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Research Paper

Advancing multispecies fishery management in China: Lessons from international experience

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A R T I C L E I N F O

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A B S T R A C T

China's 13th Five-Year Plan elevated the national mandate for environmental sustainability. Chinese fisheries are characterized by full retention of high diversity catch harvested using unselective gears, creating ecological risks. Therefore, China launched pilot projects in management by Total Allowable Catch (TAC) in five coastal provinces in 2017 and 2018 to build experience with output controls. Fujian province launched an important pilot in its swimming crab fishery, the first to adopt a multispecies approach. To guide Fujian and other provinces in multispecies management, a workshop in April 2018 shared international experience. The workshop considered 13 case studies spanning a wide range of underlying scientific models and types of harvest controls. Multispecies harvest controls based on simple survey- or index-based models that aggregate trends for many species are typically operationally easier for managers and fishers. However, inadequate management can cause declines of individual species, sometimes leading to adoption of species-specific models and then species-specific harvest controls. This transition often incurs economic costs through scientific and management demands, and constraints on harvest of co-occurring species. The lessons revealed by the case studies suggest multispecies TACs might be effective in the Fujian swimming crab fishery given the modest number of species with similar and productive life history traits, and the market demand for all species. Continued experimentation with different management approaches through pilot projects can enable China to maintain progress toward sustainable fisheries goals under the 14th Five-Year Plan.

Declaration of interest

The authors claim no competing or conflicting interests associated with this manuscript.

1. Introduction

Ecological sustainability has been increasing as a national policy priority in China for many years, including clear support for the United Nations Sustainable Development Goals (Kuhn 2016). The 13th Five-Year Plan established the strongest national environmental

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imperative to date, encapsulated in China by the concept of "ecological civilization" (Central Committee of the Communist Party of China [Central Committee], 2016). This concept remains prominent in the 14th Five-Year Plan (Xinhua News Agency 2021). Consequently, ministries charged with oversight of environmental sectors in China issued policies consistent with the vision of the 13th Five-Year Plan, the outcomes of which informed the 14th Five-Year Plan. For the fisheries sector, the Ministry of Agriculture (MOA; now the Ministry of Agriculture and Rural Affairs, MARA) announced an ambitious suite of objectives addressing reforms in fishing capacity, total catch, stock assessment, monitoring, enforcement, ecosystem restoration and protection, fishing rights and organizations, and management (Ministry of Agriculture and Rural Affairs of the PRC [MARA], 2017; Huang and He 2019; Shu et al., 2020). Reinforcing these policy changes is the rising affluence in Chinese society, bringing with it increasing public demand for improved environmental stewardship (Costello 2017; Szuwalski et al., 2020). These policy and societal changes represent what is perhaps the most significant opportunity in China's history to build sustainable fisheries that meet economic, social, and ecological goals (Cao et al., 2017).

Among the objectives of Chinese fisheries policy is a target to reduce nationwide marine catch from more than 13,000 mt to 10,000 mt over the duration of the five-year plan from 2016 to 2020. Individual provinces were charged with lowering their marine catch by at least 23.6% to help achieve the national goal, and then setting limits on marine catch to keep within the new target (Ministry of Agriculture and Rural Affairs of the PRC [MARA], 2017; Huang and He 2019; Shu et al., 2020). One important tactic in this transition is more widespread use of output controls, including Total Allowable Catch (TAC), which is actually required by the current national fisheries law yet has not been effectively enforced before 2017. This direction is consistent with international experience, which shows that output controls are generally more effective than input or effort controls at keeping within fishing mortality thresholds and achieving biomass targets for managed species (Melnychuk et al., 2012; Liu et al., 2016). However, output controls also entail greater costs and require additional capacity for stock assessment and monitoring (Walters and Parma 1996; Mangin et al., 2018). These burdens likely make implementation of species-specific TACs across the highly diverse catch of China's fishing fleets untenable (Szuwalski et al., 2020; Shu et al., 2020). China has issued policies to limit catch in the past (Shen and Heino 2014), but those policies were largely not enforced and unsuccessful. This was due in part to the cost and capacity issues associated with management by output controls, which are especially significant for a nation with the world's largest fishing fleet and total catch.

