Sci.* 55, 2539–2547. doi: 10.1139/f98-127

Haltuch, M. A., Brooks, E. N., Brodziak, J., Devine, J. A., Johnson, K. F., Klibansky, N., et al. (2019). Unraveling the recruitment problem: a review of environmentally-informed forecasting and management strategy evaluation. *Fish. Res.* 217, 198–216. doi: 10.1016/j.fishres.2018.12.016

Hayashi, A., Yasuda, T., Kuroda, H., and Takahashi, M. (2019). *Stock assessment and evaluation for Japanese anchovy Engraulis japonicus (fiscal year 2018) in Marine fisheries stock assessment and evaluation for Japanese waters (fiscal year 2018/2019)*. Kanagawa: Fisheries Agency and Fisheries Research and Education Agency of Japan, 971–1001.

Hiyama, Y., Yoda, M., and Ohshimo, S. (2002). Stock size fluctuations in chub mackerel (Scomber japonicus) in the East China Sea and the Japan/East Sea. *Fish. Oceanogr.* 11, 347–353. doi: 10.1046/j.1365-2419.2002.00217.x

Hutchings, J. (2000). Collapse and recovery of marine fishes. *Nature* 406, 882–885. doi: 10.1038/35022565

Iversen, S. A., Zhu, D., Johannessen, A., and Toresen, R. (1993). Stock size, distribution and biology of anchovy in the Yellow Sea and East China Sea. *Fish. Res.* 16, 147–163. doi: 10.1016/0165-7836(93)90049-d

Ji, F., Guo, X., Wang, Y., and Takayama, K. (2020). Response of the Japanese flying squid (Todarodes pacificus) in the Japan Sea to future climate warming scenarios. *Clim. Change* 159, 601–618. doi: 10.1007/s10584-020-02689-3

Kaga, T., Yamashita, N., Okamoto, S., and Hamatsu, Y. (2019). *Stock Assessment and Evaluation for Japanese Flying Squid Todarodes pacificus (fiscal year 2018) in Marine fisheries stock assessment and evaluation for Japanese waters (fiscal year 2018/2019)*. Kanagawa: Fisheries Agency and Fisheries Research and Education Agency of Japan, 652–697.

Katsukawa, T. (2002). Switching fishes for non-equilibrium bioresorces. *Fish. Sci.* 68, 162–165. doi: 10.2331/fishsci.68.sup1_162

Kawauchi, Y., Yoda, M., and Aonuma, Y. (2019). *Stock Assessment and Evaluation for Yellowback Sea-Bream Dentex hypselosomus (fiscal year 2018) in Marine fisheries stock assessment and evaluation for Japanese waters (fiscal year 2018/2019)*. Kanagawa: Fisheries Agency and Fisheries Research and Education Agency of Japan, 1531–1553.

Kuroda, H., Yoda, M., Hayashi, A., Takegaki, S., Sasaki, C., and Takahashi, M. (2019b). *Stock Assessment and Evaluation for Blue Mackerel Scomber Australasicus (Fiscal Year 2018) in Marine Fisheries Stock Assessment and Evaluation for Japanese Waters (Fiscal Year 2018/2019)*. Kanagawa: Fisheries Agency and Fisheries Research and Education Agency of Japan, 279–309.

Kuroda, H., Yoda, M., Yasuda, T., Suzuki, K., Sosei, T., Sasa, C., et al. (2019a). *Stock Assessment and Evaluation for Chub Mackerel Scomber Japonicus (Fiscal Year 2018) in Marine Fisheries Stock Assessment and Evaluation for Japanese Waters (Fiscal Year 2018/2019)*. Kanagawa: Fisheries Agency and Fisheries Research and Education Agency of Japan, 209–247.

Lee, S. G., and Rahimi Midani, A. (2014). Productivity change under the vessel buyback program in Korean fisheries. *Fish. Sci.* 81, 21–28. doi: 10.1007/s12562-014-0829-4

Liao, C. H., Lan, K. W., Ho, H. Y., Wang, K. Y., and Wu, Y. L. (2018). Variation in the Catch Rate and Distribution of Swordtip Squid Uroteuthis edulis Associated with Factors of the Oceanic Environment in the Southern East China Sea. *Mar. Coastal Fish.* 10, 452–464. doi: 10.1002/mcf2.10039

Limbong, D., Hayashi, K., and Shirakihara, K. (1991). Seasonal distribution and migration of thecommon mackerel in the southwestern Japan Sea and the East China Sea. *Nippon Suisan Gakkaishi* 57, 63–68. doi: 10.2331/suisan.57.63

Ludwig, D., and Walters, C. J. (1981). Measurement errors and uncertainty in parameter estimates for stock and recruitment. *Can. J. Fish. Aquat. Sci.* 38, 711–720. doi: 10.1139/f81-094

Makino, M. (2018). Rebuilding and full utilization of alternating pelagic species around Japan: a social-ecological approach. *FAO Fish. Aquac. Tech. Pap* 630, 61–73.

Marshall, K. N., Koehn, L. E., Levin, P. S., Essington, T. E., and Jensen, O. P. (2018). Inclusion of ecosystem information in US fish stock assessments suggests progress toward ecosystem-based fisheries management. *ICES J. Mar. Sci.* 76, 1–9. doi: 10.1093/icesjms/fsy152

Martell, S., and Froese, R. (2013). A simple method for estimating MSY from catch and resilience. *Fish Fish.* 14, 504–514. doi: 10.1111/j.1467-2979.2012.00485.x

Maunder, M. N., and Thorson, J. T. (2018). Modeling temporal variation in recruitment in fisheries stock assessment: a review of theory and practice. *Fish. Res.* 217, 71–86. doi: 10.1016/j.fishres.2018.12.014

MFNZ (2008). *Harvest Strategy Standard for New Zealand Fisheries*. Wellington: Ministry of Fisheries.

Millar, R. B., and Meyer, R. (1999). "Nonlinear State-space Modeling of Fisheries Biomass Dynamics using Metropolis-Hastings within Gibbs Sampling," in *Technical Report STAT9901*, (Auckland: University of Auckland), 33.

Motomitsu, T., and Yoda, M. (2019). *Stock Assessment and Evaluation for Japanese Spanish Mackerel Scomberomorus niphonius (fiscal year 2018) in Marine fisheries stock assessment and evaluation for Japanese waters (fiscal year 2018/2019)*. Kanagawa: Fisheries Agency and Fisheries Research and Education Agency of Japan, 1708–1723.

MSA (2007). *Magnuson-Stevens Fishery Conservation and Management Act, Public Law 94–265. As amended by the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act (P.L. 109-479)*. Available online at: http://www.nmfs.noaa.gov/msa2005/docs/MSA_amended_msa%20_20070112_FINAL.pdf (accessed December 19, 2014).

Musick, J. A. (1999). Criteria to define extinction risk in marine fishes. *Fish* 24, 6–14. doi: 10.1577/1548-8446(1999)024<0006:ctderi>2.0.co;2

Nishikawa, H. (2018). Relationship between recruitment of Japanese sardine (*Sardinops melanostictus*) and environment of larval habitat in the low-stock period (1995-2010). *Fish. Oceanogr.* 28, 131–142. doi: 10.1111/fog.12397

Nishikawa, H., Yasuda, I., Komatsu, K., Sasaki, H., Sasai, Y., Setou, T., et al. (2013). Winter mixed layer depth and spring bloom along the Kuroshio front: implications for the Japanese sardine stock. *Mar. Ecol.* 487, 217–229. doi: 10.3354/meps10201

Ohshimo, S. (1996). Acoustic estimation of biomass and school character of the Japanese anchovy Engraulis japonicus in the East China Sea and the Yellow Sea. *Fish. Sci.* 62, 344–349. doi: 10.2331/fishsci.62.344

Ohshimo, S., Tanaka, H., and Hiyama, Y. (2009). Long-term stock assessment and growth changes of the Japanese sardine (Sardinops melanostictus) in the Sea of Japan and East China Sea from 1953 to 2006. *Fish. Oceanogr.* 18, 346–358. doi: 10.1111/j.1365-2419.2009.00516.x

Palomares, M. L. D., Froese, R., Derrick, B., Nöel, S.-L., Tsui, G., Woroniak, J., et al. (2018). "A preliminary global assessment of the status of exploited marine fish and invertebrate populations," in *A Report Prepared by the Sea Around US for OCEANA*, (Vancouver: The University of British Columbia), 64.

Plummer, M. (2003). "JAGS: a program for analysis of Bayesian graphical models using Gibbs sampling," in *Proceedings of the 3rd International Workshop on Distributed Statistical Computing (DSC 2003) March 20-22, Vienna, 2003*, eds K. Hornik, F. Leisch, and A. Zeileis (Vienna: Vienna Technical University), 20–22.

R Core Team (2013). *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing.

Sakai, T., Kawauchi, Y., and Aonuma, Y. (2019). *Stock Assessment and Evaluation for Black Scraper Thamnaconus modestus (fiscal year 2018) in Marine Fisheries Stock Assessment and Evaluation for Japanese waters (fiscal year 2018/2019)*. Kanagawa: Fisheries Agency and Fisheries Research and Education Agency of Japan, 2047–2061.

Schaefer, M. B. (1954). Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Inter Am. Trop. Tuna Comm. Bull.* 1, 23–56.

Schaefer, M. B. (1957). A study of the dynamics of the fishery for yellowfin tuna in the eastern tropical Pacific Ocean. *Inter Am. Trop. Tuna Comm. Bull.* 2, 243–285.

Sogawa, S., Hidaka, K., Kamimura, Y., Takahashi, M., Saito, H., Okazaki, Y., et al. (2019). Environmental characteristics of spawning and nursery grounds of Japanese sardine and mackerels in the Kuroshio and Kuroshio Extension area. *Fish. Oceanogr.* 28, 454–467. doi: 10.1111/fog.12423

Suzuki, K., Yasuda, T., Kuroda, H., and Takahashi, M. (2019). *Stock Assessment and Evaluation for Red-Eye Round Herring Etrumeus micropus (fiscal year 2018) in Marine fisheries stock assessment and evaluation for Japanese waters (fiscal year 2018/2019)*. Kanagawa: Fisheries Agency and Fisheries Research and Education Agency of Japan, 805–832.

Takasuka, A., Oozeki, Y., and Aoki, I. (2007). Optimal growth temperature hypothesis: why do anchovy flourish and sardine collapse or vice versa under the same ocean regime? *Can. J. Fish. Aquat. Sci.* 64, 768–776. doi: 10.1139/f07-052

Tashiro, K., and Iwatsuki, I. (1995). Growth and feeding habits in reared Japanese centropomid fish Lates japonicus. *Nippon Suisan Gakk.* 61, 684–688. doi: 10.2331/suisan.61.684

Wang, Y., Liu, Q., and Ye, Z. (2006). A Bayesian analysis on the anchovy stock (Engraulis japonicus) in the Yellow Sea. *Fish. Res.* 82, 87–94. doi: 10.1016/j.fishres.2006.08.007

Yamada, U., Horikawa, H., Nakabo, T., and Tokimura, M. (2007). *Scomber japonicus. Fish of the East China Sea and Yellow Sea*. Kanagawa: Tokai University Press, 972–979.

Yasuda, T., Kuroda, H., Hayashi, A., Yoda, M., Suzuki, K., and Takahashi, M. (2019). *Stock Assessment and Evaluation for South American Pilchard Sardinops melanostictus (fiscal year 2018) in Marine fisheries Stock Assessment and Evaluation for Japanese waters (fiscal year 2018/2019)*. Kanagawa: Fisheries Agency and Fisheries Research and Education Agency of Japan, 57–95.

Yasuda, T., Yukami, R., and Ohshimo, S. (2014). Fishing ground hotspots reveal long-term variation in chub mackerel Scomber japonicus habitat in the East China Sea. *Mar. Ecol. Prog. Ser.* 501, 239–250. doi: 10.3354/meps10679

Yatsu, A. (2019). Review of population dynamics and management of small pelagic fishes around the Japanese Archipelago. *Fish. Sci.* 85, 611–639. doi: 10.1007/s12562-019-01305-3

Yoda, M., Kuroda, H., Sasaki, C., and Takahashi, M. (2019). *Stock Assessment and Evaluation for Japanese Jack Mackerel Trachurus japonicus (fiscal year 2018) in Marine fisheries Stock Assessment and Evaluation for Japanese waters (fiscal year 2018/2019)*. Kanagawa: Fisheries Agency and Fisheries Research and Education Agency of Japan, 131–162.

Yoda, M., and Takahashi, M. (2018). *Stock Assessment and Evaluation for Swordtip Squid Uroteuthis edulis (Fiscal Year 2017) in Marine Fisheries Stock Assessment and Evaluation for Japanese Waters (Fiscal Year 2017/2018)*. Kanagawa: Fisheries Agency and Fisheries Research and Education Agency of Japan, 2110–2125.

Yoda, M., and Takahashi, M. (2019). *Stock Assessment and Evaluation for Swordtip Squid Uroteuthis edulis (Fiscal Year 2018) in Marine Fisheries Stock Assessment and Evaluation for Japanese Waters (Fiscal Year 2018/2019)*, Kanagawa: Fisheries Agency and Fisheries Research and Education Agency of Japan. 2218–2233.

Yoda, M., and Yoneda, M. (2009). Assessment of reproductive potential in multiple-spawning fish with indeterminate fecundity: a case study of yellow sea bream *Dentex hypselosomusin* the East China Sea. *J. Fish Biol.* 74, 2338–2354. doi: 10.1111/j.1095-8649.2009.02246.x

Yun, S. D., and Nam, J. (2017). Application of a bioeconomic model to Spanish mackerel in the seas of Korea. *Fish. Sci.* 83, 1061–1076. doi: 10.1007/s12562-017-1131-z

Zhang, C. I., and Lee, J. B. (2001). Stock assessment and management implications of horse mackerel (*Trachurus japonicus*) in Korean waters, based on the relationships between recruitment and the ocean environment. *Prog. Oceanogr.* 49, 513–537. doi: 10.1016/s0079-6611(01)00038-6

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Marine Science

ORIGINAL RESEARCH
published: 13 November 2020
doi: 10.3389/fmars.2020.525363

Assessment of 11 Exploited Fish and Invertebrate Populations in the Japan Sea Using the CMSY and BSM Methods

Shanshan Zhang[1,2,3], Yibang Wang[1,4], Yuanchao Wang[1,2,3], Cui Liang[1,2,5]* and Weiwei Xian[1,2,5]*

[1] Key Laboratory of Marine Ecology and Environmental Sciences, Institute of Oceanology, Chinese Academy of Sciences (CAS), Qingdao, China, [2] Laboratory for Marine Ecology and Environmental Science, Qingdao National Laboratory for Marine Science and Technology, Qingdao, China, [3] University of Chinese Academy of Sciences, Beijing, China, [4] Qingdao University of Science and Technology, Qingdao, China, [5] Center for Ocean Mega-Science, Chinese Academy of Sciences, Qingdao, China

OPEN ACCESS

Edited by:
Maria Lourdes D. Palomares, University of British Columbia, Canada

Reviewed by:
Gabriel Vianna, University of Western Australia, Australia
Rainer Froese, GEOMAR Helmholtz Center for Ocean Research Kiel, Germany

***Correspondence:**
Cui Liang
liangc@qdio.ac.cn
Weiwei Xian
wwxian@qdio.ac.cn

Specialty section:
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

Received: *09 January 2020*
Accepted: *24 September 2020*
Published: *13 November 2020*

Citation:
Zhang S, Wang Y, Wang Y, Liang C and Xian W (2020) Assessment of 11 Exploited Fish and Invertebrate Populations in the Japan Sea Using the CMSY and BSM Methods. Front. Mar. Sci. 7:525363. doi: 10.3389/fmars.2020.525363

The catch-maximum sustainable yield (CMSY) method and a closely related Bayesian state-space Schaefer surplus production model (BSM) were combined with published catch data and catch per unit effort (CPUE) time series or spawning stock biomass (SSB) data to evaluate fisheries reference points for exploited resources of the Japan Sea. Eleven fish and invertebrate stocks were assessed; outcomes obtained through this analysis were the carrying capacity, biomass trajectory, maximum sustainable yield, and related parameters of each stock. Results showed that the stock of *Arctoscopus japonicus* was slightly overfished; the stocks of *Cleisthenes pinetorum*, *Hippoglossoides dubius*, *Paralichthys olivaceus*, and *Chionoecetes opilio* were overfished; and the stocks of *Eopsetta grigorjewi*, *Pagrus major*, *Gadus chalcogrammus*, and *Glossanodon semifasciatus* were grossly overfished; *Pseudopleuronectes herzensteini* was proved to be severely depleted; only *Pandalus eous* was in good condition. These results are consistent with the few previous studies on the status of fish species around the Japan Sea, where overfishing is becoming increasingly apparent. These assessments provide a basis for guiding the use, management, and rebuilding of fishery resources in the Japan Sea.

Keywords: data-limited stock assessment, maximum sustainable yield, fisheries management, the Japan Sea and environs, CMSY and BSM

INTRODUCTION

Fish biomass is declining worldwide due to overexploitation and poor fisheries management (Watson and Pauly, 2001; Tremblay-Boyer et al., 2011; Watson et al., 2013), as confirmed by regional studies (Christensen et al., 2003; Liang and Pauly, 2017; Froese et al., 2018). With the increase of fishing pressure since the 1960s, the biomass of the main commercial stocks in the northern hemisphere started to decline, and the situation worsened in the 1980s and 1990s (Pauly, 2008). The depletion of fishery resources resulted in a series of problems, which have greatly limited the functioning and productive capacity of marine ecosystems (Pauly and Zeller, 2016; Liu et al., 2019).

In order to alleviate fishing pressure and restore fishery resources, a series of management and protection measures, based on scientific stock assessments, have been implemented. However, most global fish stocks remain unassessed, due to the lack of data and/or experts. In developed countries, the proportion of assessed fish stocks ranges from 10 to 50%. In developing countries, the proportion is usually lower, between 5 and 20% (Costello et al., 2012). Traditional stock assessment methods are typically based both on survey and fishery data, which are hard to be accessed, and more than 90% of the global fishery stocks are data-limited (Geromont and Butterworth, 2015). Therefore, more assessment methods based on sparse data need to be developed and adopted (Liu et al., 2019). The Monte Carlo method for capturing maximum sustainable yield (CMSY) developed by Froese et al. (2017) and the closely related Bayesian state-space Schaefer production model (BSM) provide a new solution. These two methods use only catch data (CMSY) or catch and abundance data (BSM) to assess the status of developed fish stocks. The main advantage of BSM compared to other implementations of surplus production models is its focus on "informative priors" and the acceptance of short and incomplete catch per unit effort (CPUE; Froese et al., 2017). Froese et al. (2018) successfully applied these methods to 397 European stocks to examine their current status, exploitation pattern, future catch, and profitability.

Japan is one of the most important fishing countries in East Asia, and fishery production occupies an important position in its national economy. In 1997, the Japanese Fisheries Agency has introduced the Total Allowable Catch (TAC) system, combined with traditional effort limitations (Makino, 2011; FAO, 2018). Since then, the Fisheries Research Agency of Japan (FRA) has released annual assessment reports for main commercial stocks, based on data sets obtained from fisheries and research surveys, such as catches, fishing efforts, length frequencies, and catch-at-age data. Some basic information about the status of the exploited stocks are presented, mainly including (1) length composition and the age structure of the catch, (2) the estimation of recruitment, (3) the variation of catches and biomass, and (4) suggested next-year catches. However, the official assessments lack the estimation of maximum sustainable yield (MSY) and relative biomass (B/B_0; stock size relative to unexploited stock), which are important fisheries reference points for management. Besides, the information published by FRA is exclusively in Japanese, and it makes much of the information relatively inaccessible outside Japan.

Therefore, in this contribution, we abstracted catch and biomass data of 11 exploited stocks in the Japan Sea from the official reports, including nine fish stocks (*Arctoscopus japonicus*, *Cleisthenes pinetorum*, *Eopsetta grigorjewi*, *Hippoglossoides dubius*, *Pseudopleuronectes herzensteini*, *Paralichthys olivaceus*, *Pagrus major*, *Gadus chalcogrammus*, and *Glossanodon semifasciatus*) and two invertebrate stocks (*Chionoecetes opilio* and *Pandalus eous*), and assessed them with CMSY and BSM methods. In the results, we provided estimates of the intrinsic population growth rate (r), carrying capacity (k), MSY, relative biomass, and stock status for the stocks in question, and then compared the MSY estimates with reported catches, calculating how much catch was lost due to the lack of MSY. Based on CMSY and BSM methods, this contribution presented new insights about the exploitation and status of these 11 stocks, which can make a point for better management.

MATERIALS AND METHODS

Data Sources

Altogether, 11 stocks in the Japan Sea were analyzed (**Table 1**). Fishing entities exploring the stocks in the Japan Sea include Japan, South Korea, Russia, and North Korea. Japan is the dominant fishing nation in this area, and the catch and CPUE data from Japan represent the overall trend. Besides, the successive catch and biomass data are not available from other countries; thus, only fishery data from Japan were used in our contribution. All of the data used for stock assessments were abstracted from published reports from the Fisheries Agency of Japan in 2018 (full data set, see **Supplementary Material 1** for details).

Methods of the CMSY and BSM

The CMSY and BSM methods used in this study are extensively described in Froese et al. (2017). Given that all 11 populations have available CPUE or SSB data in addition to their catch data, they were analyzed by both CMSY and BSM methods. All algorithms and analyses are implemented through the R code provided by Froese et al. (2017).

The prior of r range is required in implementing CMSY and BSM methods. To define the prior boundaries of r for the 11 stocks evaluated, the proxies of resilience provided in FishBase[1] or SeaLifeBase[2] were converted to r ranges (**Table 2**).

Setting Prior Biomass Ranges

Both the CMSY and BSM methods require estimates of relative biomass (B_t/k), the proportion of the carrying capacity that is present at the beginning and end of the time series, i.e., B_{start}/k and B_{end}/k (Froese et al., 2017). **Table 3** summarized prior estimates of relative biomass we set for the 11 stocks, based on their depletion level at the beginning and end of the time series, and optionally in an intermediate year. Data source came from published reports from the Fisheries Agency of Japan (2018), where biomass variation was presented. We set the initial depletion level of *A. japonicus*, *H. dubius*, *P. olivaceus*, *G. chalcogrammus*, and *G. semifasciatus* as *low* (B_{start}/k = 0.4–0.8), and *C. pinetorum*, *P. herzensteini, P. major*, *C. opilio*, and *P. eous* as *medium* (B_{start}/k = 0.2–0.6). For *E. grigorjewi*, whose time series of catch data begins after 1990, the Fisheries Agency of Japan (2018) reported low initial biomass due to the rapid development of fishing techniques; thus, we set its B_{start}/k as *strong* (B_{start}/k = 0.01–0.4). We chose a *strong* depletion at the end year of the time series for *A. japonicus*, *E. grigorjewi*, *P. herzensteini*, and *G. chalcogrammus*. For the other stocks, we found sources suggesting *medium* depletion. We also included

[1] www.fishbase.org

[2] www.sealifebase.org

TABLE 1 | Summary of catch and CPUE data of 11 exploited populations in the Japan Sea.