China adopts a unique experimental approach to public policy development, whereby pilot projects at the provincial and municipal levels build experience with new approaches in small-scale and relatively controlled settings (Heilmann 2008; Kuhn 2016). Effective approaches identified through pilot projects can then be scaled up into new national policies if the conditions in the pilot project are sufficiently representative of other contexts to facilitate replication and expansion (*sensu* Battista et al., 2017). This approach has been used to shape policy reforms in commerce (Heilmann 2008), health care (You and Kobayashi 2009), energy (Dong et al., 2015), land management (Banks et al., 2003), agriculture (Deng et al., 2010), and other sectors. For the first time, pilot projects are now being used to experiment with output controls in China's fisheries sector. Specifically, the new national fisheries policy directed five coastal provinces – Liaoning, Shandong, Zhejiang, Fujian, and Guangdong – to initiate pilot projects in management by TACs in 2017, with all 11 coastal provinces to have pilots underway by 2020 (Ministry of Agriculture and Rural Affairs of the PRC [MARA], 2017). These pilot projects aim to enable scientists, managers, enforcement officers, and the fishing industry to develop the practical experience needed to make the current policy for expanded use of output controls workable.

Shandong and Zhejiang began their pilot projects in 2017, and Liaoning, Fujian, and Guangdong began their pilot projects in 2018 (Huang and He 2019; Shu et al., 2020). Fujian province selected the multispecies swimming crab fishery, making it the first pilot that does not focus on a single species, with Guangdong subsequently selecting its multispecies shellfish fishery for their pilot. The Fujian and Guangdong pilots are significant because most fisheries in China are characterized by unselective gears, high species diversity, and full utilization of the catch (Szuwalski et al. 2017, 2020). In order to meet its ambitious new fisheries policy goals, China will need to develop scientific and management approaches that are appropriate in this context. The multispecies pilots are important in building experience in those approaches, which motivated the Fisheries Research Institute of Fujian and the China Society of Fisheries to convene a workshop on international experiences in multispecies fisheries management from April 26–27, 2018 in Xiamen, Fujian province, to inform design of the Fujian swimming crab pilot and other fisheries management objectives in China.

The workshop considered emerging scientific concepts, such as catch accounting based on energy flow, or 'plankton shares', and new ecosystem models that are not yet being used to make management decisions but could do so in the future (Gaichas et al., 2012, 2016; Szuwalski et al., 2017; DePiper et al., 2021). However, the primary focus of the workshop was case studies in multispecies fisheries management in practice from around the world that can inform new approaches in China (Table 1; Fig. 1). Here, we summarize the practical experiences and lessons learned from these case studies. We briefly review the case studies, synthesize those experiences to develop more general insights on multispecies fisheries management, evaluate prospects for multispecies management in the Fujian swimming crab fishery in particular, and consider how to develop strategies that most effectively manage multispecies fisheries generally. The international experiences addressed in the workshop can be informative as China begins to implement the 14th Five-Year Plan and new fisheries policies that emerge from MARA and the coastal provinces.

2. Case studies

A total of 13 case studies were considered in the workshop (Table 1; Fig. 1). Selection of case studies aimed to bring together different types of fisheries in different contexts using different management approaches, although a practical constraint was the availability of suitable speakers familiar with different fisheries. Priority was given to case studies that use TAC management, either alone or in combination with effort controls. In practice, however, case studies of TAC-based management in multispecies fisheries were limited, so the workshop also examined multispecies fisheries using primarily effort controls. Some case studies also used spatial management tools along with TACs and/or effort controls. We did not consider case studies that use Territorial Use Rights for Fishing (TURFs) as the primary approach. TURFs are important tools for management of multispecies fisheries, especially small-scale fisheries in nearshore environments and capacity-limited contexts (Barner et al., 2015; Quynh et al., 2017), and therefore were the primary focus of a follow-up workshop held in Zhoushan, Zhejiang Province, in July 2018.