Scientific name (Common name)	Catch	Additional data*	Region	Method
Arctoscopus japonicus (Japanese sandfish)	1971–2017	CPUE (1972–2017)	(1) the Central and western Japan Sea	BSM
Cleisthenes pinetorum (Sôhachi)	1966–2017	CPUE (1972–2017)	(2) the Western Japan Sea	BSM
Eopsetta grigorjewi (shotted halibut)	1993–2017	SSB (1993–2017)	(3) the Japan Sea	BSM
Hippoglossoides dubius (flathead flounder)	1972–2017	CPUE (1972–2017)	(4) the Japan Sea	BSM
Pseudopleuronectes herzensteini (yellow striped flounder)	1971–2017	CPUE (1979–2017)	(5) the Japan Sea	CMSY
Paralichthys olivaceus (bastard halibut)	1970–2017	SSB (1986–2017)	(6) the Western Japan Sea	BSM
Pagrus major (red seabream)	1969–2017	SSB (1986–2017)	(7) the Western Japan Sea	BSM
Gadus chalcogrammus (Alaska pollock)	1980–2017	SSB (1980–2017)	(8) the Northern Japan Sea	BSM
Glossanodon semifasciatus (deep-sea smelt)	1975–2017	CPUE (1975–2017)	(9) the Japan Sea	BSM
Chionoecetes opilio (snow crab)	1986–2017	CPUE (1986–2017)	(10) the Western Hokkaido regions	BSM
Pandalus eous (Alaskan pink shrimp)	1980–2017	CPUE (1980–2016)	(11) the Japan Sea	BSM

**Note that the catch and CPUE for all the assessed stocks came from the Japan fisheries agency (https://www.jfa.maff.go.jp/e/index.html), and the CPUE data were corrected for the increase in fishing power by assuming an annual increase of 2% (Palomares and Pauly, 2019).*

intermediate biomass priors for some stocks in the analysis as this approach can greatly improve the accuracy of the models (**Table 3**; Froese et al., 2017).

The CMSY method generates the geometric mean and 95% confidence intervals for each parameter estimate (Schaefer, 1954; Ricker, 1975). When additional constraints were available (e.g., CPUE or SSB), we also ran the BSM method (Froese et al., 2017). The predicted relative total biomass (B/B_{MSY}) in the last year is used to assess the stock status derived from BSM and CMSY methods (**Table 4**; Palomares et al., 2018), where $2 \times B_{end}/k = B_{MSY}$, as MSY is taken at 0.5 k.

RESULTS

CMSY and BSM methods were applied to the 11 stocks. Given that BSM combines information from both catch and biomass data and had more reliable estimates, only BSM results were presented here. Most stocks covered in this study showed similar biomass trajectories, with high biomass occurring at the beginning of time series and low biomass in recent years. Here, we took *P. olivaceus* as an example to illustrate the output. The full results of the other species were presented in **Supplementary Material 2**.

TABLE 2 | Ranges of intrinsic population growth rates (year^{-1}) suggested by FishBase (www.fishbase.org) and SeaLifeBase (www.sealifebase.ca) for the populations studied.

Scientific name (Common name)	Prior *r* range	Resilience (*r*)
Arctoscopus japonicus (Japanese sandfish)	0.2–0.8	Medium
Cleisthenes pinetorum (Sôhachi)	0.2–0.8	Medium
Eopsetta grigorjewi (shotted halibut)	0.2–0.8	Medium
Hippoglossoides dubius (flathead flounder)	0.05–0.5	Low
Pseudopleuronectes herzensteini (yellow striped flounder)	0.2–0.8	Medium
Paralichthys olivaceus (bastard halibut)	0.2–0.8	Medium
Pagrus major (red seabream)	0.05–0.5	Low
Gadus chalcogrammus (Alaska pollock)	0.05–0.5	Low
Glossanodon semifasciatus (deep-sea smelt)	0.6–1.5	High
Chionoecetes opilio (snow crab)	0.2–0.8	Medium
Pandalus eous (Alaskan pink shrimp)	0.6–1.5	High

Figure 1A shows a good correlation between carrying capacity (k) and r values with both CMSY and BSM methods producing a "best" r–k pair with a 95% confidence interval (CI). The biomass trajectories generated by CMSY and BSM for the *P. olivaceus* (**Figure 1B**) agree well with the CPUE observations. The predicted *P. olivaceus* catch over time shows fluctuations around the MSY (the MSY estimate was 1,440 tons per year; **Table 5** and **Figure 1C**) of about ± 500 tons year^{-1}, with an overall decline from 1980 to 2017. The predicted relative total biomass (B/B_{MSY}) also declined from the mid-1970s to 2000 and then flattened. From the results of our assessment, the current status of *P. olivaceus* stock is overfished (**Figure 1D**; $B/B_{MSY} = 0.724$). The match between the predicted *P. olivaceus* catch and the observed catch was within 95% confidence intervals for the entire model time period (**Figure 1E**). The CPUE observation was also within the 95% confidence interval of the predictions for the entire time period (**Figure 1F**). Residuals were very small and could be ignored (**Supplementary Material 2**).

Status of the 11 stocks can be defined according to their terminal B/B_{MSY} estimates. **Table 5** summarized r, k, MSY, relative biomass, and status for 11 stocks assessed using the BSM methods. Catch and relative biomass trajectories were visually shown in **Figures 2**, **3**. Except for *P. eous*, the terminal B/B_{MSY} values for the other 10 assessed stocks were less than 1, indicating that these stocks were overfished at different levels (**Table 5**). The stock of *A. japonicus* was slightly overfished (**Table 5**; $0.8 < B/B_{MSY} < 1$; **Figure 2A**) in recent years, although it suffered an overfished (**Table 5**; $B_{end}/B_{MSY} < 0.5$) stage in the late 1990s. Four stocks, including *C. pinetorum*, *H. dubius*, *P. olivaceus*, and *C. opilio* were overfished (**Table 5**; $0.5 < B_{end}/B_{MSY} < 0.8$), as shown in **Figures 2B,D,F,J**, while they were in good condition in the early years of the time series. The stocks of *E. grigorjewi*, *P. major*, *G. chalcogrammus*, and *G. semifasciatus* (**Figures 2C,G,H,I**) were grossly overfished ($B_{end}/B_{MSY} < 0.5$) according to the definition of fish stock status

TABLE 3 | Suggested ranges of B_{start}/k, B_{int}/k, and B_{end}/k for the period before catch data became available*.

Scientific name (Common name)	B_{start}/k		B_{int}/k		B_{end}/k		Data sources
	Suggested prior	Depletion level	Suggested prior (Year)	Depletion level	Suggested prior	Depletion level	
Arctoscopus japonicus (Japanese sandfish)	0.4–0.8	Low	–	–	0.01–0.4	Strong	All priors refer to the Fisheries Agency of Japan, 2018
Cleisthenes pinetorum (Sôhachi)	0.2–0.6	Medium	0.2–0.6 (1999)	Medium	0.2–0.6	Medium	
Eopsetta grigorjewi (shotted halibut)	0.01–0.4	Strong	–	–	0.01–0.4	Strong	
Hippoglossoides dubius (flathead flounder)	0.4–0.8	Low	0.01–0.4 (1992)	Strong	0.2–0.6	Medium	
Pseudopleuronectes herzensteini (yellow striped flounder)	0.2–0.6	Medium	–	–	0.01–0.4	Strong	
Paralichthys olivaceus (bastard halibut)	0.4–0.8	Low	–	–	0.2–0.6	Medium	
Pagrus major (red seabream)	0.2–0.6	Medium	0.01–0.4 (1990)	Strong	0.2–0.6	Medium	
Gadus chalcogrammus (Alaska pollock)	0.4–0.8	Low	0.01–0.4 (2008)	Strong	0.01–0.4	Strong	
Glossanodon semifasciatus (deep-sea smelt)	0.4–0.8	Low	0.01–0.4 (1986)	Strong	0.2–0.6	Medium	
Chionoecetes opilio (snow crab)	0.2–0.6	Medium	-	-	0.2–0.6	Medium	
Pandalus eous (Alaskan pink shrimp)	0.2–0.6	Medium	0.2–0.6 (2010)	Medium	0.2–0.6	Medium	

**See Supplementary Material to Froese et al. (2017) and published scientific reports from the Fisheries Agency of Japan in 2018.*

in Palomares et al. (2018). The stock of *P. herzensteini* was severely depleted (**Figure 2E**; $B_{end}/B_{MSY} < 0.2$). Only *P. eous* was healthy ($B_{end}/B_{MSY} = 1$) as shown in **Figure 2K** and **Table 5**.

A fishing pressure (F/F_{MSY})–stock state (B/B_{MSY}) plot was used to further illustrate the status of 11 stocks in question. As was shown in **Figure 4**, eight stocks are overexploited and/or outside of safe biological limits in the final years of time series. *C. opilio* and *A. japonicus* are distributed in the yellow area, which means that they are benefiting from low fishing pressure, and the stocks are recovering. *P. eous* is distributed in a green area, indicating that it is exploited by sustainable fishing pressure and the biomass can produce high yields close to MSY (**Figure 4**).

With the MSY estimates given by the BSM method, we contrasted it with the corresponding reported catches, highlighting how much catch was lost due to inefficient management (**Figure 3**). The results showed that catch losses of the nine stocks (*P. major* and *G. chalcogrammus* not included) varied from 135 tons (*C. opilio*) to 106,022 tons (*A. japonicus*), with an average of 25,112 tons. The total catches of *P. major* and *G. chalcogrammus* were more than their total MSYs, which indicated that in recent years, the stocks in the Japan Sea were still in great fishing pressure.

TABLE 4 | Definition of fish stock status, based on F/F_{MSY} and B/B_{MSY} in the final year of a time series*.

F/F_{MSY}	B_{end}/B_{MSY}	Stock status
=1	=1	Healthy
	0.8–1.0	Slightly overfished (Recovering)
	0.5–0.8	Overfished (Recovering)
>1	0.5–1.0	
	0.2–0.5	Grossly overfished (Outside of safe biological limits)
	0–0.2	Severely depleted (Collapsed)

**From Froese et al. (2018) and Palomares et al. (2018).*

DISCUSSION

With the increased use of power trawlers and other new fishing gears, the growing demand for seafood has led to overexploitation of marine resources, and the fishing industry has witnessed a net decline in recruitment and profits in the past 20 years (Pitcher and Lam, 2015; Wang et al., 2020). The depletion of fishery resources would generate a major impact on fishing countries, especially for Japan, where the fishing industry plays an important role, and seafood is an essential source of animal protein.

Rational exploitation of fishery resources requires scientific stock assessment. Most traditional stock assessment models require large amounts of data, which limits their implementation to data-rich species (Carruthers et al., 2014). Relatively little attention has been paid to other species (Pauly, 2006; Costello et al., 2012). In this contribution, the data-limited stock assessment methods CMSY and BSM were applied to 11 important commercial fish and invertebrate stocks in the Japan Sea. The BSM method helped fully understand the nature of stock dynamics by using catch and biomass (CPUE or SSB) data and provided estimates for important fisheries reference points, i.e., MSY and relative biomass, which were not available in the original official assessment reports (Fisheries Agency of Japan, 2018). This study presented new insights about the exploitation and status of these 11 stocks and provided management implications for the stocks in question.

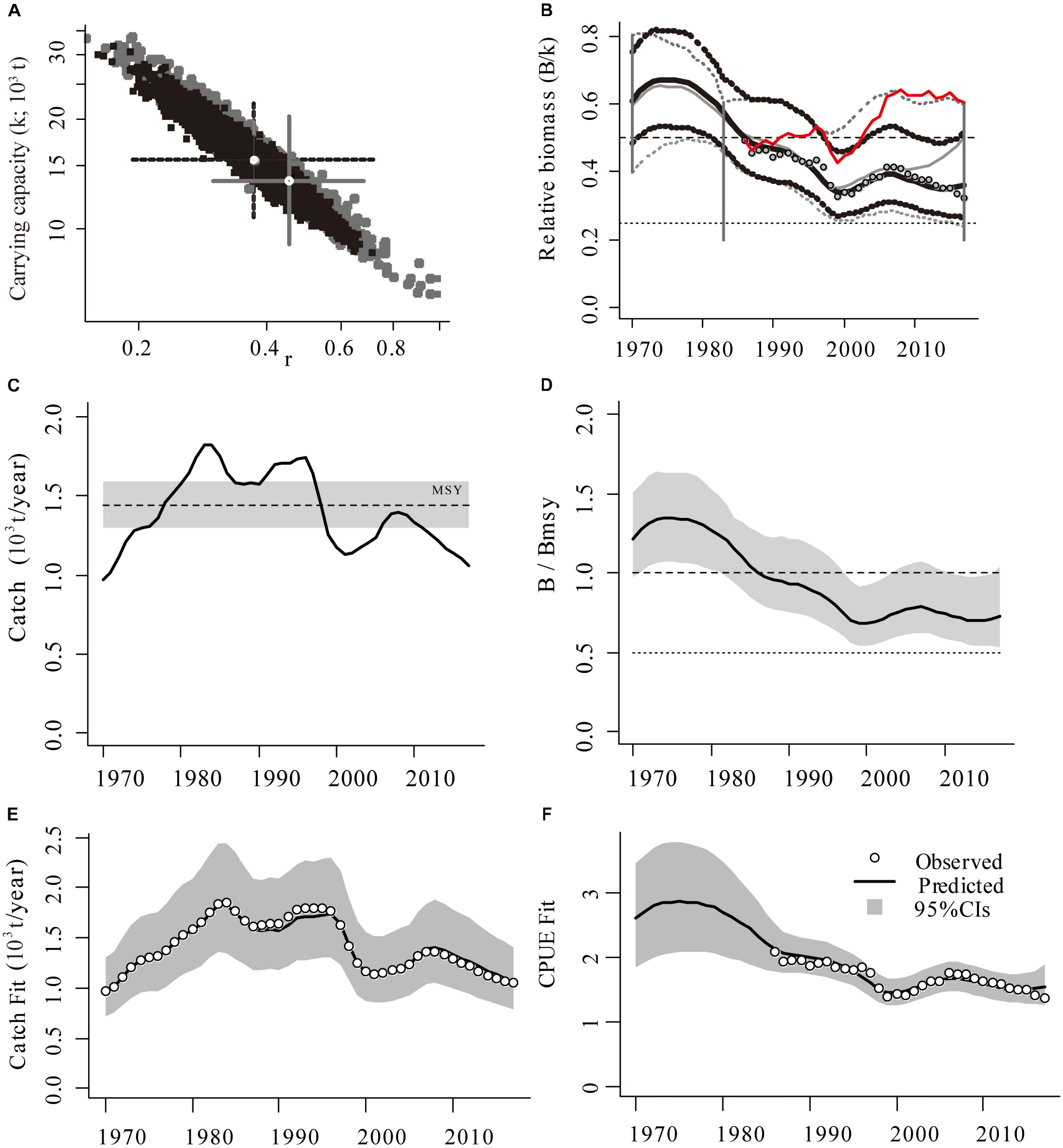


FIGURE 1 | (A) Example of the viable *r–k* pairs from CMSY (in gray) and BSM (in black) methods. **(B)** The crosses indicate the most probable pairs and their 95% confidence intervals (solid cross: CMSY; dotted cross: BSM; Red curve: the correction of CPUE for effort creep). **(C)** Catches relative to MSY with indication of 95% confidence limits in gray, and **(D)** development of predicted relative total biomass (B/B_{MSY}), with the gray area indicating uncertainty. **(E)** The fit of the median of predicted catch, with approximate 95% confidence limits, to the observed catch (points), and **(F)** a similar graph for predicted vs. observed CPUE (for *Paralichthys olivaceus*).

Long-term trends in fisheries production in Japan peaked in the late 1980s and then declined sharply with the collapse of Japanese sardine (Tian et al., 2006; Ren and Liu, 2020). The reason was mainly due to heavy fishing, followed by the effect of the reduction in seawater temperature during this period (Tian et al., 2006). In addition to Japanese sardines, the production of other fish species has also declined since the 1980s, such as the nine fish stocks in our contribution (**Figure 3**). The

TABLE 5 | Summary of *r*, *k*, *MSY*, relative biomass, and status for 11 populations assessed using the BSM methods.

Scientific name (Common name)	r (year^{-1})	k (10^3 t)	MSY (10^3 t·year^{-1})	B_{end}/k	F/F_{MSY}	B/B_{MSY}	Status
Arctoscopus japonicus (Japanese sandfish)	0.315	234	18.4	0.489	0.78	0.979	Slightly overfished
Cleisthenes pinetorum (Sôhachi)	0.403	36.4	3.67	0.251	1.17	0.502	Overfished
Eopsetta grigorjewi (shotted halibut)	0.355	16.7	1.48	0.123	1.87	0.245	Grossly overfished
Hippoglossoides dubius (Flathead flounder)	0.194	80.3	3.89	0.284	1.17	0.568	Overfished
Pseudopleuronectes herzensteini (yellow striped flounder)	0.397	7.19	0.713	0.091	3.10	0.182	Severely depleted
Paralichthys olivaceus (Bastard halibut)	0.373	15.4	1.44	0.362	1.11	0.724	Overfished
Pagrus major (red seabream)	0.135	186	6.26	0.220	2.43	0.440	Grossly overfished
Gadus chalcogrammus (Alaska pollock)	0.336	413	31.7	0.162	1.28	0.230	Grossly overfished
Glossanodon semifasciatus (Deep-sea smelt)	0.603	22.5	3.39	0.167	1.35	0.334	Grossly overfished
Chionoecetes opilio (snow crab)	0.333	0.434	0.036	0.467	0.58	0.658	Overfished
Pandalus eous (Alaskan pink shrimp)	0.972	6.44	1.37	0.558	1.00	1.170	Healthy

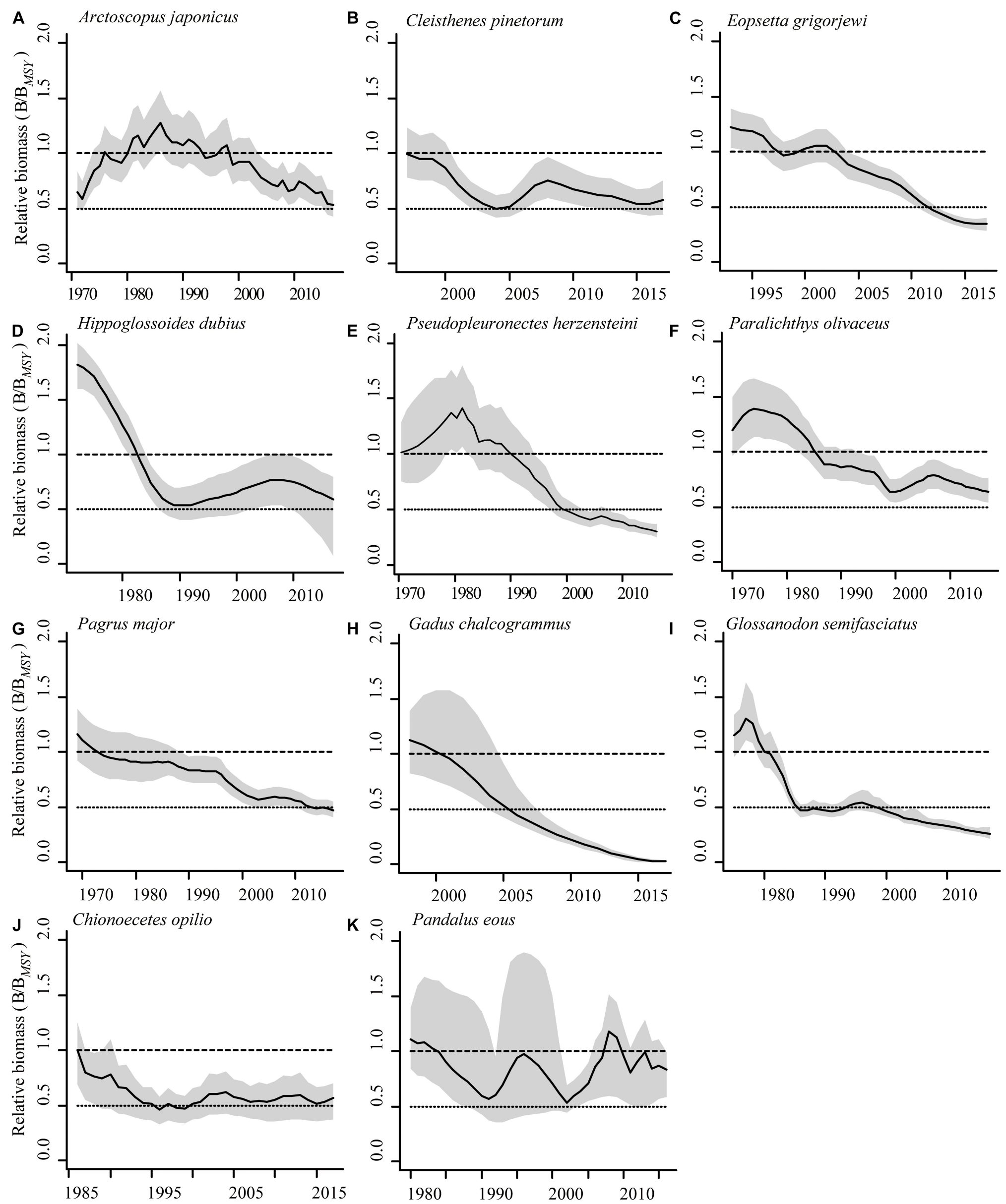


FIGURE 2 | Trajectories of relative total biomass (B/B_{MSY}) of 11 stocks in the Japan Sea.

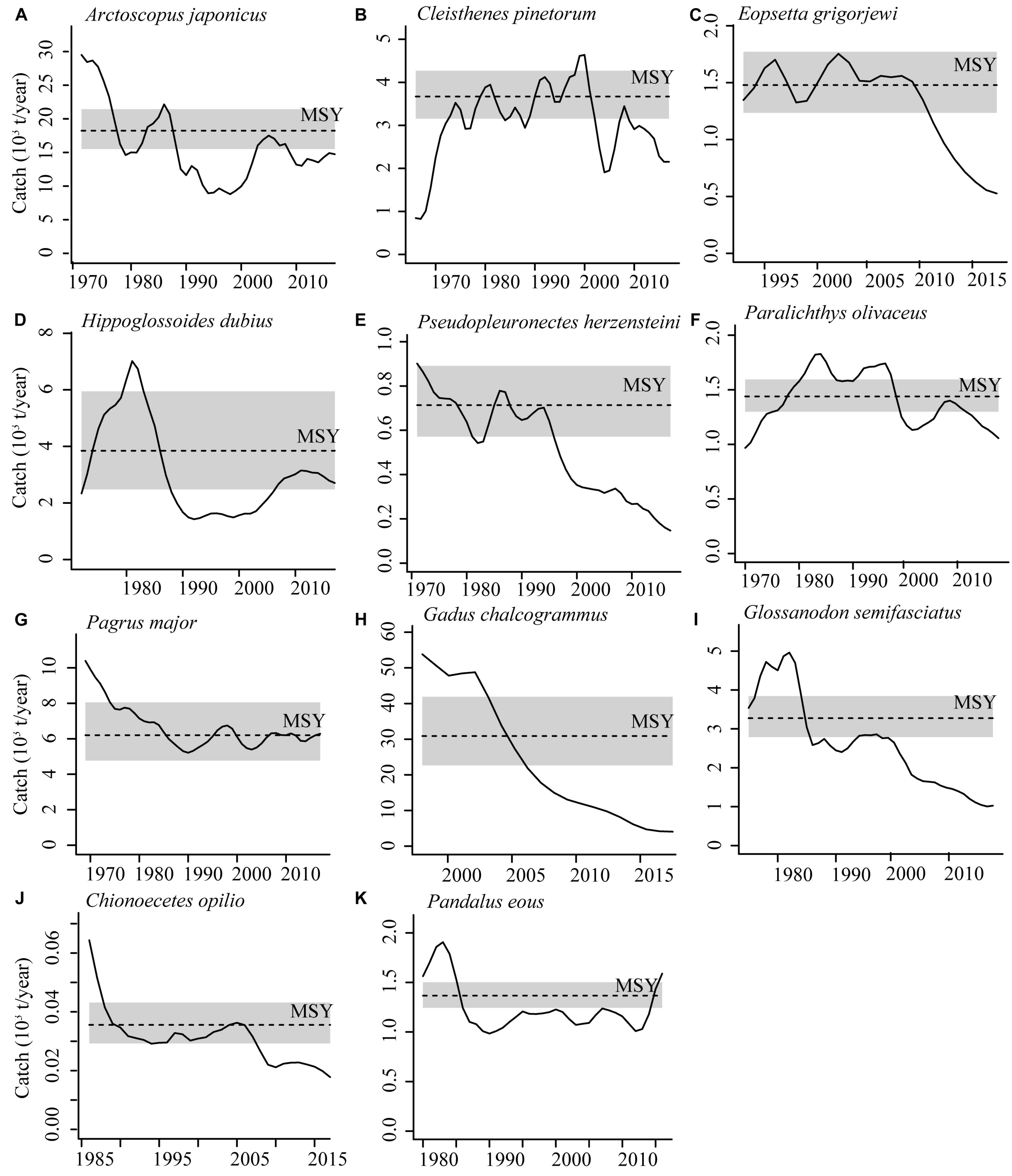


FIGURE 3 | Trajectories of catch of 11 stocks in the Japan Sea.

decline in catch generally corresponds to biomass depletion (**Figure 2**), and our results are consistent with the few previous studies on these stocks. An assessment of extinction risk for marine fishes also highlighted the over-fishing of *P. major* (Comeros-Raynal et al., 2016; Shin et al., 2018), which was consistent with our assessment (**Figure 2G**) and should be taken seriously. In addition, the status assessment conducted for the commercially important species *P. herzensteini* was also similar to our results (**Figure 2E**), which showed that the stock declined to a low level in recent years (Fisheries Research Institute of Hokkaido Research Organization, 2017; Joh and Wada, 2018). Based on the total catch, *G. chalcogrammus* is the second most important fish species in the world. From Alaska to northern Japan, about 3 million tons of *G. chalcogrammus* are caught annually (FAO, 2010). The Fisheries Agency of Japan and our BSM model have both reported the low level of

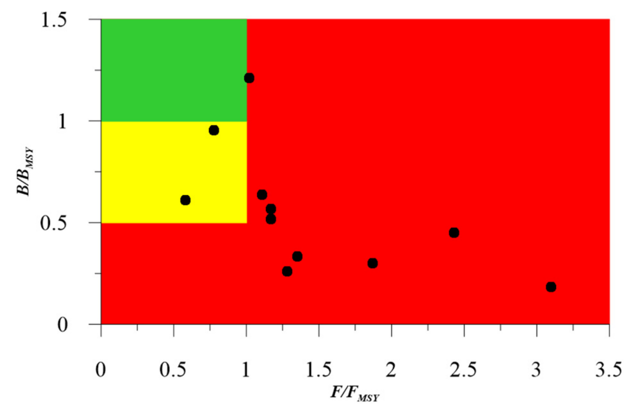


FIGURE 4 | Presentation of 11 stocks in Japan Sea in a pressure (F/F_{MSY})–stock state (B/B_{MSY}) plot, for the last years with available data (2016–2017). Red area: stocks that are being overfished or are outside of safe biological limits; yellow area: recovering stocks; green area: stocks subject to sustainable fishing pressure and of a healthy stock biomass that can produce high yields close to MSY.

G. chalcogrammus resource in 2018 (Fisheries Agency of Japan, 2018; **Figure 3H**).

Since 1950, global invertebrate catches have rapidly expanded with a sixfold increase in biomass and double the number of taxa reported. By 2004, 34% of invertebrate fisheries were overexploited, collapsed, or closed (Anderson et al., 2011). In the Japan Sea, catch of invertebrate species (e.g., crab, pink shrimp) was high during most of the 1970–1980s, but it declined to generally low catches in the 1990s (Tian et al., 2008). At the same time, a variety of stock management measures were carried out in the southwestern coastal regions of the Japan Sea (Yamasaki, 1994). These measures seem to have had a positive effect on the stocks: the declining trend of *C. opilio* in landings ceased in 1995 and the stocks gradually increased until 2000 (Kon et al., 2003). The population gradually recovered by 2011, but then dropped again before 2015; it seems to have improved in recent years (Mao et al., 2019). The results simulated by the BSM method in the study are similar to this trend (**Figures 2J**, 3J). *P. eous* is another important invertebrate fishery in the North Pacific due to its short life cycle (Koeller et al., 2003; Ouellet and Chabot, 2005). The biomass of *P. eous* along the coast of Honshu Island modeled by the BSM method showed a decreasing trend from the 1980s to the early 1990s, followed by a rapid increase from the end of the 1990s until 2000. *P. eous* is the only stock that our study found at a healthy level, which was also reported a high biomass level in the Fisheries Agency of Japan report (Fisheries Agency of Japan, 2018).

Among the 11 stocks in question, 10 stocks have current biomass that is smaller than 50% of unexploited biomass ($B_{end}/B_0 < 0.5$ or $B_{end}/B_{MSY} < 1$), which means that these stocks are not large enough to produce MSY or fulfill their ecosystem roles as prey or predator and are likely ill prepared for climate change due to restricted genetic variability. Moreover, our results showed that if the current fishing pressure was maintained, the stock status of eight stocks would be getting worse, except for *C. opilio*, *A. japonicus*, and *P. eous*, whose current fishing pressure was lower than or equal to the one that would generate MSY (**Figure 4** and **Table 5**).

A proper conceptualization of MSY was first proposed by Schaefer (1954), and MSY has now been legally and widely adopted for world fisheries with intent to enable fishermen to obtain a maximum catch that is sustainable and to protect overfished stocks (CCRF, 2004; ISEU, 2006). Based on the estimates of MSY generated by the BSM method and the reported catches, nine stocks' catches were lower than their MSYs, and the lost catch varied among different stocks. The other two stocks, i.e., *P. herzensteini* and *P. major*, whose reported catches were higher than their MSYs, correspond to high F/F_{MSY} and low B/B_{MSY}, indicating that both of them are suffering from overexploitation, and more efficient management measures are needed.

As one of the most important fishery countries, Japan has been committed to the rational exploitation and protection of fishery resources. Now, by using only fishery data, CMSY and BSM methods provide a new way to estimate stock dynamics and important fisheries reference points, which will enrich the current official reports, and solve the dilemma for data sparse stocks. We expect that the quantitative assessments conducted in our contribution will contribute to future improvements in fisheries and management systems in Japan Sea and help us understand the state of global fisheries resources in greater details.

CONCLUSION

The CMSY and BSM methods were used to estimate important fish stocks in the Japan Sea. Of 11 stocks studied, 1 stock was slightly overfished, 4 stocks were overfished, 4 stocks were grossly overfished, and 1 was severely depleted; only 1 stock, *P. eous,* was in good condition (healthy). This result suggests that fisheries managers in Japan should implement recovery measures. With regard to the CMSY and BSM methods we deployed, we conclude that the results obtained using these methods are very consistent with the limited observations of these 11 stocks in the Japan Sea. For the assessment of data-limited stocks, both are very effective and useful.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

SZ analyzed the data and wrote the original draft. YBW and YCW collected the data and provided guidance on the data analysis and structure of our contribution. CL and WX were responsible for conceptualization, methodology, and reviewing and editing the manuscript. All authors contributed to the article and approved the submitted version.

FUNDING

This work was supported by grants from the National Natural Science Foundation of China (Nos. 41976094 and 31872568), the Key Deployment Project of Center for Ocean Mega-Science, Chinese Academy of Sciences (COMS2019Q14), and the Youth Innovation Promotion Association CAS.

ACKNOWLEDGMENTS

SZ acknowledges China Scholarship Council (CSC) for the support. We thank the *Sea Around Us* Pauly and M. L. Palomares for co-hosting a CMSY workshop in Qingdao in June 2019. We thank R. Froese for his participation via Skype at the workshop. We also thank Patricia L. Yager for her comments on our manuscript and polishing the language.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.525363/full#supplementary-material

REFERENCES

Anderson, S. C., Flemming, J. M., Watson, R., and Lotze, H. K. (2011). Rapid global expansion of invertebrate fisheries: trends, drivers, and ecosystem effects. *PLoS One* 6:e14735. doi: 10.1371/journal.pone.0014735

Carruthers, T. R., Punt, A. E., Walters, C. J., MacCall, A., McAllister, M. K., Dick, E. J., et al. (2014). Evaluating methods for setting catch limits in data-limited fisheries. *Fish. Res.* 153, 48–68. doi: 10.1016/j.fishres.2013.12.014

CCRF, (2004). *Code of Conduct for Responsible Fisheries*. Rome: FAO.

Christensen, V., Guénette, S., Heymans, J. J., Walters, C. J., Watson, R., Zeller, D., et al. (2003). Hundred-year decline of North Atlantic predatory fishes. *Fish Fish.* 4, 1–24. doi: 10.1046/j.1467-2979.2003.00103.x

Comeros-Raynal, M. T., Polidoro, B. A., Broatch, J., Mann, B. Q., Gorman, C., Buxton, C. D., et al. (2016). Key predictors of extinction in sea breams and porgies (Family: sparidae). *Biol. Conservat.* 202, 88–98. doi: 10.1016/j.biocon.2016.08.027

Costello, C., Ovando, D., Hilborn, R., Gains, S. D., Deschenes, O., and Lester, S. E. (2012). Status and solutions for the world's unassessed fisheries. *Science* 338, 517–520. doi: 10.1126/science.1223389

FAO, (2010). *The State of World Fisheries and Aquaculture*. Rome: Food and Agriculture Organization.

FAO, (2018). *The State of World Fisheries and Aquaculture*. Rome: Food and Agriculture Organization.

Fisheries Agency of Japan, (2018). *Marine fisheries stock assessment for Japanese waters in 2018*. Cianjhen: Fisheries Agency. Available online at: https://www.jfa.maff.go.jp/e/index.html

Fisheries Research Institute of Hokkaido Research Organization, (2017). *Reports of Stock Assessment for Fishery Resources Around Hokkaido in 2017*. http://www.fishexp.hro.or.jp/exp/central/kanri/SigenHyoka/Kokai/. [in Japanese] (accessed January, 2020).

Froese, R., Demirel, N., Coro, G., Kleisner, K. M., and Winker, H. (2017). Estimating fisheries reference points from catch and resilience. *Fish Fish.* 18, 506–526. doi: 10.1111/faf.12190

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A. C., Dimarchopoulou, D., et al. (2018). Status and rebuilding of European fisheries. *Mar. Pol.* 93, 159–170. doi: 10.1016/j.marpol.2018.04.018

Geromont, H. F., and Butterworth, D. S. (2015). *FAO Report: a Review of Assessment Methods and the Development of Management Procedures for Data-poor Fisheries. The Marine Resource Assessment and Management Group (MARAM)*. South Africa: University of Cape Town.

ISEU, (2006). *Implementing Sustainability in EU Fisheries through Maximum Sustainable Yield, CEC, COM 360*. Brussels: ISEU.

Joh, M., and Wada, A. (2018). Inter-annual and spatial difference in hatch date and settlement date distribution and planktonic larval duration in yellow striped flounder *Pseudopleuronectes herzensteini*. *J. Sea Res.* 137, 26–34. doi: 10.1016/j.seares.2018.04.002

Koeller, P. A., Covey, M., and King, M. (2003). Is size at sex transition an indicator of growth or abundance in pandalid shrimp? *Fish Res.* 65, 217–230. doi: 10.1016/j.fishres.2003.09.016

Kon, T., Adachi, T., and Suzuki, Y. (2003). Distribution of snow crab, *Chionoecetes spp*., larvae off Wakasa Bay in the Sea of Japan. *Fish. Sci.* 69, 1109–1115. doi: 10.1111/j.0919-9268.2003.00735.x

Liang, C., and Pauly, D. (2017). Fisheries impacts on China's coastal ecosystems: unmasking a pervasive 'fishing down' effect. *PLoS One* 12:e0173296. doi: 10.1371/journal.pone.0173296

Liu, Z. L., Yuan, X. W., Yang, L. L., Yan, L. P., and Cheng, J. H. (2019). Stock assessment and management strategies for small yellow croaker in the East China Sea based on data-limited assessment models. *J. Fish. Sci. China* 26, 621–635. doi: 10.3724/SP.J.1118.2019.18291

Makino, M. (2011). Fisheries management in Japan: its institutional features and case studies. *Springer Sci. Bus. Med.* 2, 32–35. doi: 10.1007/978-94-007-1777-0

Mao, X., Guo, X., Kubota, T., and Wang, Y. (2019). Numerical studies on snow crab (Chionoecetes opilio) larval survival and transport in the Sea of Japan. *Prog. Oceanograp.* 179:102204. doi: 10.1016/j.pocean.2019.102204

Ouellet, P., and Chabot, D. (2005). Rearing *Pandalus borealis* (Krøyer) larvae in the laboratory. *Mar. Biol.* 147, 869–880. doi: 10.1007/s00227-005-1625-6

Palomares, M., and Pauly, D. (2019). On the creeping increase of vessels' fishing power. *Ecol. Soc.* 24:31. doi: 10.5751/ES-11136-240331

Palomares, M. L., Froese, R., Derrick, B., Nöel, S., Tsui, G., Woroniak, J., et al. (2018). *A Preliminary Global Assessment of the Status of Exploited Marine Fish and Invertebrate Populations. A Report Prepared by the Sea Around Us for OCEANA*. Vancouver: The University of British Columbia.

Pauly, D. (2006). Major trends in small-scale marine fisheries, with emphasis on developing countries, and some implications for the social sciences. *Maritime Stud.* 4, 7–22.

Pauly, D. (2008). Global fisheries: a brief review. *J. Biol. Res. Thessaloniki* 9, 3–9.

Pauly, D., and Zeller, D. (2016). Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nat. Commun.* 7:10244. doi: 10.1038/ncomms10244

Pitcher, T. J., and Lam, M. E. (2015). Fish commoditization and the historical origins of catching fish for profit. *Maritime Stud.* 14:2. doi: 10.1186/s40152-014-0014-5

Ren, Q., and Liu, M. (2020). Assessing northwest pacific fishery stocks using two new methods : the monte carlo catch-MSY (CMSY) and the Bayesian Schaefer Model (BSM). *Front. Mar. Sci.* 7:430. doi: 10.3389/fmars.2020.00430

Ricker, W. E. (1975). *Computation and Interpretation of Biological Statistics of Fish Populations*. Ottawa: Department of the Environment, Fisheries and Marine Service.

Schaefer, M. B. (1954). Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Int. Am. Trop. Tuna Com. Bull.* 1, 23–56.

Shin, G. H., Shin, Y., Jung, M., Hong, J. M., Lee, S., Subramaniyam, S., et al. (2018). First draft genome for red sea bream of family Sparidae. *Front. Genet.* 9:643. doi: 10.3389/fgene.2018.00643

Tian, Y., Kidokoro, H., and Watanabe, T. (2006). Long-term changes in the fish community structure from the Tsushima warm current region of the Japan/East Sea with an emphasis on the impacts of fishing and climate regime shift over the last four decades. *Prog. Oceanography* 68, 217–237. doi: 10.1016/j.pocean.2006.02.009

Tian, Y., Kidokoro, H., Watanabe, T., and Iguchi, N. (2008). The late 1980s regime shift in the ecosystem of Tsushima warm current in the Japan/East Sea: Evidence from historical data and possible mechanisms. *Prog. Oceanography.* 77, 127–145. doi: 10.1016/j.pocean.2008.03.007

Tremblay-Boyer, L., Gascuel, D., Watson, R., Christensen, V., and Pauly, D. (2011). Modelling the effects of shing on the biomass of the world's oceans from 1950 to 2006. *Mar. Ecol. Prog. Ser.* 442, 169–185. doi: 10.3354/meps09375

Wang, Y., Wang, Y., Liang, C., Zhang, H., and Xian, W. (2020). Assessment of 12 fish species in the northwest pacific using the CMSY and BSM methods. *Front. Mar. Sci.* 7:616. doi: 10.3389/fmars.2020.00616

Watson, R., Cheung, W. W. L., Anticamara, J., Sumaila, U. R., Zeller, D., and Pauly, D. (2013). Global marine yield halved as fishing intensity redoubles. *Fish Fish.* 14, 493–503. doi: 10.1111/j.1467-2979.2012.00483.x

Watson, R., and Pauly, D. (2001). Systematic distortions in world fisheries catch trends. *Nature* 414, 534–536. doi: 10.1038/35107050

Yamasaki, A. (1994). Studies on stock management of snow crab *Chionoecetes opilio* based on biology. *Spec. Rep. Kyoto Inst. Ocean. Fish. Sci.* 4, 1–53.

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Marine Science

ORIGINAL RESEARCH
published: 23 November 2020
doi: 10.3389/fmars.2020.483993

Assessments of 16 Exploited Fish Stocks in Chinese Waters Using the CMSY and BSM Methods

Lu Zhai[1]*, *Cui Liang*[2,3] *and Daniel Pauly*[4]

[1] Fisheries College, Ocean University of China, Qingdao, China, [2] CAS Key Laboratory of Marine Ecology and Environmental Sciences, Institute of Oceanology, Chinese Academy of Sciences, Qingdao, China, [3] Laboratory for Marine Ecology and Environmental Science, Qingdao National Laboratory for Marine Science and Technology, Qingdao, China, [4] Sea Around Us, Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, BC, Canada

Sixteen marine fish species (populations) exploited by Chinese fisheries were assessed, using published time series of catch and the CMSY and BSM methods. Given the catch times series as inputs, some ancillary information and reasonable constraints, carrying capacity, maximum sustainable yield, and likely time series of biomass and exploitation rate were estimated. The results show that one (7%) of the assessed species was severely depleted, four species (27%) were fully/overfished, six (40%) were outside of safe biological limits, one species (7%) was recovering and three species (20%) were in a healthy state at the end year of their assessment. However, one species, Pacific sardine (*Sardinops sagax*), could not be assessed using CMSY, as the exceedingly large fluctuations of its biomass were mainly environmentally driven. These results correspond with previous knowledge on the status of fish populations along the coast of China, where overfishing is rampant. Based on these assessments, some of the benefits that would result from a reduction of the excessive fishing effort are outlined.

Keywords: data-poor fisheries, Chinese coastal fisheries, biomass declines, CMSY, stock assessments

OPEN ACCESS

Edited by:
Athanassios C. Tsikliras,
Aristotle University of Thessaloniki, Greece

Reviewed by:
Gianpaolo Coro,
Istituto di Scienza e Tecnologie dell'Informazione "Alessandro Faedo" (ISTI), Italy
Donna Dimarchopoulou,
University of Rhode Island, United States

***Correspondence:**
Lu Zhai
zhailu0708@hotmail.com

Specialty section:
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

Received: *10 July 2019*
Accepted: *29 October 2020*
Published: *23 November 2020*

Citation:
Zhai L, Liang C and Pauly D (2020) Assessments of 16 Exploited Fish Stocks in Chinese Waters Using the CMSY and BSM Methods. Front. Mar. Sci. 7:483993. doi: 10.3389/fmars.2020.483993

INTRODUCTION

China is the country with the world's largest marine fisheries catch (FAO, 2018). It is widely agreed that China's domestic fisheries resources are overexploited (Shen and Heino, 2014). However, it seems that overfishing has gradually changed the structure and function of marine ecosystems of China's coastal seas (Zhai and Pauly, 2020) and that the state of its domestic resources is the main reason for its current emphasis on distant-water fishing (Mallory, 2013).

China's fisheries management system has been gradually improving since the 1980s (Huang and He, 2019). Its most powerful regulations are the "double control" system and summer fishing moratoria (Shen and Heino, 2014). The former are regulations of both the total number of marine engine-powered fishing vessels and their total engine power; the latter have been implemented since 1995 and extended from 3 to 4 months and more in many areas (Ministry of Agriculture and Rural Affairs of the People's Republic of China [MARA], 2018). Also, some other regulations and programs are being implemented including vessel buyback, alternative employment opportunities for fishers (Song, 2007) and a 10 year fishing ban in the Yangtze River Basin (Ministry of Agriculture and Rural Affairs of the People's Republic of China [MARA], 2019).

China has carried out a large number of fishery resource surveys and stock assessment work in recent years, but still faces difficulties due to a lack of historical data. Thus, there are still deficiencies regarding China's fish stock assessments: the range of species covered by assessments is narrow, evaluation methods are limited and the results are not usually expressed as B/B_{MSY}, i.e., the ratio of stock biomass to the biomass that can produce the maximum sustainable yield (MSY) or other management-relevant indicators. Until recently, very few stock assessments were conducted that allowed for estimating the potential for stock rebuilding (Villasante et al., 2013), although this dire situation is now being overcome (see Zhai and Pauly, 2019; Ji et al., 2019; Liang et al., 2020a,b; Wang et al., 2020; Zhang et al., 2020).

Here, the newly developed CMSY method (Froese et al., 2017), catch time series and some **Supplementary Information** are used to infer likely biomass trajectories for 16 species of exploited fish along Chinese coastlines. This method was shown to be adequate for the assessment of hundreds of fish stocks in and around Europe (Froese et al., 2017, 2018; Demirel et al., 2020). Moreover, a number of contributions show that the method can be used for stock assessment in China (Ji et al., 2019; Liang et al., 2020b; Wang et al., 2020).

Also, a Bayesian state-space implementation of the Schaefer model (BSM; Froese et al., 2017) is applied here with the same catch time series and priors, and additional catch/effort (*C/f*, or CPUE) and/or biomass data, to assess the biomass and exploitation rate, and thus to assess the stock status and extent of overfishing in Chinese and adjacent waters. This contribution is a further example of the study of data-poor fisheries and our results provide information toward a science-based management of China's fisheries.

MATERIALS AND METHODS

Data Sources

The main features of the catch time series and additional information available for 16 fish populations investigated here are given in **Table 1**, while the data sources are shown in **Supplementary Table 1**. All species investigated here are important commercial fish in China since the 1950s that have more than 10 years of catch data.

The CMSY and BSM Methods

The principle of the CMSY method is that, given catch time series and using a Monte Carlo approach, multiple biomass trajectories of the biomass of the stock in question are traced, and the parameters retained that generated the biomass trajectory (or trajectories) that is (are) compatible with the time series of catches, and a number of constraints (Froese et al., 2017). Here, "compatible" means that, among other things, the stock does not crash, i.e., its biomass does not drop to zero.

When, as is the case here, relative abundance data, such as CPUE or spawning stock biomass (SSB), are also available, a Bayesian state-space implementation of the Schaefer production model (BSM; Millar and Meyer, 1999) is applied to estimate the intrinsic rate of population growth (r) and unexploited stock size (or carrying capacity; k) of each stock (Froese et al., 2017).

The CMSY and BSM methods are based on the logic of the surplus-production model of Schaefer (1954, 1957). Thus, they assume that from 1 year (t) to the next ($t + 1$), the biomass (B_t) follows the equation:

$$B_{t+1} = B_t + r\left(1 - B_t/k\right) B_t - C_t \quad (1)$$

where r is the intrinsic rate of population growth, k the carrying capacity, and C_t is the catch in year t.