The outcome of balancing these objectives and constraints was that the majority of case studies ultimately examined at the workshop were from temperate regions in the U.S.A., Europe, and Australia, along with four from tropical or sub-tropical regions in Australia and Asia (Fig. 1). There were more candidate case studies of multispecies management systems in northern temperate nations where capacity for science, governance, monitoring, and enforcement is generally greater. Figs. 3–7 are taken directly from presentations at the workshop, and the associated speakers along with any relevant citations are noted in each.

Not all of the case studies were completely distinct fisheries. For example, the groundfish and skate fisheries in New England, U.S.A., are the focus of different management plans but are prosecuted concurrently

Table 1
Approaches used in case studies considered in the international workshop on multispecies fishery management, including the underlying scientific models and primary harvest controls, with references that provide more information on the management program for each fishery. Case study numbers match Fig. 1 and Table 2. MSE = Management Strategy Evaluation; TAC = Total Allowable Catch; ITQ=Individual Transferable Quota; ITE=Individual Transferable Effort; PSA=Productivity-Susceptibility Analysis.

Fishery	Scientific models	Harvest controls	References
1. New England groundfish	Age-structured and index-based assessments	Single-species TACs allocated as tradable quotas to permit holders in harvest cooperatives	New England Fishery Management Council, 2021a
2. New England herring	Age-structured assessment with consumption data; MSE examines effects of alternative harvest control rules on predator biology	Fleet-wide TAC distributed among four management areas; fishery closes in a management area when 90% of TAC is caught	New England Fishery Management Council, 2021b
3. New England skates	Index-based assessment for each species in the complex	Trip limits set to achieve target multispecies TAC; retention of overfished species prohibited	New England Fishery Management Council, 2021c
4. North Sea groundfish	Mostly age-structured assessments with some index-based assessments	Single-species TACs allocated among neighboring nations, then sub-allocated as ITQs	European Parliament and Council of the European Union, 2018
5. North Sea skates & rays	Index-based single-species assessments (formerly aggregated)	Fleet-wide multispecies TAC with area closures	ScientificTechnical and Economic Committee for Fisheries [STECF], 2017
6. Western Europe slope deep sea sharks	Life history evaluation and swept-area biomass estimate	Fleet-wide multispecies TAC (currently = 0)	Council of the European Union, 2016
7. Thailand trawl	Fox production model for all species aggregated	Total fishing days estimated to catch 80% of multispecies MSY allocated among vessels	Department of Fisheries-Thailand, 2015
8. Fujian swimming crab TAC pilot	Recent catch in pilot study area	Fleet-wide multispecies TAC for pilot area, which closed when 95% of TAC is caught	Boenish et al. (2021a)
9. Northwest Australia reef fish	Age-structured assessments for four indicator species; 12 additional species checked by periodic monitoring	ITE shares (time allowed to access designated management zones) allocated among vessels	Department of Fisheries-Western Australia, 2016
10. Northern Australia prawn	Bio-economic model	ITE shares (trawl headline length) allocated among vessels	Australian Fisheries Management Agency [AFMS], 2021a
11a. Southeast Australia shark & scale-fish: Most finfish	Age-structured assessments for ITQ species; index-based assessments and PSA for secondary species	TACs allocated as ITQs for 16 primary target species with various input controls for other species	Australian Fisheries Management Agency [AFMS], 2021b
11 b. Southeast Australia shark & scale-fish: Scorpaenids	Age structured assessments	Multispecies TAC allocated as ITQs	Australian Fisheries Management Agency [AFMS], 2021b
11c. Southeast Australia shark & scale-fish: Deep water sharks	Aggregate CPUE trends with age-structured and index-based assessments to track individual species	Area closures aim to minimize fishing mortality with multispecies TAC allocated as ITQs to cap fishing mortality	Australian Fisheries Management Agency [AFMS], 2021b

by many of the same vessels, and the three case studies from Southeastern Australia are ‘sub-fisheries’ under a single management plan. There are some differences in the approaches applied for different species within a single case study, particularly in terms of the scientific models used (Table 1). However, the overall combination of approaches used in each case study represents a unique scientific and management strategy that distinguishes it from the others considered.