However, Eq. (1) is slightly modified when the biomass falls below 0.25k, to allow for depensation or reduced recruitment when stock size is severely depleted (Froese et al., 2017):

$$B_{t+1} = B_t + \left(4rB_t/k\right)\left(1 - B_t/k\right) B_t - C_t \mid B_t/k < 0.25 \quad (2)$$

where the term $4rB_t/k$ ensures a linear decline of recruitment below half of the biomass capable of generating MSY.

Prior Information

The R code implementing the CMSY method incorporates a routine which estimates wide (uniform) priors for k (Froese et al., 2017), whose output were here accepted:

$$k_{low} = \max(C)/r_{high};\ k_{high} = 4\max(C)/r_{low} \quad (3)$$

where k_{low} and k_{high} are the lower and upper bounds of the prior range of k, max(C) is the maximum catch in the time series and r_{low} and r_{high} are the lower and upper bound of the range of r-values that the CMSY method explores. This is expressed by

$$k_{low} = 2\max(C)/r_{high};\ k_{high} = 12\max(C)/r_{low} \quad (4)$$

where the variables and parameters are defined as in Eq. (3).

As stated in Froese et al. (2017), when running the BSM method, the estimated standard deviation of r in log-space is described by a uniform distribution between 0.001 irf and 0.02 irf by

$$\text{irf} = 3/\left(r_{high} - r_{low}\right) \quad (5)$$

where irf is an inverse range factor to determine r range, and r_{high} and r_{low} is provided in **Table 2**.

The k estimation by BSM also assumes that k has a log-normal distribution, while the mean of k provides the reasonable central value. The standard deviation of k is assumed to be a quarter of the distance between the central value and the lower bound of the k-range (McAllister et al., 2001).

Additionally, the BSM method allows the estimation of the catchability coefficient q, which relates biomass to CPUE, when the latter is available. For this, priors are defined as

$$q_{low} = 0.25r_{pgm}\text{CPUE}_{mean}/C_{mean};\ q_{high} = 0.5r_{high}/\text{CPUE}_{mean} \quad (6)$$

where q_{low} and q_{high} are the lower prior and higher prior for the catchability coefficient respectively; r_{pgm} is the geometric mean of the prior range for r; CPUE_{mean} is the mean CPUE over the last 5 or 10 years; C_{mean} is mean catch over the same period.

For stocks with low recent prior biomass, the ranges of multipliers are 0.25–0.5 for q_{low} and 0.5–1 for q_{high}.

TABLE 1 | Summary of data available for the stock assessments presented here (the data themselves and data sources are presented in **Supplementary Table 1**).

Scientific name (common name)	Region	Catch	Additional data
Clupea pallasi (Pacific herring)[1,2]	Chinese waters[3]	1989–2014	CPUE (2001–2014)
Sardinops sagax (Pacific sardine)	Sea of Japan and ECS	1951–2006	None
Engraulis japonicus (Japanese anchovy)[1,2]	Chinese water	1989–2014	CPUE (1979–1997)
Coilia mystus (Osbeck's grenadier anchovy)[2]	Yangtze River and Estuary, and ECS	1960–2007	CPUE (1995–1999)
Ilisha elongata (elongate ilisha)[1,2]	Chinese water	1978–2014	CPUE (2001–2014)
Decapterus muroadsi (amberstripe scad)[2]	ECS	1973–2013	CPUE (1998–2013)
Scomber australasicus (spotted mackerel)	ECS	1992–2013	SSB (2006–2010)
Scomberomorus niphonius (Japanese Spanish mackerel)	ECS	1984–2013	None
Trichiurus lepturus (largehead hairtail)[2]	Chinese waters	1956–2014	CPUE(1998–2013)
Branchiostegus japonicus (horsehead tilefish)	ECS	1985–2013	None
Larimichthys crocea (large yellow croaker)[2]	ECS	1956–2002	CPUE(1990–2002)
Larimichthys polyactis (yellow croaker)[2]	Chinese waters	1956–2014	CPUE(2010–2014)
Pagrus major (red seabream)	East China Sea	1969–2013	SSB (1986–2013)
Paralichthys olivaceus (Japanese flounder)	East China Sea	1975–2013	SSB (1993–2013)
Thamnaconus modestus (bluefin leatherjacket)[2]	YS and ECS	1973–2000	CPUE (1980–1993)
Muraenesox cinereus (pike eel)[2]	Chinese and Taiwan waters	1979–2017	CPUE (2005–2017)

[1]The catch data of E. japonicus in 1992, of C. pallasi in 2006, and of I. elongata in 1995 and 2006 were interpolated from the two adjacent years' catches. [2]The CPUE is corrected by 2% each year on account of technical development (Palomares and Pauly, 2019). [3]"Chinese" refers to "Chinese mainland" in this study; SSB, spawning stock biomass; YS, Yellow Sea; ECS, East China Sea.

The intrinsic rate of population growth (r) is largely determined by the size and age at first maturity of individuals of the species in question, and FishBase[1] (Froese and Pauly, 2019), based on these and other traits, provides ranges of likely values ("priors") for all fish species (Froese et al., 2000). Also, a resilience classification based on the stock fecundity was proposed by Musick (1999). The available resilience ranges and those selected for the 16 stocks studied here are given in **Table 2**.

Additionally, two constraints are required for the CMSY method, i.e., the faction of carrying capacity that the biomass was exhibiting just before the first annual catch in the available time series is subtracted (B_{start}/k; see Eq. 1) and the faction of carrying capacity that the biomass reached at the end of the catch time series, again expressed as a fraction of k (B_{end}/k). The first of these constraints is a function of the fishing pressure to which the population (or stock) in question was exposed to prior to the period for which catch data are available, and which would have reduced the biomass below carrying capacity.

[1]http://www.fishbase.org/

TABLE 2 | Ranges suggested by FishBase (see text footnote 1) for population growth rate (in year^{-1}).

Resilience (r)	Suggested prior	Range assumed for the stocks in Table 1
High	0.6–1.5	*E. japonicus; C. mystus*
Medium	0.2–0.8	*C. pallasi; S. sagax; I. elongata; D. muroadsi; S. australasicus; S. niphonius; B. japonicus; L. crocea; L. polyactis; P. olivaceus; T. modestus; T. lepturus; M. cinereus*
Low	0.05–0.5	*P. major*
Very low	0.015–0.1	–

Table 3 presents suggested ranges of B_{start}/k and B_{end}/k for the stocks in **Table 1**. Note that for some species that were already exploited in the 1950s, we selected a very low depletion (B_{start}/k = 0.8–1) for the start of the series because of the low technology that was deployed at the time (Zhan et al., 1986; Yang, 1988; Zhang and Hua, 1990; Yu and Zheng, 2000; Liu, 2005; Xu and Liu, 2007; Wang et al., 2011; Xu et al., 2014; Yan et al., 2014). For some other species, we selected a low range (B_{start}/k = 0.4–0.8), in view of the fact that from the 1970s to the 1990s, a massive increase of fishing effort occurred, and the technological sophistication of that effort also increased (Zhu, 1992; Qiu, 1995; Lu et al., 1998; Bo et al., 2005).

There are two exceptions here, *Larimichthys polyactis* and *Sardinops sagax*, were set at the strong (0.01–0.4) and very strong (0.01–0.2) depletion, respectively (**Table 3**). For *L. polyactis*, the catch of the stock in the final year increased to 2∼3 times that of the start year (Lin et al., 2004; Yan et al., 2014). Thus, we have a good reason to assume that *L. polyactis* was already strongly overfished in the mid-1950s.

The B_{start}/k for *S. sagax* was set at a very strong depletion (0.01–0.2; see **Table 3**) to force its biomass at the start of the assessment period to be very low. This biomass subsequently increased due to environmental factors (Wei and Li, 1986; Lluch-Belda et al., 1989), a topic to which we will return.

The second constraint, the expected biomass at the end relative to carrying capacity (B_{end}/k), should be roughly reflective of the fishing pressure which generated the available catch time series. **Table 3** presents suggested ranges of B_{end}/k, i.e., the fraction of the population initially present that is left in the water, set based on the default rules of CMSY method (Froese et al., 2017).

The last constraint, i.e., the ratio of biomass reached during an intermediate year to carrying capacity (B_{int}/k), can be used if such

TABLE 3 | Suggested ranges of the fraction B_{start}/k and B_{end}/k for the biomass depletion before catch data are available*.

Depletion	Suggested prior	Assumed level of prior depletion of the stocks in Table 1	
		B_{start}/k	B_{end}/k
Very low	0.8–1	*C. pallasi; E. japonicus; C. mystus; I. elongata; T. lepturus; L. crocea; T. modestus; S. niphonius; M. cinereus*	–
Low	0.4–0.8	*D. muroadsi; S. australasicus; B. japonicus; P. major;P. olivaceus*	–
Medium	0.2–0.6	–	*E. japonicus; I. elongata*
Strong	0.01–0.4	*L. polyactis*	*S. sagax; C. mystus; D. muroadsi; T. lepturus; B. japonicus; P. major; T. modestus*
Very strong	0.01–0.2	*S. sagax***	*C. pallasi; L. crocea*

*See **Supplementary Material** to Froese et al. (2017); **A very low range was selected here to enable the CMSY method to simulate the environmentally driven massive increase of the biomass of S. sagax in the 1970s and 1980s (see text).*

knowledge is available. We set "default" B_{int}/k for all stocks in this study except for *Engraulis japonicus* (Japanese anchovy; int. year is 2009, prior range is 0.2–0.6; Li et al., 2015).

The CMSY method identifies the r and k values generating viable biomass trajectories (if any), then output the geometric means and confidence intervals of these estimates. As well, various parameters that can be derived from r and k, notably MSY = $0.25r{\cdot}k$, $F_{MSY} = 0.5r$ and $B_{MSY} = 0.5k$ (Schaefer, 1954; Ricker, 1975) are also estimated.

The BSM method can run with additional constraints, such as SSB or catch/effort (C/f, or CPUE) (Froese et al., 2017), which represent (relative) abundance. In this case, the viable biomass trajectories will take account of the (relative) abundance data, even if they pertain to a shorter period than the catch data (**Table 1**). In the process, an estimate of the catchability coefficient $q = (C/f)/B$ is also produced as an average for the period with CPUE data (see Eq. 6).

Four of the sixteen stocks in the study, i.e., *E. japonicus, Coilia mystus, L. polyactis* and *Muraenesox cinereus* with more than one SSB or CPUE time series, we used a routine "Bcrumb," to interpolate and average SSB or CPUE for them. This routine was developed as a component of JARA (Just Another Redlist Assessment) described in Winker and Sherley (2019). Moreover, considering the technological improvement of the fishery, the CPUE is corrected by 2% increases every year according to Palomares and Pauly (2019), given gear and other technological improvements of the industrial sector.

The ratio B/B_{MSY} in the final year, which is often used to express stock status, is estimated by both CMSY as well as BSM. For management purposes, the more precise results of BSM may be preferred over the results of a CMSY assessment. **Table 4** presents suggestion of fish stock status based on B/B_{MSY} and

TABLE 4 | Definition of fish stock status, based on B/B_{MSY} in the final year of a time series*.

B/B_{MSY}	F/F_{MSY}	Stock status
≥1	<1	Healthy stock
0.5–1.0	<1	Recovering stock
<0.5	<1	Stock outside of safe biological limits
0.5–1.0	>1	Fully/overfished stock
0.2–0.5	>1	Stock outside of safe biological limits
<0.2	>1	Severely depleted stock

See Froese et al. (2018).

F/F_{MSY} in final year. (Note that $2{\cdot}B_{end}/k = B_{MSY}/k$, as MSY is taken at $0.5k$).

RESULTS

Altogether 16 fish populations were analyzed by CMSY method, with 13 also assessed using the BSM methods, as CPUE/biomass data were available for them. The results of estimated r-k for *Scomberomorus niphonius* and *E. japonicus* are shown in **Figure 1** as examples, while all other results are shown in **Table 5** and **Supplementary Figure 1**(except for *S. sagax*).

In **Figure 1A**, featuring Japanese Spanish mackerel (*S. niphonius*) and **Figure 1B**, featuring Japanese anchovy (*E. japonicus*), the viable r-k pairs (gray) were obtained by the CMSY method, and the solid crosses identify the most probable r-k pairs, along with their 95% confidence intervals. In **Figure 1B**, the BSM method used (relative) abundance data (i.e., SSB/CPUE), and the viable r-k pairs it estimated are in black. The dotted cross identifies the most probable r-k pair, and its 95% confidence intervals. The overlaps between the two clouds of dots (and hence the closeness of the two crosses) implies that the results of the two methods are similar, and thus more credible than if they did not overlap.

The biomass trends resulting from the CMSY and BSM analyses are shown in the different panels of **Figure 2**. In each panel, the key item is the biomass trajectory (solid black line) and its 95% confidence intervals (dotted line). The horizontal dashed line represents B_{MSY}, while the vertical solid lines show the priors on biomass range at the start and end of time series. Finally, the open dots indicate corrected CPUE trends of the 13 stocks for which such data was available.

As shown in **Figure 2**, the biomass of all species generally declined, although a few species, notably *L. polyactis*, substantially recovered. The mean B/B_{MSY} for 15 stocks is 0.59 ± 0.10 (SE) and mean B_{end}/k is 0.29 ± 0.05 (SE).

The results demonstrate that the exploitation rate (i.e., F) for 9 species of the 15 are higher than F_{MSY}. The average value for 15 species is 1.39 ± 0.26 (SE). The species *Clupea pallasi* have the highest exploitation rate of 4.33 (**Table 5** and **Supplementary Figure 2**).

According to the definition of fish stock status (see **Table 4**), the average status of China's coastal fish stock assessed here is fully/overfished. Three of the assessed stocks were healthy, one

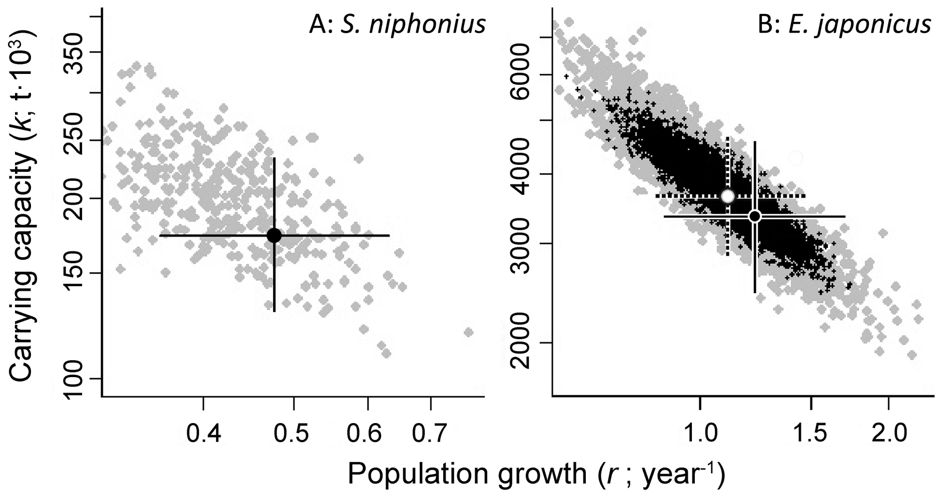


FIGURE 1 | Examples of the identification of viable and best trajectories (as defined by values of *r* and *k*), for the populations of **(A)** Japanese Spanish mackerel (*S. niphonius*) and **(B)** Japanese anchovy (*E. japonicus*). In **(A)**, the viable *r-k* pairs (gray) were obtained by the CMSY method, and the solid crosses identify the most probable *r-k* pairs, along with their 95% confidence intervals; in **(B)**, the viable *r-k* pairs (black) were obtained by the BSM method, the dotted cross identifies the most probable *r-k* pair, and its 95% confidence intervals.

TABLE 5 | Estimates of *r*, *k*, MSY, B/B_{MSY} and status as obtained by CMSY and/or BSM method for 15 fish stocks of China's coastal seas. The result in normal font are based on the BSM method, i.e., they used catch and additional relative abundance data; the results in bold font are only based on catch time series and CMSY*.

Species	*r* (year^{-1})	*K* (10^3 *t*)	MSY(10^3 *t*·year^{-1})	F/F_{MSY}	B/B_{MSY}	B_{end}/k	Status
mean				1.39 ± 0.26	0.59 ± 0.09	0.29 ± 0.05	
C. pallasi (Pacific herring)	0.48	222	27	4.33	0.27	0.14	Stock outside of safe biological limits
E. japonicus (Japanese anchovy)	1.12	3643	1017	0.68	1.30	0.65	Healthy stock
C. mystus (Osbeck's grenadier anchovy)	0.71	8	1	0.31	0.55	0.27	Recovering stock
I. elongata (elongate ilisha)	0.80	423	84	1.60	0.56	0.28	Fully/overfished stock
D. muroadsi (amberstripe scad)	0.32	543	44	1.33	0.26	0.13	Stock outside of safe biological limits
S. australasicus (spotted mackerel)	0.61	371	57	1.33	0.67	0.34	Fully/overfished stock
S. niphonius (Japanese Spanish mackerel)	**0.48**	**173**	**21**	**1.28**	**0.48**	**0.24**	Stock outside of safe biological limits
T. lepturus (largehead hairtail)	0.75	6049	1130	1.73	0.56	0.28	Fully/overfished stock
B. japonicus (horsehead tilefish)	**0.32**	**78**	**6**	**0.77**	**0.25**	**0.13**	Stock outside of safe biological limits
L. crocea (large yellow croaker)	0.35	1215	107	1.05	0.17	0.08	Severely depleted stock
L. polyactis (yellow croaker)	0.44	3348	372	0.81	1.19	0.59	Healthy stock
P. major (red seabream)	0.25	108	7	1.51	0.59	0.30	Fully/overfished stock
P. olivaceus (Japanese flounder)	0.50	13	2	0.69	1.14	0.57	Healthy stock
T. modestus (bluefin leatherjacket)	0.33	1963	162	0.67	0.37	0.18	Stock outside of safe biological limits
M. cinereus (pike eel)	0.49	2389	295	2.72	0.48	0.24	Stock outside of safe biological limits

**Pacific sardine (S. sagax) is not included here because its dynamics was mainly driven by environmental fluctuations (see text).*

was recovering, six were outside of safe biological limits, four were fully/overfished, one was severely depleted (see **Figure 3**).

DISCUSSION

Time series of catches such as analyzed here are scarce for Chinese waters; however, the few that are available provided the impression of massive overfishing, consistent with other analyses (Liang and Pauly, 2017b; Zhai and Pauly, 2019; Liang et al., 2020a,b). All of the thirteen stocks with CPUE or SSB included in this contribution were well fitted by the CMSY and BSM methods, i.e., the most likely estimated *r-k* pair are included within the 95% confidence intervals of each other (see **Supplementary Figure 1**). Similarly, Ji et al. (2019) found a good match between the estimates of population parameters of *Trichiurus lepturus* in the Yellow and Bohai Seas obtained by using CMSY and those from the Schaefer and Fox models. Thus, the CMSY method can for assessing data-limited fisheries, although the related BSM methods, which additional information (e.g., CPUE data) produces narrower confidence intervals (Ren and Liu, 2020).

The intrinsic rate of population growth (*r*) is key in defining the response of populations to challenges such as fisheries (Cheung et al., 2005; Anderson et al., 2008). FishBase (see text

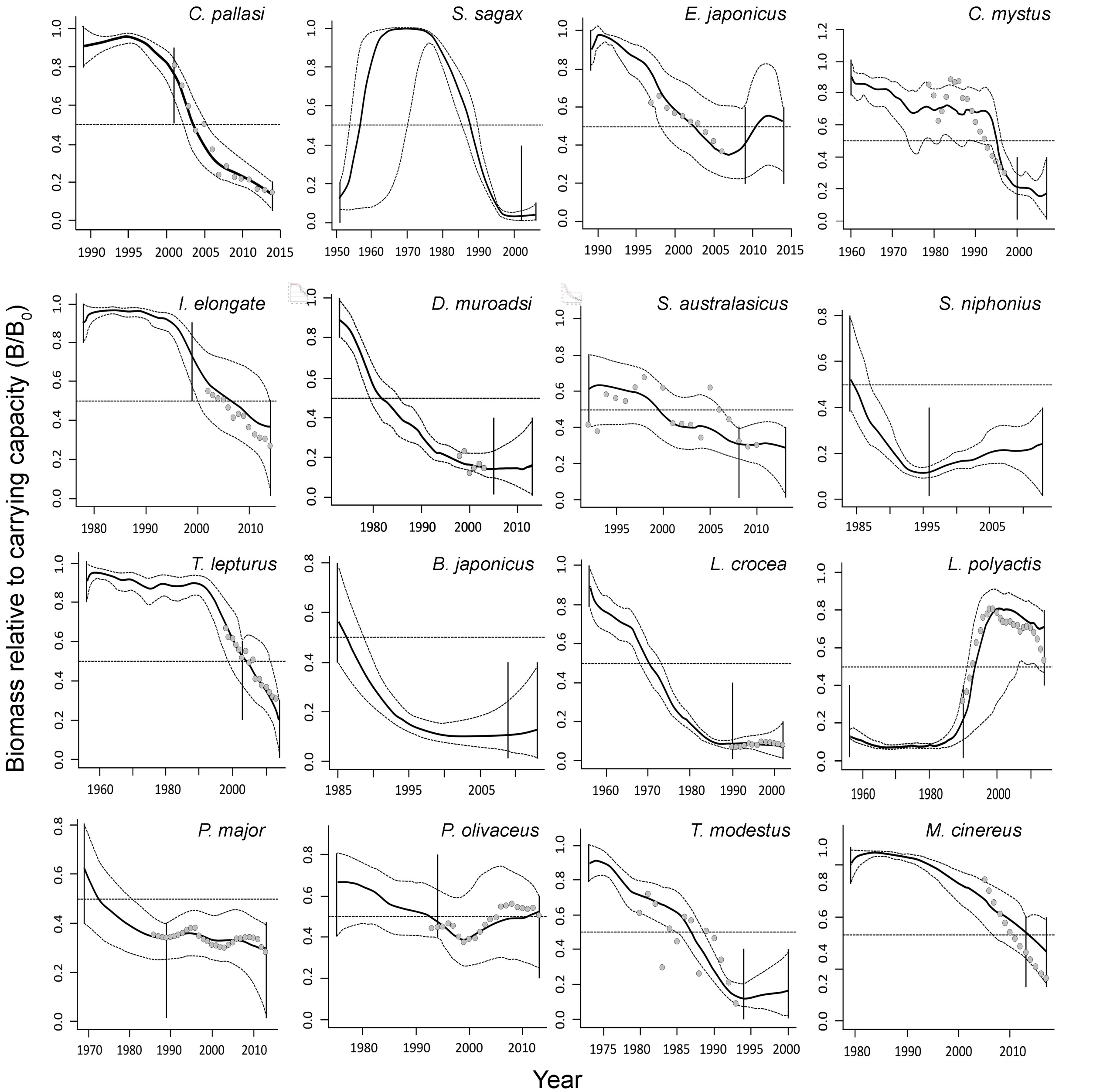


FIGURE 2 | Biomass trajectories of 16 single-species stocks in **Table 1**, as estimated by the CMSY method (solid black lines) and their uncertainty (gray dashed lines), related abundance series (gray dots; SSB and corrected CPUE by 2% every year), when available, and vertical lines represented priors (from **Tables 3**, **4**). Except for *S. sagax* (see text), all of these trajectories are due to excessively high catches.

footnote 1; Froese and Pauly, 2019) provides estimated ranges of *r* for fish populations based on life-history traits of fish populations which are very useful, as they compensate for the lack of estimates from local data.

The uncertainties of catch, SSB or CPUE data, which may result, e.g., from discards not having been considered, or unreported catch issues, will lead to errors in the assessment. In these cases, the local experience of fisheries experts should be accounted for when screening the data sets and results.

The catches of most of the species investigated here exhibited an explosive growth in the 1990s and/or the 2000s, then stagnated and declined. This feature basically coincides with China's fishery development history. Fisheries of China developed gradually from the 1950s to the 1970s, then rapidly in 1980s and 1990s, with its total catch peaking in the 2000s (Anon, 1963-2019; Shen and Heino, 2014; **Supplementary Figure 3**). Even though China's national catch statistics were over-reported in the 1990s, resulting in distortions in the catch and CPUE data (Watson and Pauly, 2001), the rapid growth of China's

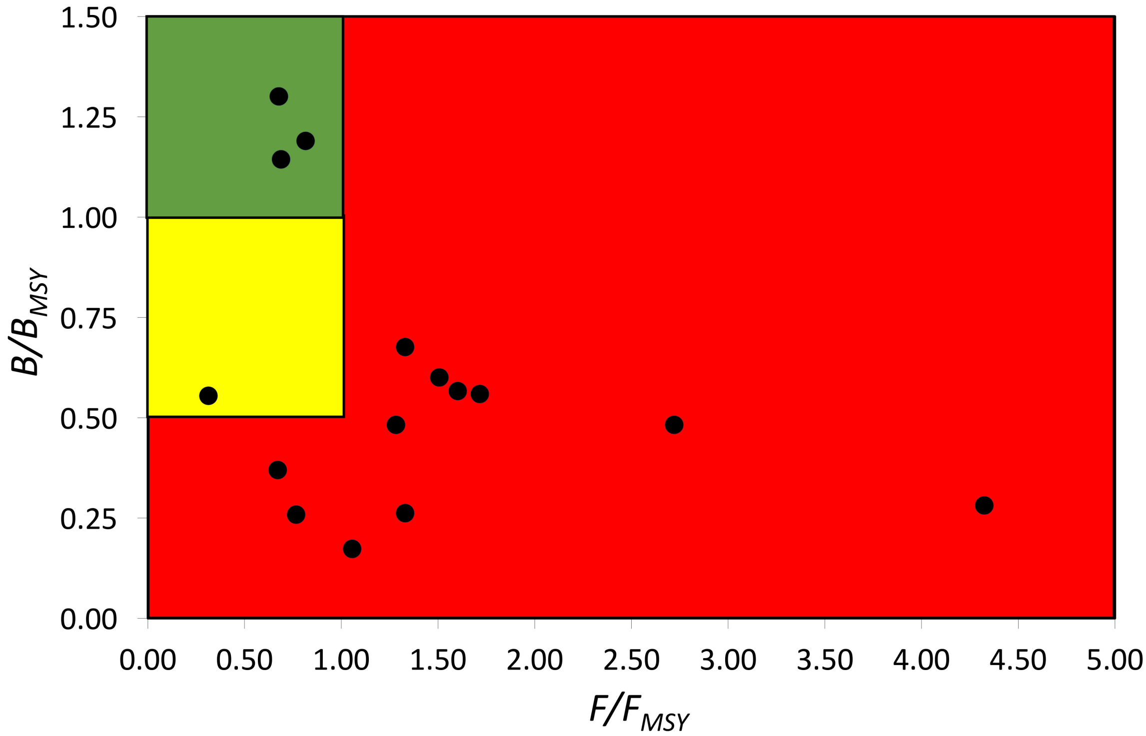


FIGURE 3 | Pressure (F/F_{MSY}) – status (B/B_{MSY}) plot of 15 fish stocks of China's coastal seas for the last years with available data (2000–2017). Red area: stocks that are being overfished or are outside of safe biological limits; yellow area: recovering stocks; green area: stocks subject to sustainable fishing pressure and of a healthy stock biomass that can produce high yields close to MSY.

overall fishing effort in undeniable, and it had a strong effect on the structure of its coastal ecosystems (Zhai and Pauly, 2019).

Some important fish species, such as *Decapterus muroadsi, Branchiostegus japonicus,* and *Larimichthys crocea*, were already strongly exploited in the 1950s. Thus, the stock of large yellow croaker (*L. crocea*), a prized species in China, was quickly depleted when China developed its industrial fisheries; it finally collapsed in 1974, once Chinese and South Korean fleet reached its overwintering grounds (Xu and Liu, 2007), rendering it commercially extinct (Zhao et al., 2002). Although protection measures for the spawning grounds of large yellow croaker were put in place by China in the early 1980s, the stock was severely depleted, and does not seem able to recover (Liu and Sadovy de Mitcheson, 2008).

Another important commercial species of China, yellow croaker (*L. polyactis*), showed first signs of overexploitation in the 1960s, but they were masked by the offshore expansion of the fisheries (Liang and Pauly, 2017a) and large catches of other species (Fei, 1980). The catch of yellow croaker initially decreased, but later appeared to increase to more than two times than that in the 1950s. This stock recovery was the result of China's and South Korea's protective measures, notably a 6-year total ban on fishing in its main spawning ground in the southern Yellow Sea in the 1980s (Lee and Midani, 2014; Yan et al., 2014). However, the recovery of yellow croaker came at a cost, as the adult individuals became much smaller, and reached maturity at smaller sizes (Dieckmann et al., 2005; Yan et al., 2014), as can be expected on theoretical grounds (Pauly, 1984, 2019).

Japanese anchovy (*E. japonicus*), which had one of three populations found not to be overfished, is a very common and important small pelagic fish, especially as food for other commercial species. As a low-value species (Yu and Zheng, 2000), it was largely a bycatch species until the mid-1980s, when it became the target species of reduction (i.e., fishmeal) fisheries (Zhu et al., 1990; Tang et al., 2002) and thus began to show up in China fisheries statistics and fisheries research. While this research showed that Japanese anchovy was overfished around 2006 (Li et al., 2015), its stock seems to have recovered since, possibly because the top predators in China's coastal seas have been fished out, which reduced predation pressure on small pelagic fish.

Japanese flounder (*Paralichthys olivaceus*), another stock that is currently in good shape, was depleted in the early 1990s. Then, management measures, which include restocking (via the release of juveniles) were put in place and strengthened, which allowed the population to recover (Zhou, 2011).

Osbeck's grenadier anchovy (*C. mystus*), is the only stock found to be recovering. This anchovy is an amphidromous species that is very popular with consumers along the Yangtze River; in fact, it was one of the most important resource species of the Yangtze Estuary before the 1960s (Wang and Ni, 1984; Zheng, 2012). It became even more valuable in the last 30 years, as the populations of associated species, such as Reeves shad (*Tenualosa reevesii*) and the noodlefish (*Salanx prognathus*) strongly declined (Ni, 1999). The environment of *C. mystus* is very vulnerable to human activities and terrigenous pollution. Thus, we laud the decision to prohibit the harvesting of Osbeck's grenadier anchovy in the Yangtze River and its estuary, as published on February 1, 2019 (Anon, 2019), and the 10 years' fishing ban for the entire Yangtze River Basin that began in January 2020. These decisions, if vigorously implemented, may help the stock to recover, in spite of the pollution and degradation of its habitat (Yang et al., 2012). Note, finally that the stock of *C. mystus* in the Min River Estuary was found to be in good shape (Zhang et al., 2020), thus suggesting a strong influence of local conditions.

Pacific sardine (*S. sagax*), also known as "South American pilchard" (see text footnote 1; Froese and Pauly, 2019), ranges across the entire Pacific and beyond, and has supported many huge fisheries, notably off Chile and Peru, California (Steinbeck, 1945; Cisneros-Mata et al., 1995; Yáñez et al., 2001), and Japan (Watanabe et al., 1995). The stocks of Pacific sardine fluctuate strongly in response to climatic events, often in similar ways across very distant regions (Lluch-Belda et al., 1989, 1992; Deyle et al., 2013), which led to high catches in China in the 1970s and 1980s (Wang, 1985). As the 2-parameter CMSY model cannot readily accommodate massive changes in biomass due to environmental fluctuations, Pacific sardine treated as if it was overfished in 1950–1975. This allowed its biomass to increase until the 1980s (as occurred in reality), then to decline due to strong fishing pressure and the fading of the environmental conditions that had generated the massive increase. However, we did not report on it "MSY" or other statistics, which would be unrealistic.

CONCLUSION

In conclusion, most stocks we studied have biomasses that are much lower than B_{MSY}, i.e., the biomass associated with MSY. Thus, China loses millions of tonnes every year of potential catch to overfishing, and huge sums in the form of subsidies to fisheries that exploit overfished coastal stocks (Mallory, 2016). Although mariculture and the release of juveniles are maintaining several stocks, this is not a sustainable proposition; also, these measures lead to genetic diversity losses (Wang et al., 2012). Aquaculture should not be expected to maintain wild fish populations. Prudent fisheries management, on the other hand, can do this, and counter fisheries resources degradation. China has now taken measures to control its excessive fishing effort and we hope that the present study will serve as supporting scientific evidence toward fishing effort reduction.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

LZ was responsible for data collection, formal analysis, and writing original draft. CL was responsible for data curation, reviewing, and editing the manuscript. DP was responsible for conceptualization, methodology, and supervision. All authors contributed to the article and approved the submitted version.

FUNDING

LZ's studies in Canada were funded by the China Scholarship Council (CSC). CL's work was funded by Qingdao Postdoctoral Applied Research Project, NSFC-Shandong Joint Fund for Marine Ecology and Environmental Sciences (grant number U1606404). DP's research was supported by the *Sea Around Us*, funded by the Oak Foundation, the Marisla Foundation, the David and Lucile Packard Foundation, the Minderoo Foundation, and the Bloomberg Philanthropies through RARE.

ACKNOWLEDGMENTS

LZ would like to thank the China Scholarship Council (CSC). CL thanks the Qingdao Postdoctoral Applied Research Project. DP acknowledges support by the *Sea Around Us*, funded by a number of philanthropic foundations. The authors also thank Rainer Froese for his comments on an early draft of this contribution and Evelyn Liu for the figures.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.483993/full#supplementary-material

REFERENCES

Anderson, C. N., Hsieh, C. H., Sandin, S. A., Hewitt, R., Hollowed, A., Beddington, J., et al. (2008). Why fishing magnifies fluctuations in fish abundance. *Nature* 452, 835–839. doi: 10.1038/nature06851

Anon (2019). *Full Coverage of the Closed Fishing System in Key River Basins in China*. Beijing: Information of the Ministry of Agriculture and Rural Affairs, People's Republic of China.

Anon (1963-2019). *China Fishery Statistical Yearbook*. Beijing: China Agriculture Press.

Bo, Z. L., Zhou, W. X., Xue, L. J., and Chen, W. P. (2005). Survey of *Branchiostegus* resource in the north part of the East China Sea and in the southern part of Yellow Sea. *J. Fish. China* 29, 676–681.

Cheung, W. W. L., Pitcher, T. J., and Pauly, D. (2005). A fuzzy logic expert system to estimate intrinsic extinction vulnerabilities of marine fishes to fishing. *Biol. Conserv.* 124, 97–111. doi: 10.1016/j.biocon.2005.01.017

Cisneros-Mata, M. A., Nevárez-Martínez, M. O., and Hammann, M. G. (1995). The rise and fall of the Pacific sardine, *Sardinops sagax caeruleus* Girard, in the Gulf of California, Mexico. *CalCOFl Rep.* 36, 136–143.

Demirel, N., Zengin, M., and Ulman, A. (2020). First large-scale eastern mediterranean and black sea stock assessment reveals a dramatic decline. *Front. Mar. Sci.* 7:103. doi: 10.3389/fmars.2020.00103

Deyle, E. R., Fogarty, M., Hsieh, C.-H., Kaufman, L., MacCall, A. D., Munch, S. B., et al. (2013). Predicting climate effects on Pacific sardine. *Proc. Natl. Acad. Sci.* 110, 6430–6435. doi: 10.1073/pnas.1215506110

Dieckmann, U., Heino, M., and Jin, X. (2005). Shrinking fish: fisheries-induced evolution in the Yellow Sea. *Options Autumn* 2005:8.

FAO (2018). *The State of World Fisheries and Aquaculture 2018*. Rome: Food and Agriculture Organization of the United Nations.

Fei, H. N. (1980). Characteristics of aquatic resources and recommendations for enhanced management. *China Fish.* 3, 4–5.

Froese, R., Demirel, N., Coro, G., Kleisner, K. M., and Winker, H. (2017). Estimating fisheries reference points from catch and resilience. *Fish Fish.* 18, 506–526. doi: 10.1111/faf.12190

Froese, R., Palomares, M. L. D., and Pauly, D. (2000). "Estimation of life history key facts of fishes," in *FishBase 2000: Concepts, Design and Data Sources*, eds R. Froese and D. Pauly (Los Baños: ICLARM), 167–175.

Froese, R., and Pauly, D. (2019). *FishBase*. Cambridge, MA: World Wide Web electronic publication.

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A. C., Dimarchopoulou, D., et al. (2018). Status and rebuilding of European fisheries. *Mar. Policy* 93, 159–170. doi: 10.1016/j.marpol.2018.04.018

Huang, S. L., and He, Y. R. (2019). Management of China's capture fisheries: review and prospect. *Aquac. Fish.* 4, 173–182. doi: 10.1016/j.aaf.2019.05.004

Ji, Y. P., Liu, Q., Liao, B. C., Zhang, Q. Q., and Han, Y. N. (2019). Estimating biological reference points for largehead hairtail (*Trichiurus lepturus*) fishery in the Yellow Sea and Bohai Sea. *Acta Oceanol. Sin.* 38, 20–26. doi: 10.1016/j.fishres.2011.05.007

Lee, S.-G., and Midani, A. R. (2014). National comprehensive approaches for rebuilding fisheries in South Korea. *Mar. Policy* 45, 156–162. doi: 10.1016/j.marpol.2013.12.010

Li, Q. C., Zou, Y., Zhang, S. H., Wang, Y. J., Zhao, D., and Song, A. H. (2015). Changes in main fish stocks in Bohai Sea around Shandong Province. *Fish. Sci.* 34, 647–651. doi: 10.16378/j.cnki.1003-1111.2015.10.009

Liang, C., and Pauly, D. (2017a). Fisheries impacts on china's coastal ecosystems: unmasking a pervasive 'fishing down' effect. *PLoS One* 12:e0173296. doi: 10.1371/journal.pone.0173296

Liang, C., and Pauly, D. (2017b). Growth and mortality of exploited fishes in China's coastal seas and their uses for yield-per-recruit analyses. *J. Appl. Ichthyol.* 33, 746–756. doi: 10.1111/jai.13379

Liang, C., Xian, W. W., Liu, S. D., and Pauly, D. (2020a). Assessments of 14 exploited fish and invertebrate stocks in Chinese waters using the LBB method. *Front. Mar. Sci.* 7:314. doi: 10.3389/fmars.2020.00314

Liang, C., Xian, W. W., and Pauly, D. (2020b). Assessments of 15 exploited fish stocks in Chinese, South Korean and Japanese waters using the CMSY and BSM methods. *Front. Mar. Sci.* 7:623. doi: 10.3389/fmars.2020.00623

Lin, L. S., Cheng, J. H., Ren, Y. P., and Ling, J. Z. (2004). Analysis of population biology of small yellow croaker *Pseudosciaena polyactis* in the East China Sea region. *J. Fish. Sci. China* 1, 333–338.

Liu, H. X. (2005). *Study of Year-Recruit-Model for Spotted Mackerel, Scomber Australasicus, in the Waters off Northeastern Taiwan*. dissertation/doctoral thesis, National Taiwan University, Taiwan.

Liu, M., and Sadovy de Mitcheson, Y. (2008). Profile of a fishery collapse: why mariculture failed to save the large yellow croaker. *Fish Fish.* 9, 219–242. doi: 10.1111/j.1467-2979.2008.00278.x

Lluch-Belda, D., Crawford, R. J. M., Kawasaki, T., MacCall, A. D., Parrish, R. H., Schwartzlose, R. A., et al. (1989). World-wide fluctuations of sardine and anchovy stocks: the regime problem. *S. Afr. J. Mar. Sci.* 8, 195–205. doi: 10.2989/02577618909504561

Lluch-Belda, D., Schwartzlose, R. A., Serra, R., Parrish, R., Kawasaki, T., Hedgecock, D., et al. (1992). Sardine and anchovy regime fluctuations of abundance in four regions of the world oceans: a workshop report. *Fish. Oceanogr.* 1, 339–347. doi: 10.1111/j.1365-2419.1992.tb00006.x

Lu, Z. B., Yan, Y. M., and Du, Q. (1998). Variation of fishery resources and estimation of suitable fishing efforts in Xiamen coastal waters. *J. Oceanogr. Taiwan Strait.* 17, 309–316.

Mallory, T. G. (2013). China's distant water fishing industry: evolving policies and implications. *Mar. Policy* 38, 99–108. doi: 10.1016/j.marpol.2012.05.024

Mallory, T. G. (2016). Fisheries subsidies in China: quantitative and qualitative assessment of policy coherence and effectiveness. *Mar. Policy* 68, 74–82. doi: 10.1016/j.marpol.2016.01.028

McAllister, M. K., Pikitch, E. K., and Babcock, E. A. (2001). Using demographic methods to construct Bayesian priors for the intrinsic rate of increase in the Schaefer model and implications for stock rebuilding. *Can. J. Fish. Aquat. Sci.* 58, 1871–1890. doi: 10.1139/f01-114

Millar, R. B., and Meyer, R. (1999). *Nonlinear State-Space Modeling of Fisheries Biomass Dynamics using the Gibbs Sampler*. Auckland: Department of Statistics, The University of Auckland. Technical Report STAT9901.

Ministry of Agriculture and Rural Affairs of the People's Republic of China [MARA] (2018). *Announcement of the MARA [2018, No. 1]: Announcement of the Ministry of Agriculture on the Adjustment of the Summer Fishing Moratorium System*. Beijing: MARA.

Ministry of Agriculture and Rural Affairs of the People's Republic of China [MARA] (2019). *Announcement of the MARA[2019, No. 4]: Announcement on the Area and Time of the Ban on Fishing in Key Waters of the Yangtze River Basin*. Beijing: MARA.

Musick, J. A. (1999). Criteria to define extinction risk in marine fishes. *Fisheries* 24, 6–14. doi: 10.1577/1548-8446(1999)024<0006:ctderi>2.0.co;2

Ni, Y. (1999). Fishery resources conservation for *Coilia mystus* in the Changjiang Estuary. *J. Fish. Sci. China* 6, 75–77.

Palomares, M. L. D., and Pauly, D. (2019). On the creeping increase of vessels' fishing power. *Ecol. Soc.* 24:31. doi: 10.2307/26796991

Pauly, D. (1984). A mechanism for the juvenile-to-adult transition in fishes. *J. du Conseil int. pour l'Exploration de la Mer* 41, 280–284. doi: 10.1093/icesjms/41.3.280

Pauly, D. (2019). *Gasping Fish and Panting Squids: Oxygen, Temperature and the Growth of Water-Breathing Animals – 2nd Edition. Excellence in Ecology*. Oldendorf: International Ecology Institute.

Qiu, S. Y. (1995). Dynamics of Japanese spanish mackerel, *Scomberomorus niphonius* (Cuvier et Valenciennes) stocks in the yellow sea and bohai sea. *Modern Fish. Inform.* 10, 16–19.

Ren, Q. Q., and Liu, M. (2020). Assessing northwest Pacific fishery stocks using two new methods: the monte Carlo Catch-MSY (CMSY) and the bayesian schaefer model (BSM). *Front. Mar. Sci.* 7:430. doi: 10.3389/fmars.2020.00430

Ricker, W. E. (1975). Computation and interpretation of biological statistics of fish populations. *Bull. Fish. Res. Bd. Can.* 191, 382p.

Schaefer, M. B. (1954). Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Inter Am. Trop. Tuna Commission Bull.* 1, 23–56.

Schaefer, M. B. (1957). A study of the dynamics of the fishery for yellowfin tuna in the eastern tropical Pacific Ocean. *Inter Am. Trop. Tuna Commission Bull.* 2, 243–285.

Shen, G., and Heino, M. (2014). An overview of marine fisheries management in China. *Mar. Policy* 44, 265–272. doi: 10.1016/j.marpol.2013.09.012

Song, L. Q. (2007). *Study on Dual-Transform of Marine Fishermen in China*. Qingdao: China Ocean University Press.

Steinbeck, J. (1945). *Cannery Row*. New York: Viking Press, 208p.

Tang, M. Z., Lian, D. J., Lu, Y., and Yin, X. W. (2002). Fisheries administration and changes of Anchovy resources in the East and Yellow Sea. *Fish. Sci.* 21, 44–45.

Villasante, S., Rodríguez-González, D., Antelo, M., Rivero-Rodríguez, S., de Santiago, J. A., and Macho, G. (2013). All fish for China? *Ambio*. 42, 923–936. doi: 10.1007/s13280-013-0448-9

Wang, L., Shi, X., Su, Y., Meng, Z., and Lin, H. (2012). Loss of genetic diversity in the cultured stocks of the large yellow croaker, *Larimichthys crocea*, revealed by microsatellites. *Int. J. Mol. Sci.* 13, 5584–5597. doi: 10.3390/ijms13055584

Wang, Y. B., Wang, Y., Liang, C., Zhang, H., and Xian, W. W. (2020). Assessment of 12 fish species in the northwest Pacific using the CMSY and BSM methods. *Front. Mar. Sci.* 7:616. doi: 10.3389/fmars.2020.00616

Wang, Y. H., and Ni, Y. (1984). On the fisheries resources and their exploitation of the Changjiang (Yangtze) River Estuary in Shanghai Region. *J. Fish. China* 8, 147–159.

Wang, Q. H. (1985). Preliminary study on the *Sardinops melanosticta* (T&S) in the Yellow Sea. *J. Shandong Ocean Univ.* 15, 85–93.

Wang, Y. Z., Jia, X. P., Lin, Z. J., and Sun, D. R. (2011). Response of *Trichiurus lepturus* catches to fishing and climate variability in the East China Sea. *J. Fish. China* 35, 1881–1889.

Watanabe, Y., Zenitani, H., and Kimura, R. (1995). Population decline of the Japanese sardine *Sardinops melanostictus* owing to recruitment failures. *Can. J. Fish. Aquat. Sci.* 52, 1609–1616. doi: 10.1139/f95-154

Watson, R., and Pauly, D. (2001). Systematic distortions in world fisheries catch trends. *Nature* 414, 534–536. doi: 10.1038/35107050

Wei, S., and Li, F. G. (1986). Life habits and resource changes of *S. sagax*. *Foreign Aquat.* 1, 41–44.

Winker, H., and Sherley, R. (2019). JARA: 'Just Another Red-List Assessment'. *bioRxiv* [preprint]. doi: 10.1101/672899

Xu, K. D., and Liu, Z. F. (2007). The current stock of large yellow croaker *Pseudosciaena crocea* in the East China Sea with respects of its stock decline. *J. Dalian Fish. Univ.* 22, 392–395.

Xu, S. S., Song, J. M., Li, X. G., Yuan, H. M., Li, N., and Duan, L. Q. (2014). Variation Characteristics of Catch Structure in the Bohai Sea and Its Influencing Factors. *J. Nat. Resour.* 29, 500–506.

Yan, L. P., Liu, Z. L., Zhang, H., Ling, J. Z., Yuan, X. W., and Li, S. F. (2014). Evolution of biological resource characteristics and resource quantity of small yellow croaker. *Mar. Fish.* 36, 481–488.