Notably, most of the case studies are fisheries for bony fishes or elasmobranchs, with the exception of the Northern Australia prawn fishery and Fujian swimming crab TAC pilot. All but one of the initial TAC pilot projects in China focus on invertebrate species, with the exception being a second pilot in Zhejiang focused on its anchovy fishery (Huang and He 2019), although a large proportion of the national fisheries catch is finfish (Szuwalski et al., 2017). Therefore, the applicability of the finfish management models examined in the workshop for invertebrate fisheries warrants further consideration.

3. Synthesis

The case studies reveal four general combinations of underlying scientific models and harvest controls developed using those models in terms of whether each is structured to consider species within the fishery individually or addresses multiple species together (Table 2; Fig. 2). The types of scientific models used in the case studies span a wide spectrum, including basic life history information, catch trends or survey indices, risk assessments, analytical age-structured stock assessments, and Management Strategy Evaluation (MSE) models. Although the workshop was motivated by China’s provincial pilot projects in TAC management, the case studies include a variety of harvest controls, including input controls, output controls, and spatial restrictions. Input controls and spatial restrictions can be the primary harvest controls, but also often complement TACs to achieve more effective overall management. The four combinations are as follows:

1. Aggregate scientific models + multispecies harvest controls: Models consider multiple species simultaneously, with harvest controls then developed and implemented for the complex of species as a whole. In these case studies, data limitations precluded species-specific scientific assessments, operational issues precluded use of single-species harvest controls, or both. Operational constraints include the ability of fishers to avoid or discriminate individual species, the capacity for management to monitor and enforce complex regulations, or common objectives for multiple species best achieved by single measures applied to the group of species collectively rather than for each individually. Scientific models are often simple catch- or survey-based approaches that aggregate multiple species in a single biomass index. Harvest controls can be multispecies TACs or multispecies effort controls, possibly with spatial measures as well. Case