Yáñez, E., Barbieri, M. A., Silva, C., Nieto, K., and Espíndola, F. (2001). Climate variability and pelagic fisheries in northern Chile. *Prog. Oceanogr.* 49, 581–596. doi: 10.1016/S0079-6611(01)00042-8

Yang, H., Xie, P., Ni, L. Y., and Flower, R. J. (2012). Pollution in the Yangtze. *Science* 337:410. doi: 10.1126/science.337.6093.410-a

Yang, J. M. (1988). Status of fishery resources development in the western Huanghai Sea (Yellow Sea). *Mar. Sci.* 4, 70–71.

Yu, C. G., and Zheng, B. (2000). Current situation and countermeasures of the utilization of *Engraulis japonicus* resources in zhejiang offshore. *Mar. Fish.* 1, 23–26.

Zhai, L., and Pauly, D. (2019). Yield-per-recruit, utility-per-recruit, and relative biomass of 21 exploited fish species in China's coastal seas. *Front. Mar. Sci.* 6:724. doi: 10.3389/fmars.2019.00724

Zhai, L., and Pauly, D. (2020). Construction and interpretation of particle size distribution spectra from 19 Ecopath models of Chinese coastal ecosystems. *Front. Mar. Sci.* 7:298. doi: 10.3389/fmars.2020.00298

Zhan, B. Y., Lou, D. C., and Zhong, J. S. (1986). An assessment of the filefish population and rational exploitations of the resource. *J. Fish. China* 10, 409–418.

Zhang, G. X., and Hua, J. D. (1990). Changes in the resources of the *Coilia mystus* in the Yangtze River Estuary and estimation of its maximum sustainable yield. 131–134.

Zhang, L. L., Ren, Q. Q., Liu, M., Xu, Q., Kang, B., and Lin, J. J. (2020). Fishery stock assessments in the Min River Estuary and its adjacent waters of southern China using the length-based Bayesian estimation (LBB) method. *Front. Mar. Sci.* 7:507. doi: 10.3389/fmars.2020.00507

Zhao, S. L., Wang, R. X., and Liu, X. S. (2002). Reason of exhaustion of resources of *Pseudosciaena crocea* in zhoushan fishing ground and the measures of protection and proliferation. *J. Zhejiang Ocean Univ.* 21, 162–165.

Zheng, Y. (2012). Evaluation of *Coilia mystus* of the Yangtze River. *J. Anhui Agric.* 40, 17140–17143.

Zhou, X. R. (2011). Multiplication release and ecological restoration. *Biol. Teach.* 36, 7–8.

Zhu, D. S., Chen, Y. Z., and Wang, W. X. (1990). Investigation and study on acoustic evaluation of carp and other economic fish resources in the East Yellow Sea. *Mar. Fish. Res.* 11, 18–23.

Zhu, X. H. (1992). Population dynamics of the bastard halibut, *Paralichthys oflivaceus* (T.&S.) and management of its resource. *Oceanol. Limnol. Sin.* 23, 270–297.

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer DD declared a past co-authorship with one of the authors, DP, to the handling editor.

frontiers in Marine Science

ORIGINAL RESEARCH
published: 26 May 2020
doi: 10.3389/fmars.2020.00298

Construction and Interpretation of Particle Size Distribution Spectra From 19 Ecopath Models of Chinese Coastal Ecosystems

Lu Zhai[1]* *and Daniel Pauly*[2]

[1] *Fisheries College, Ocean University of China, Qingdao, China,* [2] *Sea Around Us, Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, BC, Canada*

To assess the changes that fisheries have imposed on the functioning of coastal marine ecosystems in China, 19 published Ecopath models were used to construct particle size distribution (PSD) spectra. The results show that high biomass of jellyfish from ranching operation impacted almost all of the ecosystems studied here. As well, an increasing impact of fisheries was demonstrated, via steeper PSD slopes, for ecosystems with models covering two or more periods. Models of nearshore areas, i.e., bays and estuaries, exhibited steeper PSD slopes than models of offshore areas. The PSD slopes were also correlated with total catch (TC), mean trophic level of catch, and the Shannon–Wiener diversity index (H'), which can be computed from Ecopath models. A multiple regression predicting the PSD slopes from year and mean trophic level of the catch explained 38.5% of the variance in the slopes. Overall, this study confirmed the status of depletion in China's marine fisheries resources. In addition, it established that including a PSD while constructing an Ecopath model, which is straightforward, will improve it, and allow more insights to be obtained from it regarding the impact of fishing on marine ecosystems.

Keywords: Ecopath food web model, farmed jellyfish, fishing down food web, China's marine ecosystems, PSD spectra

OPEN ACCESS

Edited by:
António V. Sykes, University of Algarve, Portugal

Reviewed by:
Valeria Mamouridis, Independent Researcher, Rome, Italy
Hui Zhang, Chinese Academy of Sciences, China

***Correspondence:**
Lu Zhai
zhailu0708@hotmail.com

Specialty section:
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

Received: *27 January 2020*
Accepted: *14 April 2020*
Published: *26 May 2020*

Citation:
Zhai L and Pauly D (2020) Construction and Interpretation of Particle Size Distribution Spectra From 19 Ecopath Models of Chinese Coastal Ecosystems. Front. Mar. Sci. 7:298. doi: 10.3389/fmars.2020.00298

INTRODUCTION

Marine ecosystems provide habitats to marine organisms and supply them with their nutrients (Odum and Barrett, 1971); however, the diversity of species and the multitude of interactions between them are difficult to identify and represent in models (Limburg et al., 2002; Fulton et al., 2003). Nevertheless, the Ecopath with Ecosim (EwE) modeling approach has become widely used, notably because of the relative ease with which its parameters can be estimated (Christensen and Pauly, 1992; Pauly et al., 2000; Coll et al., 2015; Colléter et al., 2015) and its ability to realistically represent the structure of food web within a given period (with Ecopath), then to simulate over time the changes of trophic interactions between species or group thereof (with Ecosim).

China has a long coastline, often divided into three large marine ecosystems (LMEs), i.e., the Yellow Sea (including a marginal sea, the Bohai Sea), the East China Sea, and the South China Sea (Wang and Aubrey, 1987; Sherman and Hempel, 2008). The structure and functioning of these ecosystems have been impacted by climate change (Jiao et al., 2015; Liang et al., 2018), ocean acidification (Liu and He, 2012), and especially overfishing (Wang et al., 2008; Liang and Pauly, 2017a,b; Liang et al., 2018; Pauly and Liang, 2019; Zhai and Pauly, 2019).

The depletion of fisheries resources in China's coastal seas was partly mitigated by the development of mariculture. Thus, in 2018, the total coastal areas devoted to marine aquaculture was above 20,000 km^2, and production was more than 2 million tonnes (Anonymous, 2019). Indeed, the high density of mariculture enterprises and the escape of farmed animals exacerbate coastal pollution (Cao et al., 2007).

Another issue is worldwide proliferation of jellyfish (Brotz et al., 2012). While jellyfish are almost everywhere perceived as nuisance species (e.g., Lynam et al., 2005), several species are sought after in China, and some jellyfish are even farmed, or rather "ranched" (Dong et al., 2008). The increase in jellyfish in China's coastal seas in recent years are well-documented (Jiang et al., 2008; Dong et al., 2010) as is the negative impacts of jellyfish blooms on fishery and ecosystem functioning (Xian et al., 2005). For these reasons, Pauly et al. (2008) pointed out the important role of jellyfish in many ecosystems and the need to include them in food web models, which may have inspired the authors of subsequent Ecopath food web models to explicitly include jellyfish in their food webs (Lamb et al., 2019).

While the South China Sea, whose living resources are shared between numerous countries (Pauly and Liang, 2019), was modeled in the early 1990s (Pauly and Christensen, 1993), the first Ecopath model of a uniquely Chinese marine ecosystem was that of Tong et al. (2000), which sought to represent the structure of the food web in the Bohai Sea in 1982–1983. Since this pioneering effort, all of China's LMEs have been modeled by Chinese authors, i.e., the Yellow Sea (Lin et al., 2013), the East China Sea (Jiang et al., 2008), and the South China Sea (Cheung, 2007). However, many due to a perceived "lack of data," none of these authors have used Ecosim, the dynamic routine of EwE.

Here, we use 19 extant Ecopath models of Chinese coastal ecosystems for inferences on the impact of fisheries on such ecosystems using particle size distribution spectra (Sheldon et al., 1972; Guiet et al., 2016), based on these 19 models, but after they were modified such as to generate clear linear spectra. The resulting particle size distributions (PSD) spectra were then used to describe and quantify the effect of fisheries and environmental effects.

MATERIALS AND METHODS

Sources of Materials

The Ecopath models used in this study were sourced from the EcoBase (http://ecobase.ecopath.org/) and the scientific literature (**Table 1**). The geographical distribution of modeled ecosystems ranged from northern to southern China (**Figure 1**) and involves major main types of marine ecosystems, i.e., LMEs, a marginal sea, shelves, gulfs and bays, and estuaries. In addition, the models cover the 1960s to the 2010s, which encompass a period of huge changes in China's economy, including fisheries.

Basic Principles of Ecopath Modeling

Ecopath was initially conceived by Polovina (1984) as a food web model with a set of functional groups linked by biomass flows according to the principle of mass balance, and further developed by Christensen and Pauly (1992) and Pauly et al. (1993). The model is structured by a master equation, which applies to all consumer groups in the models:

$$B_i \times (P/B)_i = \sum_{j=1}^{N} B_j \times \left(\frac{Q}{B}\right)_j \times DC_{ji} + \left(\frac{P}{B}\right)_i \times B_i \times (1 - EE_i) + Y_i + E_i + BA_i \quad (1)$$

where B_i and B_j are the biomass (here in tonnes wet weight by km^{-2}) of prey i and predator j, respectively; P/B_i is the production per biomass (tonnes km^{-2} $year^{-1}$) of prey I; Q/B_i is the consumption per biomass (tonnes km^2 $year^{-1}$) of prey i; DC_{ij} is the proportion of prey i in the diet of predator j; EE_i is the ecotrophic efficiency, i.e., the fraction of i's production that is consumed within the system; Y_i is the fishery catch (tonnes km^{-2} $year^{-1}$); E_i is the net migration rate (i.e., emigration–immigration; in tonnes km^{-2} $year^{-1}$); and BA_i is the biomass accumulation rate ($year^{-1}$).

Another key equation of Ecopath is

$$Q_i = P_i + R_i + UA_i \quad (2)$$

where Q_i is the consumption (tonnes km^{-2} $year^{-1}$), P_i is the production (tonnes km^{-2} $year^{-1}$), R_i is the respiration (tonnes km^{-2} $year^{-1}$), and UA_i is the unassimilated food of group i (tonnes km^{-2} $year^{-1}$). The model assumes that the mass and energy input and output must be balanced within the time period covered by the model.

Particle Size Distribution

Particle size distribution (PSD) or size spectra within aquatic ecosystems are a powerful tool to show how much human activities and environmental-driven factors impact on aquatic ecosystem (Blanchard et al., 2017) and are usually based on sampling plankton (Hunt et al., 2015; Wallis et al., 2016) or fish (Boudreau and Dickie, 1992; Bianchi et al., 2000) using net gears that are adequate for these groups only. Irrespective of the way they are presented—which is usually as log(biomass) vs. log(body weight)—the resulting spectra frequently cover only plankton and/or or fish while regularly omitting marine mammals, i.e., they mostly cover a relatively narrow range of sizes, and thus their slopes are probably biased downward. Pauly and Christensen (2002) demonstrated that Ecopath models, which necessarily include small and large organisms with biomasses that are realistic, and mutually compatible, can be used to construct PSD, whose slopes can be compared between systems and/or with the slope of PSD estimated through field sampling.

In order to be able to use the groups' biomasses of an Ecopath model in a size spectrum, two issues must be considered:

(1) Many groups (e.g., large teleosts, which start as planktonic larvae) have ontogenies that span several (log) sizes classes or "bins," and thus, their biomass must be allocated to several bins in accordance to their relative abundances.
(2) Different size/age groups (e.g., in large species) have vastly different growth rates, as do different species occurring in the same ecosystems, and thus, they remain in bins of given sizes for periods that vary among and between the species that define a group.

TABLE 1 | Summary and adjustment of 19 adjusted Ecopath models in China's seas (biomass in tonnes km^{-2}; catch in tonnes km^{-2} year^{-1}).

No.	Area	Year	Jellyfish	AFs	Adjusted group	Biomass	Catch	Sources
1	Bohai Sea	1982	–	–	–	–	–	Tong et al., 2000; Wang et al., 2011
2	Bohai Sea	2016	+	–	Jellyfish	2.17 (0.21)	0.1 (0.01)	Rahman et al., 2019
3	Laizhou Bay	2016	–	+	Sea cucumber	150 (55)	–	Xu et al., 2019
					Oyster	97.4 (20)	–	–
4	Jimo coastal	2011	–	–	–	–	–	Su, 2016
5	Jiaozhoua Bay	1980	+	–	Jellyfish	0.05 (0.0043)	–	Ma, 2018
6	Jiaozhoua Bay	2011	–	+	–	–	–	Han et al., 2017
7	Jiaozhoua Bay	2015	+	–	Jellyfish	0.05 (0.0043)	–	Ma, 2018
8	Southern Yellow Sea	2000	+	–	Jellyfish	2.50 (0.24)	0.24 (0.02)	Lin et al., 2013
9	Hangzhou Bay	2006	–	–	Piscivorous fish	1.25 (0.41)	0.65 (0.35)	Xu et al., 2011
10	Yangtze River Estuary	2014	+	–	Bp.nf.fish	0.47 (0.30)	–	Wang, 2019
					Jellyfish	29.02 (2.79)	0.02 (0.001)	
11	East China Sea	1998	+	–	Large jellyfish	2.25 (0.22)	0.14 (0.01)	Jiang et al., 2008
					Argentinidae	0.01 (0.04)	–	
					Macrobenthos	8.0 (1.0)	–	
12	East China Sea Shelf	Early 2000s	+	–	Echinoderms	3.46 (1.0)	–	Li et al., 2009
					Jellyfish	2.15 (0.21)	0.06 (0.01)	
13	Pearl River Estuary	1981	+	–	Jellyfish	0.77 (0.07)	0.01 (0.001)	Duan et al., 2009
14	Pearl River Estuary	1998	+	–	Jellyfish	1.53 (0.15)	0.03 (0.003)	Duan et al., 2009
15	Northern S. China Sea	1970s	+	–	Jellyfish	0.11 (0.01)	0.001 (0.0001)	Cheung, 2007
16	Northern S. China Sea	2000s	+	–	Jellyfish	1.53 (0.15)	0.004 (0.0004)	Cheung, 2007
17	Beibu Gulf	1960	+	–	Jellyfish	0.89 (0.09)	0.001 (0.0001)	Chen Z. Z. et al., 2008 Chen Z. et al., 2008
18	Beibu Gulf	1999	+	–	Jellyfish	1.12 (0.11)	0.03 (0.003)	Chen Z. Z. et al., 2008
19	Beibu Gulf	2007	+	–	Jellyfish	0.80 (0.08)	0.01 (0.001)	Sun et al., 2016

+Jellyfish as separate functional group and artificial reefs (AFs); adjusted values are in brackets.
Bp.NF.fish, benthopelagic carnivorous fish.

Version 6.6 of EwE includes a routine based on Pauly and Christensen (2002), which account for these two items using, for each of the groups, the parameter of a von Bertalanffy growth function (VBGF) to express the growth of the animal therein across a range of size bins. For length, the VBGF is

$$L_t = L_{inf}\left[1 - e^{-K(t-t_0)}\right] \quad (3)$$

where L_t is the mean length at age t of the species in question; L_{inf} is the asymptotic size, i.e., the mean length attained after an infinitely long time; K is growth coefficient (here in year^{-1}); and t_0 (usually negative) is the age they would have had at a size of zero if they had always grown in the manner predicted by the equation (which they have not; see e.g., Pauly, 1998).

However, given that we are dealing with biomass, the VBGF here is combined with a length–weight relationship (LWR) of the form $W = a{\cdot}L^b$ to obtain a version of the VBGF suitable for growth in weight, i.e.,

$$W_t = W_{inf}\left[1 - e^{-K(t-t_0)}\right]^b \quad (4)$$

where W_{inf} is the mean weight attained after an infinitely long time, and the other parameters are as defined previously.

Recall that, in fisheries science and in Ecopath, it is expressed by

$$N_t = N_{t-\Delta t} \cdot e^{-Z\cdot\Delta t} \quad (5)$$

where N_t is the number at time t, $N_{t-\Delta t}$ is the number at time $t - \Delta t$, and Z is the instantaneous rate of total mortality, which happens to be equal to the P/B ratio, a parameter of Ecopath models, when growth follows the VBGF (Allen, 1971). Thus, the biomass contribution B_t of a species (or group, see below) in a given size bin can be computed from

$$B_t = N_t \cdot W_t \cdot \Delta t \quad (6)$$

where Δt is the time the group takes to grow through a bin, or weight class, with W_t as defined above; B_t is scaled over all weight classes so as to sum up to the total biomass of the group.

As for Δt, it is estimated as the time difference between the relative ages (t') computed from the inverse of the VBGF, i.e.,

$$t' = \ln\frac{\left[1 - \left(\frac{W_t}{W_{\text{inf}}}\right)^{-b}\right]}{(-K)} \quad (7)$$

where t' is the relative age corresponding to the lower or upper limit of the weight interval, and all other parameters are as

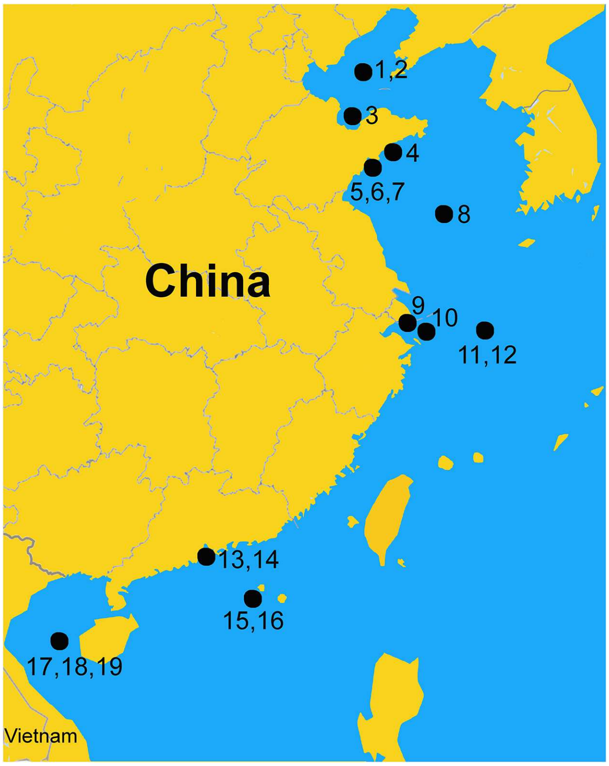


FIGURE 1 | Central point location of the area covered by 19 Ecopath models of China's coastal seas.

defined previously. Note that t_0, which allows absolute ages to be computed, is not required because Δt is computed as a difference between relative ages.

Thus, to construct a PSD when a parameterized and balanced Ecopath model is available, all that is needed are L_{inf} (or W_{inf}) and K values to deal with the ontogeny of each group (when L_{inf} only is available, a LWR must be also provided, but its exponent b can be assumed = 3; Froese, 2006; Hay et al., 2020).

The growth parameters of the species reported or assumed to contribute most of the biomass in each group were used to describe the growth of each functional group. These growth parameters originated from FishBase (www.fishbase.org), SeaLifeBase (www.sealifebase.org), and the scientific literature. When several sets of growth parameters were available, those originating from China or nearby countries were selected. For species without growth parameters, similar size species from the same genus or family were taken as substitutes (see **Table SI**). This applied also to zooplankton, of which an increasing number of species have their growth described by the VBGF (see, e.g., Wang et al., 2017).

For Ecopath models in which jellyfish were listed as a separate group, the input biomasses and catches of jellyfish were adjusted by reducing their values to the ones they would have if they had the same water content as fish, i.e., from an average of 98% to an approximate value of 75% (Palomares and Pauly, 2008). These and other minor adjustments of the 19 Ecopath models (see **Table 1**) were done for each model separately, such as avoid artificially introducing common features.

Multivariate Analyses

Nine of the indicators output by Ecopath were used for comparisons between the 19 models at hand, i.e., the slope of PSDs, mean year of coverage, mean latitude (ML) of area covered, total system throughput (TST, in tonnes km^{-2} year^{-1}), mean trophic level of the catch (MTL$_c$), mean trophic level of the ecosystem (MTL$_e$), total biomass (TB), total catch (TC), and Shannon–Wiener diversity index (H'). MTL and H' values were calculated based on functional groups instead of species. All indices except mean year and mean latitude were calculated by the program EwE 6.6 (Christensen et al., 2000).

Among these nine indicators, year, slope, MTL$_c$, MTL$_e$, and TC are the factors that can be related to fishery impacts on ecosystems. Four indicators, ML, TST, TB, and H' are environmental factors; TST is the total annual biomass flux through all direct trophic interactions, which indicate the size of ecosystems; TB and H' define the size and complexity of ecosystems from different perspectives; and ML deals with the impacts on ecosystems of different geographic locations (e.g., via temperature). These are assumed to be the most representative indicators of impacts on the ecosystems by both human and environmental factors.

Regression analysis was used to explore the relationships between the slopes of the PSD, and these indicators and multivariate analyses were performed to compare the structure and function of the ecosystems represented by the 19 models. Multidimensional scaling (MDS; Borg and Groenen, 2003) and H-clustering (Johnson, 1967; Bishop and Tipping, 1998; Fraley, 1998) were used to classify the 19 models based on the 9 indicators above, and the differences between the groups were tested by an analysis of similarities (ANOSIM). Similarity percentage analysis (SIMPER) was applied to identify the indicator associated with the difference between models. These analyses were conducted using Microsoft Excel and the Rstudio software.

RESULTS

Adjustments to the Ecopath Models

Fifteen models contained jellyfish as explicit group. They were all adjusted for water contents, i.e., there biomass was reduced (see above). In addition, their estimates of ecotrophic efficiency (EE) was increased from an average of 0.37–0.77, as suggested by a negative correlation ($p < 0.01$) between EE and biomass (see **Table 3**). This implies that their production is consumed at about twice the rate assumed by the original authors.

PSD Slopes

Figure 2, pertaining to the Bohai Sea, illustrates the model adjustments that were performed to obtain the PSD slope summarized in **Table 2**, while the adjustments required for the other models are illustrated in **Figures SI**, **SII**. For eight of the models, the adjustments lead to the PSD exhibiting markedly

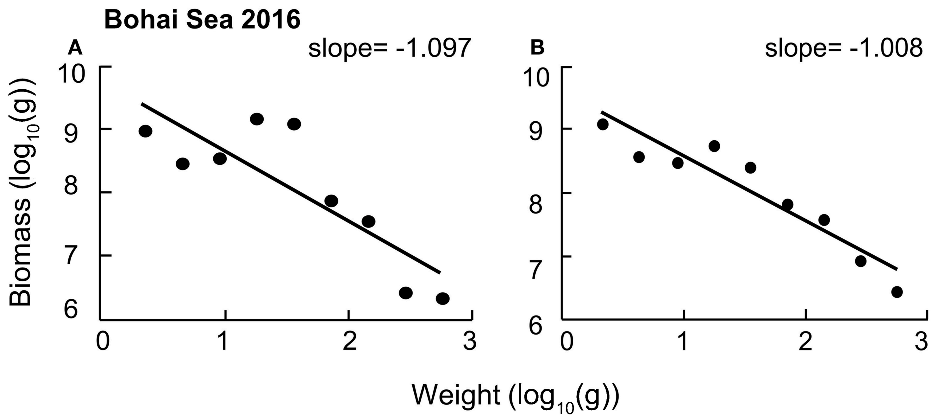


FIGURE 2 | Results of particle size distribution (PSD) for the model of Bohai Sea (2016) in China. **(A)** Before adjusting the biomass of jellyfish. **(B)** After adjusting the biomass of jellyfish.

TABLE 2 | Indices and values of models examined in China's seas from 1960s to 2010s.

No.	Models	Year	ML	TST	TB	TC	MTLc	MTLe	*H′*	Slope	Corr.
1	Bohai Sea	1982	39.5	1,339	33.5	5.2	3.0	2.8	1.8	−0.69	0.88
2	Bohai Sea	2016	39.1	10,064	26.9	2.1	2.8	2.9	1.0	−1.01 (−1.1)	0.94 (0.84)
3	Laizhou Bay	2016	37.3	5,197	168.3	63.0	2.5	2.7	1.7	−0.92 (−0.91)	0.92 (0.77)
4	Jimo coastal	2011	36.5	5,087	90.8	26.1	2.6	2.5	2.0	−0.38	0.88
5	Jiaozhou Bay	1980	36.0	9,621	148.7	146.0	2.2	3.0	2.1	−0.80	0.98
6	Jiaozhou Bay	2011	36.1	12,907	187.3	697.9	2.0	2.9	1.2	−1.39	0.93
7	Jiaozhou Bay	2015	36.0	12,971	98.4	140.5	2.0	3.0	1.3	−1.61 (−1.72)	0.97 (0.95)
8	Southern Yellow Sea	2000	34.0	5,027	51.6	1.5	3.2	3.0	1.5	−0.88 (−0.96)	0.91 (0.88)
9	Hangzhou Bay	2006	32.7	5,008	97.3	3.3	1.6	2.6	1.9	−0.61	0.86
10	Yangtze River Estuary	2014	31.4	10,737	65.2	1.0	3.3	2.8	1.3	−0.71 (−0.86)	0.89 (0.72)
11	East China Sea	1998	28.0	5,206	41.2	8.8	2.7	2.9	2.3	−0.55 (−0.56)	0.94 (0.93)
12	East China Sea Shelf	2000	28.1	1,556	58.6	5.9	3.0	3.0	2.5	−0.65 (−0.65)	0.94
13	Pearl River Estuary	1981	24.0	4,570	70.8	1.6	2.8	2.8	2.0	−0.91 (−0.84)	0.95 (0.92)
14	Pearl River Estuary	1998	24.0	1,693	32.2	3.5	2.3	2.6	1.5	−1.14 (−0.98)	0.95 (0.92)
15	Northern S. China Sea	1970	21.5	26,6102	543.6	0.9	3.1	2.9	1.1	−0.82 (−0.82)	0.93 (0.93)
16	Northern S. China Sea	2000	21.5	26,2107	501.7	7.7	2.8	2.9	0.9	−0.91 (−0.86)	0.87 (0.88)
17	Beibu Gulf	1960	19.4	3,054	92.5	2.2	3.2	2.9	1.6	−0.68 (−0.69)	0.91 (0.92)
18	Beibu Gulf	1998	19.4	4,264	90.5	9.0	2.8	2.7	1.7	−1.07 (−1.09)	0.96 (0.96)
19	Beibu Gulf	2007	20.6	4,341	59.2	5.6	2.8	2.5	2.1	−1.06 (−1.07)	0.94 (0.94)
	Average	–	–	–	–	–	2.7 ± 0.1	2.8 ± 0.04	–	–	–

Values before adjusting in brackets.

Bp.nf. fish, benthopelagic carnivorous fish; ML, mean latitude; TST, total system throughput; TB, total biomass; TC, total catch; MTLc, mean trophic level of catch; MTLe, mean trophic level of ecosystem; H′, Shannon–Wiener diversity.

closer correlation, while the remainder of the models was not affected much.

The slopes of 19 models in Chinese coastal seas are shown in **Figure 3**. The mean slope and standard error were −0.89 ± 0.069, and their range was −0.38 to −1.61. One of the main results is that, for all models representing 2 or more years of the same ecosystems, there was a clear steepening of the slopes with time (**Figure 4**), suggesting that, in recent years, the upper higher trophic levels of costal food webs have disappeared.

Multivariate Analyses

The MDS analyses and the H-clustering produced similar results, i.e., they both divided the 19 models into 5 clusters (**Figure 5**). One cluster consisted of northern South China Sea (1970s and 2000s) and another three models consisted of Jiaozhou Bay (1980, 2011, and 2015). The "stress" of MDS is an indicator of the fit of the graph to the available data. Here, the MDS result had an "excellent" fit, with a stress value of 0.01(<2.5%; Kruskal, 1964).

The ANOSIM yielded a global R of 0.70 > 0 ($p < 0.001$), implying that the difference between groups was significant. The

TABLE 3 | Ecotrophic parameters for jellyfish and farmed species in China's seas (landings in tonnes km^{-2} year^{-1}).

Species	No.	Landings	Trophic level	Ecotrophic efficiency (*EE*)	
Jellyfish	2	0.01	3.01	0.34	**0.99**
	5	0.01	2.91	0.36	**0.36**
	7	0.01	2.91	0.36	**0.36**
	8	0.02	3.06	0.22	**0.29**
	10	0.25	2.45	0.36	**0.97**
	11	0.01	3.01	0.35	**0.95**
	12	0.01	2.94	0.25	**0.98**
	13	0.001	2.82	0.25	**0.92**
	14	0.003	2.52	0.12	**1.00**
	15	0.0001	3.02	0.95	**0.98**
	16	0.15	3.10	0.44	**0.94**
	17	0.0001	3.00	0.09	**0.96**
	18	0.002	3.00	0.10	**0.97**
	19	0.001	2.75	0.08	**0.08**
	Average	–	2.89 ± 0.05	0.30 ± 0.06	**0.77 ± 0.09**
Apostichopus	3	32.82	2.00	0.37	**0.99**
Oyster	3	–	2.00	0.95	**0.95**
Shellfish	6	697.5	2.00	0.95	**0.95**
	Average	–	2.00 ± 0.00	0.76 ± 0.20	**0.96 ± 0.01**

Adjusted EE value are in bold.

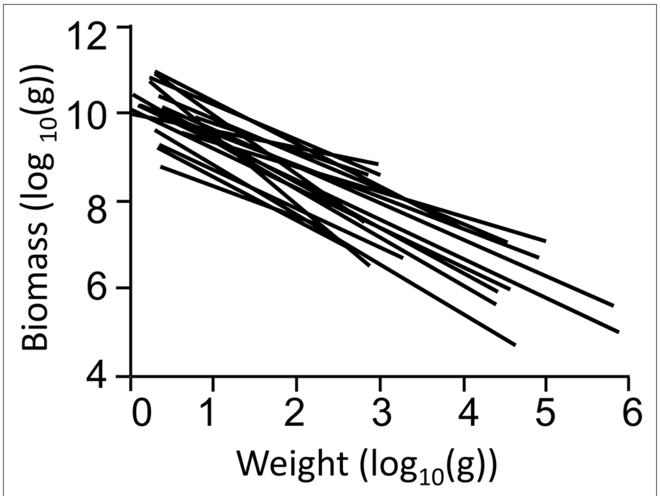


FIGURE 3 | Particle size distribution (PSD) spectra for 19 models in China's coastal ecosystems.

SIMPER analysis indicated that the main reason for the difference between the models was TST, i.e., the scale of the ecosystems; the second reason is TC.

The slopes were significantly correlated with TC, H', and TC × MTL_c when all 19 models were included (see **Figures 6A–C**). In addition, the slopes have significant relationships with year and MTL_c for the 14 models representing the same areas in different years (see **Figures 6D,E**). A multiple regression predicting the PSD slopes from year and mean trophic level of the catch had a multiple coefficient of variation (R^2) of 0.385, implying that year and mean trophic level explain 38.5% of the variance in the slopes (see **Figure 6F**).

DISCUSSION

The key insights emanating from this study are, in our opinion, that:

(1) Constructing PSD plots from balanced Ecopath models is straightforward;
(2) but jellyfish and mariculture require special treatment;
(3) PSD do reflect fishing pressure on ecosystems, and thus,
(4) PSD should become part of the completion and verification of Ecopath models.

We elaborate on these four points.

The routine of EwE 6.6 that can be downloaded from www.ecopath.org which allows for deriving PSD from Ecopath models is, as mentioned above, very easy to use. Particularly useful is a graph that shows the biomass that each group contributes to different body weight bins and which was used for the model adjustments described above.

Moreover, contrary to the situation prevailing only a few years ago, growth parameters and LWRs are increasingly available for fish in FishBase (Froese and Pauly, 2019; Hay et al., 2020), SeaLifeBase (Palomares and Pauly, 2019), and online literature (e.g., Palomares and Pauly, 2008) such that even groups for which other growth models had been used now have the VBGF to describe their growth, a trend likely to continue.

The results obtained here suggest that one of main reasons for imbalance in Chinese coastal ecosystems is due to jellyfish, whose biomass must be adjusted—if it was no done in the original models—for their extremely high water content (Palomares and Pauly, 2008) and the short duration of the period during which their biomass is high—particularly in jellyfish species that are ranched (You et al., 2007; Dong et al., 2008). In these species, the high biomass period may last only 1 or 2 months, and thus, their ecosystem impact (i.e., food consumption) must be reduced accordingly; such temporal adjustments were not done by the authors of all models.

Although not used here, temporal adjustments may also have to be performed in some cases for short-lived farmed species, e.g., those on artificial reefs, deployed along coastline to simulate the natural reefs environment, to provide a replacement for lost natural habitats to marine fisheries resources (Baine, 2001). Thus, the models for artificial reefs in Laizhou Bay showed serious impacts on the trophic flows by individual farmed species, notably by a high biomass of sea cucumber and oyster that had spilled over from a nearby farm (Xu et al., 2019). Such adjustment can be done by multiplying the mean biomass of the group while it is in the system by the fraction of the year (often <<1) that it is in the system.

Another adjustment that might have to be considered in some cases (though it was not used here) is to reduce the biomass in the smallest size group (phytoplankton and microzooplankton),

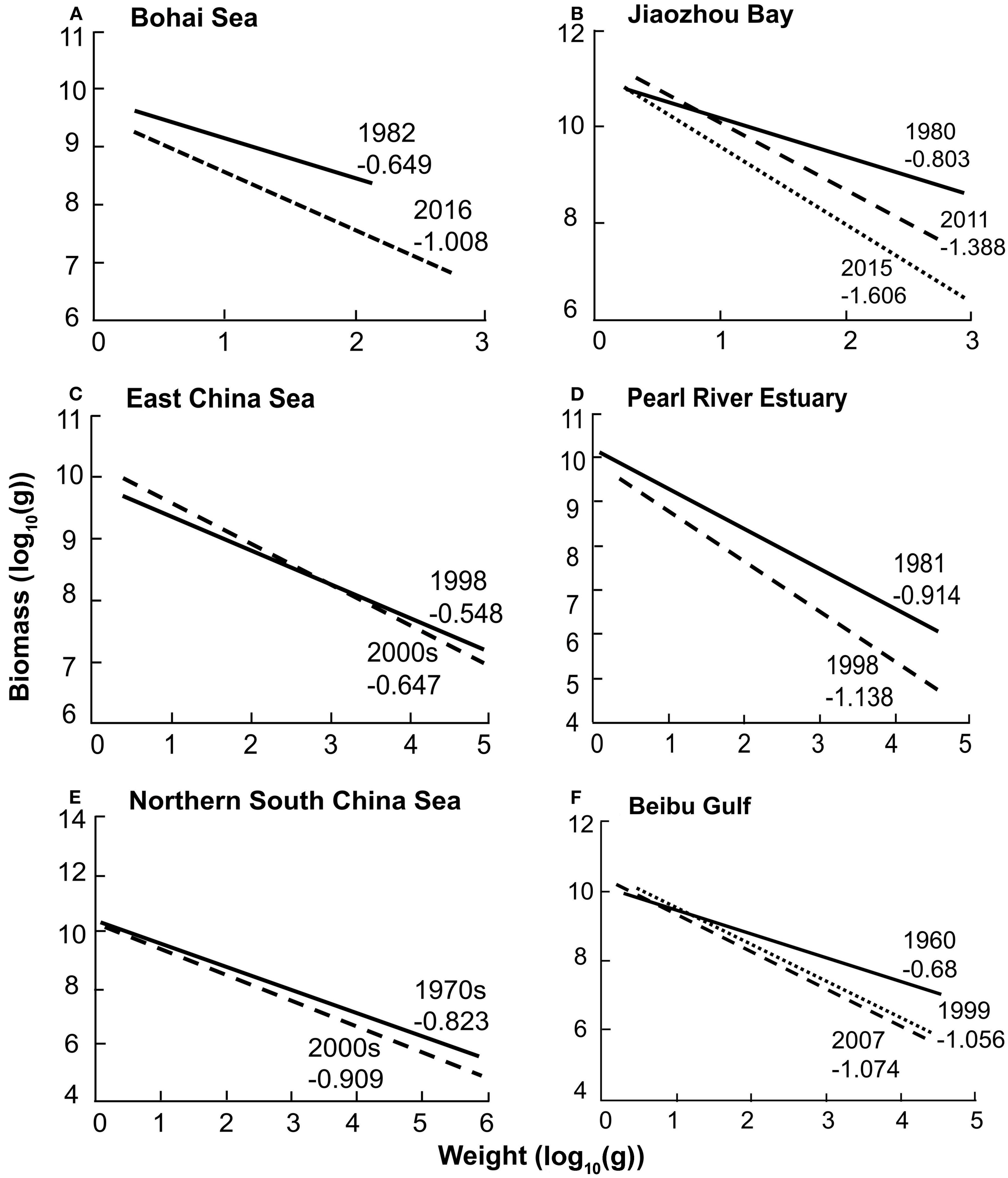


FIGURE 4 | Comparison of particle size distribution (PSD) slopes for 6six paired models in China's seas from 1960s to 2010s. **(A)** Bohai Sea; **(B)** Jiaozhou Bay; **(C)** East China Sea; **(D)** Pearl River Estuary; **(E)** Northern South China Sea; **(F)** Beibu Gulf.

when its size range is smaller than the bin size of the PSD plots (such adjustments are required for reason of arithmetic and do not imply that the Ecopath models in question are in error).

As expected, different models covering the same area exhibit PSD slopes that became steeper over time, implying more fishing pressure on these areas, which is in line with what is known of fisheries along China's coastline (Ling et al., 2006; Li et al., 2015; Teh et al., 2017). The PSD for the Bohai Sea, Jiaozhou Bay, Pearl River Estuary, Beibu Gulf, and other coastal and nearshore ecosystems had steeper slope than the PSD for the wider East China Sea and the northern South China Sea, which is consistent with the result of Liang and Pauly (2017b), who demonstrated a strong fishing down effect (which induces strongly negative PSD) along the coast of the East China Sea, followed by the

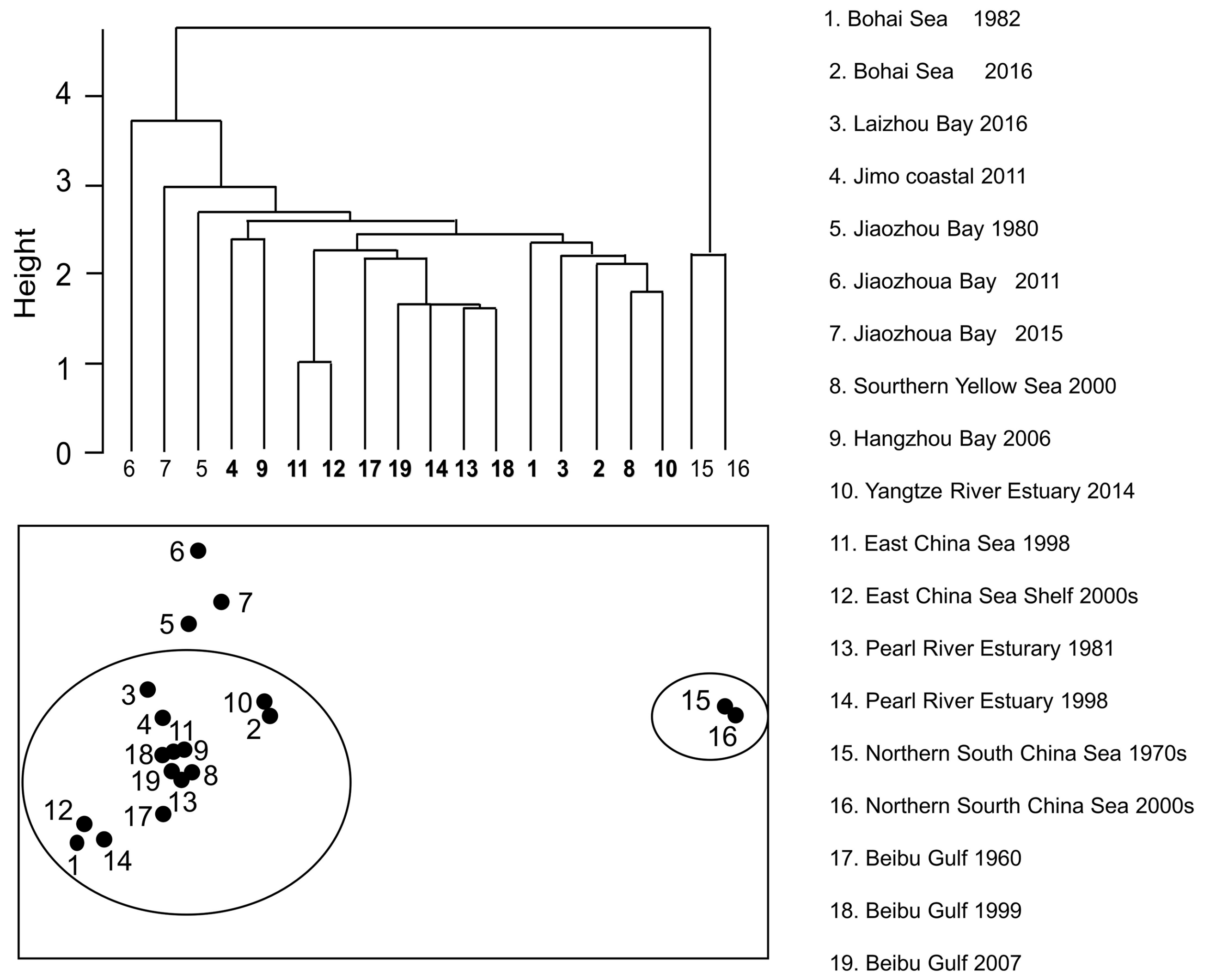


FIGURE 5 | H-clustering and multidimensional scaling (MDS) groups for 19 Ecopath models in China's coastal seas.

development of an offshore fishery, which induces another fishing down trend.

The TST index was the main reason why the northern South China Sea model is different from others, while the TC index was the main reason why the models of Jiaozhou Bay (1980, 2011, and 2015) formed a distinct group. Jiaozhou Bay is the most important shellfish mariculture site in the northern China, and its high TC values are mostly due to shellfish farming and fishing for escapees from farms. Therefore, it appears that mariculture has more impacts on the ecosystems than (over)fishing.

The steepness of the PSD slopes, which expresses fishing pressure, was significantly negatively correlated with the year and TC variables and was significantly positively correlated with H' and MTL_c. This implies that the marine ecosystems that have a high biodiversity and MTL_c would be in better shape than the others. Given a background of generalized overfishing, this would be reversed with higher TC, indicating that reducing the fishery catch is conducive to the balance of the marine ecosystems' structure and function. Moreover, the impacts of year variable is not direct, rather mainly associated with TC and the depletion of fishery resources, which increase through time. Thus, in China, if the high fishing pressure is maintained, or even increase, the PSD slope of coastal marine ecosystems will continue to decline. In addition, the slopes were positively correlated with MTL_c, implying that an ecosystem with a less negative PSD slope will have more high-trophic level fish that can be caught, which is another definition of "fishing down" (Pauly et al., 1998, 2001; Liang and Pauly, 2019).

High level of diversity is conducive to the stability of ecosystem (Elmqvist et al., 2003), and thus, models should represent that biodiversity ought to be represented. Several of the models considered here lacked large marine mammals, sharks,

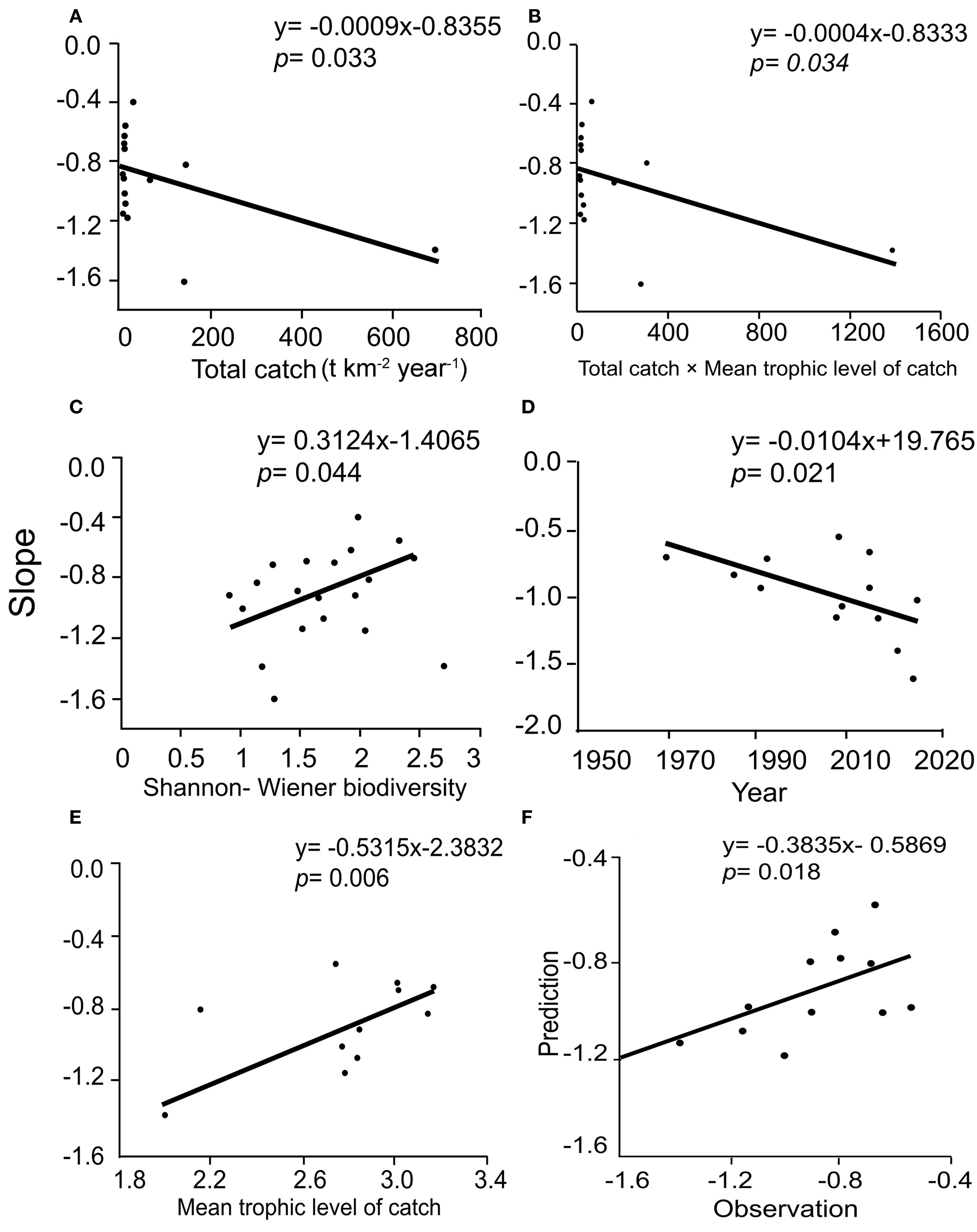


FIGURE 6 | Regression of the slopes of particle size distributions in 19 Ecopath models of Chinese coastal ecosystems against explanatory factors. **(A)** Total catch; **(B)** Total catch × mean trophic level; **(C)** Shannon-Wiener biodiversity index; **(D)** Year; **(E)** Mean trophic level of catch; **(F)** Predicted vs observed slope (see text).

and/or seabirds; while many of these larger animals do not occur along China's coast, some do, if in small numbers, and models should include them. Some PSD slopes were too steep because of the omissions.

Overall, this contribution, besides further confirming that China's coastlines are strongly exploited by fisheries, also confirmed that PSDs allow for numerous insights and inference on food web models and the ecosystems they represent. Moreover, PSDs, which are easily constructed, help identify problems with the parametrization of Ecopath models. Thus, while Ecopath-derived PSDs are not common so far (but see Palomares et al., 2009), we suggest that they should be, in China and elsewhere.

AUTHOR CONTRIBUTIONS

LZ was responsible for the data collection, formal analysis, and writing of the original draft. DP was responsible for the conceptualization, methodology, and supervision.

FUNDING

LZ research was funded by China Scholarship Council (CSC). DP research was supported by the *Sea Around Us*, which receives funding from the Oak Foundation, the Marisla Foundation, the Paul M. Angell Family Foundation, the David and Lucile Packard Foundation, the Minderoo Foundation, and the Bloomberg Philanthropies through RARE.

ACKNOWLEDGMENTS

LZ acknowledges China Scholarship Council (CSC) for the support. DP acknowledges support for the *Sea Around Us*, a research initiative funded by several philanthropic foundations, notably the Oak, Marisla, and Minderoo Foundations.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00298/full#supplementary-material

REFERENCES

Allen, K. R. (1971). Relation between production and biomass. *J. Fish. Res. Board Can.* 28, 1573–1581. doi: 10.1139/f71-236

Anonymous (2019). *China Fishery Statistical Yearbooks*. Beijing: China Agricultural Press.

Baine, M. (2001). Artificial reefs, a review of their design, application, management and performance. *Ocean Coast. Manag.* 44, 241–259. doi: 10.1016/S0964-5691(01)00048-5

Bianchi, G., Gislason, H., Graham, K., Hill, L., Jin, X., Koranteng, K., et al. (2000). Impact of fishing on size composition and diversity of demersal fish communities. *ICES J. Mar. Sci.* 57, 558–571. doi: 10.1006/jmsc.2000.0727

Bishop, C. M., and Tipping, M. E. (1998). A hierarchical latent variable model for data visualization. *IEEE Trans. Pattern Anal. Mach. Intell.* 20, 281–293. doi: 10.1109/34.667885

Blanchard, J. L., Heneghan, R. F., Everett, J. D., Trebilco, R., and Richardson, A. J. (2017). From bacteria to whales, using functional size spectra to model marine ecosystems. *Trends Ecol. Evol.* 32, 174–186. doi: 10.1016/j.tree.2016.12.003

Borg, I., and Groenen, P. J. F. (2003). Modern multidimensional scaling, theory and applications. *J. Educ. Measur.* 40, 277–280. doi: 10.1111/j.1745-3984.2003.tb01108.x

Boudreau, P. R., and Dickie, L. M. (1992). Biomass spectra of aquatic ecosystems in relation to fisheries yield. *Can. J. Fish. Aquat. Sci.* 49, 1528–1538. doi: 10.1139/f92-169

Brotz, L., Cheung, W. W. L., Kleisner, K., Pakhomov, E., and Pauly, D. (2012). "Increasing jellyfish populations, trends in large marine ecosystems," in *Jellyfish Blooms, Series IV*. eds J. E. Purcell, H. Mianzan, and J. R. Frost (Dordrecht: Springer), 3–20 doi: 10.1007/978-94-007-5316-7_2

Cao, L., Wang, W. M., Yang, Y., Yang, C. T., Yuan, Z. H., Xiong, S. B., et al. (2007). Environmental impact of aquaculture and countermeasures to aquaculture pollution in China. *Environ. Sci. Pollut. Res. Int.* 14, 452–462. doi: 10.1065/espr2007.05.426

Chen, Z., Qiu, Y. S., Jia, X. P., and Xu, S. N. (2008). Using an ecosystem modeling approach to explore possible ecosystem impacts of fishing in the Beibu Gulf, northern South China Sea. *Ecosystems* 11, 1318–1334. doi: 10.1007/s10021-008-9200-x

Chen, Z. Z., Qiu, Y. S., Jia, X. P., and Zhong, Z. H. (2008). Effects of fishing on the marine ecosystem of Beibu Gulf. *Chin. J. Appl. Ecol.* 19, 1604–1610. doi: 10.7666/d.y1291216

Cheung, W. W. L. (2007). *Vulnerability of Marine Fishes to Fishing, From Global Overview to the Northern South China Sea (Doctoral thesis), University of British Columbia,* Vancouver, Canada.

Christensen, V., and Pauly, D. (1992). ECOPATH II-a software for balancing steady-state ecosystem models and calculating network characteristics. *Ecol. Model.* 61, 169–185. doi: 10.1016/0304-3800(92)90016-8

Christensen, V., Walters, C. J., and Pauly, D. (2000). Ecopath with Ecosim: a user's guide. Vancouver, BC: University of British Columbia, Fisheries Centre, Canada and ICLARM, Penang, Malaysia, 154.

Coll, M., Akoglu, E., Arreguin-Sanchez, F., Fulton, E. A., Gascuel, D., Heymans, J. J., et al. (2015). Modelling dynamic ecosystems, venturing beyond boundaries with the Ecopath approach. *Rev. Fish Biol. Fish.* 25, 413–424. doi: 10.1007/s11160-015-9386-x

Colléter, M., Valls, A., Guitton, J., Gascuel, D., Pauly, D., and Christensen, V. (2015). Global overview of the applications of the Ecopath and Ecosim modeling approach using the ecobase model repository. *Ecol. Model.* 302, 42–53. doi: 10.1016/j.ecolmodel.2015.01.025

Dong, J., Jiang, L. X., Tan, K. F., Liu, H. Y., Purcell, J. E., Li, P. J., et al. (2008). "Stock enhancement of the edible jellyfish (*Rhopilema esculentum* Kishinouye) in Liaodong Bay, China, a review," in *Jellyfish Blooms, Causes, Consequences, and Recent Advances, 2008,* eds K. A. Pitt and J. E. Purcell (Dordrecht: Springer), 113–118. doi: 10.1007/978-1-4020-9749-2_8

Dong, Z. J., Liu, D. Y., and Keesing, J. K. (2010). Jellyfish blooms in China, dominant species, causes and consequences. *Mar. Pollut. Bull.* 60, 954–963. doi: 10.1016/j.marpolbul.2010.04.022

Duan, L. J., Li, S. Y., Liu, Y., Moreau, J., and Christensen, V. (2009). Modeling changes in the coastal ecosystem of the pearl river estuary from 1981 to 1998. *Ecol. Model.* 220, 2802–2818. doi: 10.1016/j.ecolmodel.2009.07.016

Elmqvist, T., Folke, C., Nyström, M., Peterson, G., Bengtsson, J., Walker, B., et al. (2003). Response diversity, ecosystem change, and resilience. *Front. Ecol. Environ.* 1, 488–494. doi: 10.1890/1540-9295(2003)001[0488:RDECAR]2.0.CO;2

Fraley, C. (1998). Algorithms for model-based Gaussian hierarchical clustering. *SIAM J. Sci. Comput.* 20, 270–281. doi: 10.1137/S1064827596311451

Froese, R. (2006). Cube law, condition factors and weight-length relationships, history, meta-analysis and recommendations. *J. Appl. Ichthyol.* 22, 241–253. doi: 10.1111/j.1439-0426.2006.00805.x

Froese, R., and Pauly, D. (2019). *FishBase*. Species list, World Wide Web electronic publication. Available online at: www.fishbase.org, version: 08/2019.

Fulton, E. A., Smith, A. D., and Johnson, C. R. (2003). Effect of complexity on marine ecosystem models. *Mar. Ecol. Prog. Series* 253, 1–16. doi: 10.3354/meps253001

Guiet, J., Poggiale, J. C., and Maury, O. (2016). Modelling the community size-spectrum, recent developments and new directions. *Ecol. Model.* 337, 4–14. doi: 10.1016/j.ecolmodel.2016.05.015

Han, D. Y., Xue, Y., Zhang, C. L., and Ren, Y. P. (2017). A mass balanced model of trophic structure and energy flows of a semi-closed marine ecosystem. *Acta Oceanol Sinica* 36, 60–69. doi: 10.1007/s13131-017-1071-6

Hay, A., Xian, W., Bailly, N., Liang, C., and Pauly, D. (2020). The why and how of determining length-weight relationships of fish from preserved museum specimens. *J. Appl. Ichyol.* 36, 376–382. doi: 10.1111/jai.14014

Hunt, B. P., Allain, V., Menkès, C., Lorrain, A., Graham, B., Rodier, M., et al. (2015). A coupled stable isotope-size spectrum approach to understanding pelagic food-web dynamics, a case study from the southwest sub-tropical Pacific. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 113, 208–224. doi: 10.1016/j.dsr2.2014.10.023

Jiang, H., Cheng, H. Q., Xu, H. G., Arreguín-Sánchez, F., Zetina-Rejón, M. J., Luna, P. D. M., et al. (2008). Trophic controls of jellyfish blooms and links with fisheries in the East China Sea. *Ecol. Model.* 212, 492–503. doi: 10.1016/j.ecolmodel.2007.10.048

Jiao, N. Z., Chen, D. K., Luo, Y. M., Huang, X. P., Zhang, R., Zhang, H. B., et al. (2015). Climate change and anthropogenic impacts on marine ecosystems and countermeasures in China. *Adv. Clim. Change Res.* 6, 118–125. doi: 10.1016/j.accre.2015.09.010

Johnson, S. C. (1967). Hierarchical clustering schemes. *Psychometrika* 32, 241–254. doi: 10.1007/BF02289588

Kruskal, J. B. (1964). Multidimensional scaling by optimizing goodness of fit to a nonmetric hypothesis. *Psychometrika* 29, 1–27. doi: 10.1007/BF02289565

Lamb, P. D., Hunter, E., Pinnegar, J. K., Doyle, T. K., Creer, S., and Taylor, M. I. (2019). Inclusion of jellyfish in 30+ years of Ecopath and Ecosim models. *ICES J. Mar. Sci.* 76, 1941–1950. doi: 10.1093/icesjms/fsz165

Li, Q. C., Zou, Y., Zhang, S. C., Wang, Y. J., Zhao, D., and Song, A. H. (2015). Changes in main fish stocks in Bohai Sea and Shandong Province. *Fish. Sci.* 34, 647–651. doi: 10.16378/j.cnki.1003-1111.2015.10.009

Li, Y., Chen, Y., Olson, D., Yu, N., and Chen, L. (2009). Evaluating ecosystem structure and functioning of the East China sea shelf ecosystem, China. *Hydrobiologia*. 636:331. doi: 10.1007/s10750-009-9964-9

Liang, C., and Pauly, D. (2017a). Growth and mortality of exploited fishes in China's coastal seas and their uses for yield-per-recruit analyses. *J. Appl. Ichthyol.* 33, 746–756. doi: 10.1111/jai.13379

Liang, C., and Pauly, D. (2017b). Fisheries impacts on China's coastal ecosystems, unmasking a pervasive 'fishing down' effect. *PLoS ONE*. 12:e0173296. doi: 10.1371/journal.pone.0173296

Liang, C., and Pauly, D. (2019). Masking and unmasking fishing down effects, the Bohai Sea (China) as a case study. *Ocean Coast. Manag.* 184:105033. doi: 10.1016/j.ocecoaman.2019.105033

Liang, C., Xian, W. W., and Pauly, D. (2018). Impacts of ocean warming on china's fisheries catch, application of the 'mean temperature of the catch'. *Front. Mar. Sci.* 5:26. doi: 10.3389/fmars.2018.00026

Limburg, K. E., O'Neill, R. V., Costanza, R., and Farber, S. (2002). Complex systems and valuation. *Ecol. Econ.* 41, 409–420. doi: 10.1016/S0921-8009(02)00090-3

Lin, Q., Jin, X., and Zhang, B. (2013). Trophic interactions, ecosystem structure and function in the southern Yellow Sea. *Chin. J. Oceanol. Limnol.* 31, 46–58. doi: 10.1007/s00343-013-2013-6

Ling, J. Z., Li, S. F., and Yan, L. P. (2006). Analysis on the utilization of main fishery resources in the East China Sea. *Mar. Fish.* 28, 111–116. doi: 10.13233/j.cnki.mar.fish.2006.02.005

Liu, W., and He, M. (2012). Effects of ocean acidification on the metabolic rates of three species of bivalve from southern coast of China. *Chin. J. Oceanol. Limnol.* 30, 206–211. doi: 10.1007/s00343-012-1067-1

Lynam, C. P., Heath, M. R., Hay, S. J., and Brierley, A. S. (2005). Evidence for impacts by jellyfish on North Sea herring recruitment. *Mar. Ecol. Prog. Series* 298, 157–167. doi: 10.3354/meps298157

Ma, M. L. (2018). *The structure and function of the typical semi-enclosed by ecosystem based on Ecopath model.* (Master's thesis), Shanghai Ocean University, Shanghai, China.

Odum, E. P., and Barrett, G. W. (1971). *Fundamentals of Ecology*. Philadelphia, PA: Saunders.

Palomares, M. L. D., Bailly, N., and Pauly, D. (2009). "FishBase, SeaLifeBase and database-driven ecosystem modeling," in *Ecopath 25 Years Conference Proceedings, Extended Abstracts*, eds M. L. D. Palomares, L. Cisneros-Montemayor, A. Morissette, D. Varkey, M. Coll, C. Piroddi (Fisheries Centre Research Reports), Vancouver, BC: Fisheries Centre, University of British Columbia), 156–158.

Palomares, M. L. D., and Pauly, D. (2008). "The growth of jellyfishes," in *Jellyfish Blooms, Causes, Consequences, and Recent Advances*, eds K. A. Pitt and J. E. Purcell (Dordrecht: Springer), 11–21. doi: 10.1007/978-1-4020-9749-2_2

Palomares, M. L. D., and Pauly, D. (2019). *SeaLifeBase*. World Wide Web electronic publication. www.sealifebase.org, version: 12/2019.

Pauly, D. (1998). Beyond our original horizons, the tropicalization of Beverton and Holt. *Rev. Fish Biol. Fish.* 8, 307–334. doi: 10.1023/A:1008863215253

Pauly, D., and Christensen, V. (1993). "Stratified models of large marine ecosystems, a general approach and an application to the South China Sea," in, *Stress, Mitigation and Sustainability of Large Marine Ecosystems*, eds K. Sherman., L. M. Alexander and B. D. Gold (Washington, DC: Gold American Association for the Advancement of Science), 148–174.

Pauly, D., and Christensen, V. (2002). "Chapter 10. Ecosystem models," in, *Handbook of Fish Biology and Fisheries, Vol. 2,* eds P. J. B. Hart and J. D. Reynolds (Oxford: Blackwell Science Ltd). 211–227. doi: 10.1002/9780470693919.ch10

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., and Torres, F. (1998). Fishing down marine food webs. *Science* 279, 860–863. doi: 10.1126/science.279.5352.860

Pauly, D., Christensen, V., and Walters, C. J. (2000). Ecopath, Ecosim and Ecospace as tools for evaluating ecosystem impact of fisheries. *ICES J. Mar. Sci.* 57, 697–706. doi: 10.1006/jmsc.2000.0726

Pauly, D., Graham, W., Libralato, S., Morissette, L., and Palomares, M. L. D. (2008). "Jellyfish in ecosystems, online databases and ecosystem models," in *Jellyfish Blooms, Causes, Consequences, and Recent Advances. Developments in Hydrobiology, Vol. 206,* eds K. A. Pitt and J. Purcell (Dordrecht: Springer), 67–85. doi: 10.1007/978-1-4020-9749-2_5

Pauly, D., and Liang, C. (2019). The fisheries of the South China Sea, major trends since 1950. *Mar. Policy* 32, 816–822. doi: 10.1016/j.marpol.2019.103584

Pauly, D., Palomares, M. L. D., Froese, R., Sa-a, P., Vakily, M., Preikshot, D., et al. (2001). Fishing down Canadian aquatic food webs. *Can. J. Fish. Aquat. Sci.* 58, 51–62. doi: 10.1139/f00-193

Pauly, D., Soriano-Bartz, M. L., and Palomares, M. L. D. (1993). "Improved construction, parametrization and interpretation of steady-state ecosystem models," in *Trophic Models of Aquatic Ecosystems,* eds V. Christensen and D. Pauly (Manila: ICLARM Conference Proceedings), 1–13.

Polovina, J. J. (1984). Model of a coral reef ecosystem. *Coral Reefs* 3, 1–11. doi: 10.1007/BF00306135

Rahman, M. F., Lin, Q., Shan, X. J., Chen, Y. L., Ding, X. S., and Liu, Q. (2019). Temporal changes of structure and functioning of the Bohai Sea ecosystem, insights from Ecopath models. *Thalas. Int. J. Mar. Sci.* 35, 625–641. doi: 10.1007/s41208-019-00139-1

Sheldon, R. W., Prakash, A., and Sutcliffe W. H. Jr. (1972). The size distribution of particles in the ocean. *Limnol. Oceanogr.* 17, 327–340. doi: 10.4319/lo.1972.17.3.0327

Sherman, K., and Hempel, G. (eds.). (2008). *The UNEP Large Marine Ecosystem Report, A Perspective on Changing Conditions in* LMEs of the World's Regional Seas. Nairobi, Kenya, UNEP Regional Seas Reports and Studies No. 182, p.852.

Su, M. (2016). Preliminary analysis of the Jimo coastal ecosystem with the Ecopath model. *J. Ocean Univ. China* 15, 1059–1066. doi: 10.1007/s11802-016-3078-6

Sun, L. Q., Lin, Y. S., Chen, L. X., Cao, W. Q., and Zheng, L. M. (2016). Analysis of ecosystem structure and function the northern Beibu Gulf VII, nutrition structure and keystone species selection based on Ecopath with Ecosim. *J. Trop. Oceanogr.* 35, 51–62. doi: 10.1016/j.ecss.2006.10.013

Teh, L. S., Witter, A., Cheung, W. W., Sumaila, U. R., and Yin, X. (2017). What is at stake? Status and threats to South China Sea marine fisheries. *Ambio* 46, 57–72. doi: 10.1007/s13280-016-0819-0

Tong, L., Tang, Q. S., and Pauly, D. (2000). A preliminary approach on mass-balance Ecopath model of the Bohai Sea. *J. Appl. Ecol.* 11, 435–440. doi: 10.13287/j.1001-9332.2000.0109

Wallis, J. R., Swadling, K. M., Everett, J. D., Suthers, I. M., Jones, H. J., Buchanan, P. J., et al. (2016). Zooplankton abundance and biomass size spectra in the East Antarctic sea-ice zone during the winter - spring transition. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 131, 170–181. doi: 10.1016/j.dsr2.2015.10.002

Wang, B., Yu, G., Huang, J., Wang, T., and Hu, H. Y. (2011). Probabilistic ecological risk assessment of DDTs in the Bohai Bay based on a food web bioaccumulation model. *Sci. Total Environ.* 409, 495–502. doi: 10.1016/j.scitotenv.2010.10.039

Wang, K., Hunt, B. P. V., Liang, C., Pauly, D., and Pakhomov, E. A. (2017). Reassessment of the life cycle of the pteropod *Limacina helicina* from a high resolution interannual time series in the temperate North Pacific. *ICES J. Mar. Sci.* 74, 1906–1920. doi: 10.1093/icesjms/fsx014

Wang, Y., and Aubrey, D. G. (1987). The characteristics of the China coastline. *Contin. Shelf Res.* 7, 329–349. doi: 10.1016/0278-4343(87)90104-X

Wang, Y. C. (2019). *Modelling the structure and interannual dynamics of energy flows in Yangtze Estuary and its adjacent waters* (Master's thesis), Institute of Oceanology, Chinese Academy of Sciences, Qingdao, China, 103.

Wang, Y. S., Lou, Z. P., Sun, C. C., and Sun, S. (2008). Ecological environment changes in Daya Bay, China, from 1982 to 2004. *Mar. Pollut. Bull.* 56, 1871–1879. doi: 10.1016/j.marpolbul.2008.07.017

Xian, W. W., Kang, B., and Liu, R. Y. (2005). Jellyfish blooms in the Yangtze Estuary. *Science* 307:41. doi: 10.1126/science.307.5706.41c

Xu, M., Qi, L., Zhang, L. B., Zhang, T., Yang, H. S., and Zhang, Y. L. (2019). Ecosystem attributes of trophic models before and after construction of artificial oyster reefs using Ecopath. *Aquacult. Environ. Inter.* 11, 111–127. doi: 10.3354/aei00284

Xu, S. N., Chen, Z. Z., Li, S. Y., and He, P. M. (2011). Modeling trophic structure and energy flows in a coastal artificial ecosystem using mass-balance Ecopath model. *Estuaries Coasts* 34, 351–363. doi: 10.1007/s12237-010-9323-0

You, K., Ma, C., Gao, H., Li, F., Zhang, M., Qiu, Y., et al. (2007). Research on the jellyfish (*Rhopilema esculentum* Kishinouye) and associated aquaculture techniques in China, current status. *Aquacult. Int.* 15, 479–488. doi: 10.1007/s10499-007-9114-1

Zhai, L., and Pauly, D. (2019). Yield-per-recruit, utility-per-recruit, and relative biomass of 21 exploited fish species in china's coastal seas. *Front. Mar. Sci.* 6:724. doi: 10.3389/fmars.2019.00724

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Advantages of publishing in Frontiers

OPEN ACCESS
Articles are free to read for greatest visibility and readership

FAST PUBLICATION
Around 90 days from submission to decision

HIGH QUALITY PEER-REVIEW
Rigorous, collaborative, and constructive peer-review

TRANSPARENT PEER-REVIEW
Editors and reviewers acknowledged by name on published articles

Frontiers
Avenue du Tribunal-Fédéral 34
1005 Lausanne | Switzerland

Visit us: www.frontiersin.org
Contact us: frontiersin.org/about/contact

REPRODUCIBILITY OF RESEARCH
Support open data and methods to enhance research reproducibility

DIGITAL PUBLISHING
Articles designed for optimal readership across devices

FOLLOW US
@frontiersin

IMPACT METRICS
Advanced article metrics track visibility across digital media

EXTENSIVE PROMOTION
Marketing and promotion of impactful research

LOOP RESEARCH NETWORK
Our network increases your article's readership