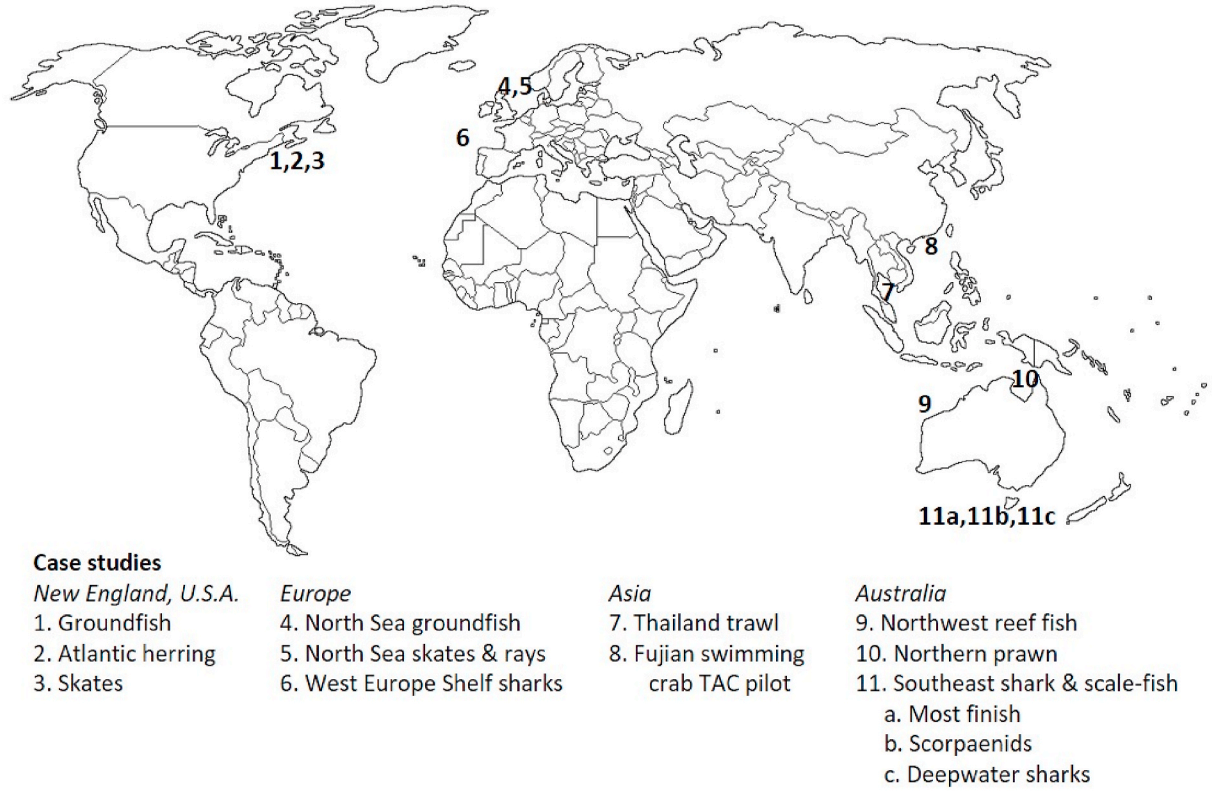

Fig. 1. Case studies considered in the international workshop on multispecies fisheries management. Case study numbers match those in Tables 1 and 2.

Table 2
Distribution of case studies considered in the international workshop on multispecies fishery management in terms of whether the underlying scientific model(s) include one species or multiple species, and whether harvest control(s) apply to individual species separately or multiple species concurrently. Case study numbers match Fig. 1 and Table 1. Note that scientific models that include multiple species span two very different types: simple data-limited models that aggregate many species into a common index (6, 7, 8, 11c), and complex mechanistic multispecies models that consider ecological interactions (2). Recent changes in the approaches used for three case studies are illustrated, suggesting that there might be a common progression through these combinations (see Fig. 2).

Harvest controls	Scientific models: One species included	Scientific models: Multiple species included
Apply to individual species	(formerly here) →	2. New England herring
	1. New England groundfish	
	4. North Sea groundfish	
	11a. Southeast Australia shark and scale-fish: Most finfish	
	(transitioning here) ↑	
Apply to multiple species	11b. Southeast Australia shark and scale-fish: Scorpaenids ←	(formerly here)
	3. New England skates	6. Western Europe slope deep sea sharks
	5. North Sea skates and rays	7. Thailand trawl
	9. Northwest Australia reef fish	8. Fujian swimming crab TAC pilot
	10. Northern Australia prawn	
	(transitioning here) ←	11c. Southeast Australia shark and scale-fish: Deep water sharks

studies considered at the workshop in this category include Western Europe slope deep sea sharks, Thailand trawl, the Fujian swimming crab TAC pilot, and the deep-water sharks sub-fishery in the Southeast Australia shark and scale-fish fishery.

2. Single-species scientific models + multispecies harvest controls: Models focus on individual species, the outcomes of which are combined to implement harvest controls for one or more groups of species as a complex. In these case studies, scientific improvements and concerns for the status of individual species within the complex motivated scientific assessments with finer taxonomic resolution, but operational issues or management objectives compel use of multispecies harvest controls. Multispecies harvest controls can be TACs or effort controls, and might be made more restrictive to address concerns for the status of individual species that is now revealed by models at the species level. This restrictiveness can affect management and compromise full utilization of all species within the complex. Case studies considered at the workshop in this category include New England skates, North Sea skates and rays, Northern Australia prawn, Northwest Australia reef fish, and the scorpaenid sub-fishery in the Southeast Australia shark and scale-fish fishery.
3. Single-species scientific models + single-species harvest controls: Models focus on individual species in the multispecies fishery, with harvest controls implemented for each of those species separately. In these cases, the scientific and management approach is similar to that used for a predominantly single-species fishery, but applied in parallel to multiple species that are caught together. Disaggregating species can lead to improved biological outcomes, but entails greater monitoring, assessment, and enforcement costs, and can introduce economic costs for the fishing fleet when management measures for depleted species hinder full utilization of healthier co-occurring stocks. Case studies considered at the workshop in this category include New England groundfish, North Sea groundfish, and the sub-fishery for most finfish species in the Southeast Australia shark and scale-fish fishery.

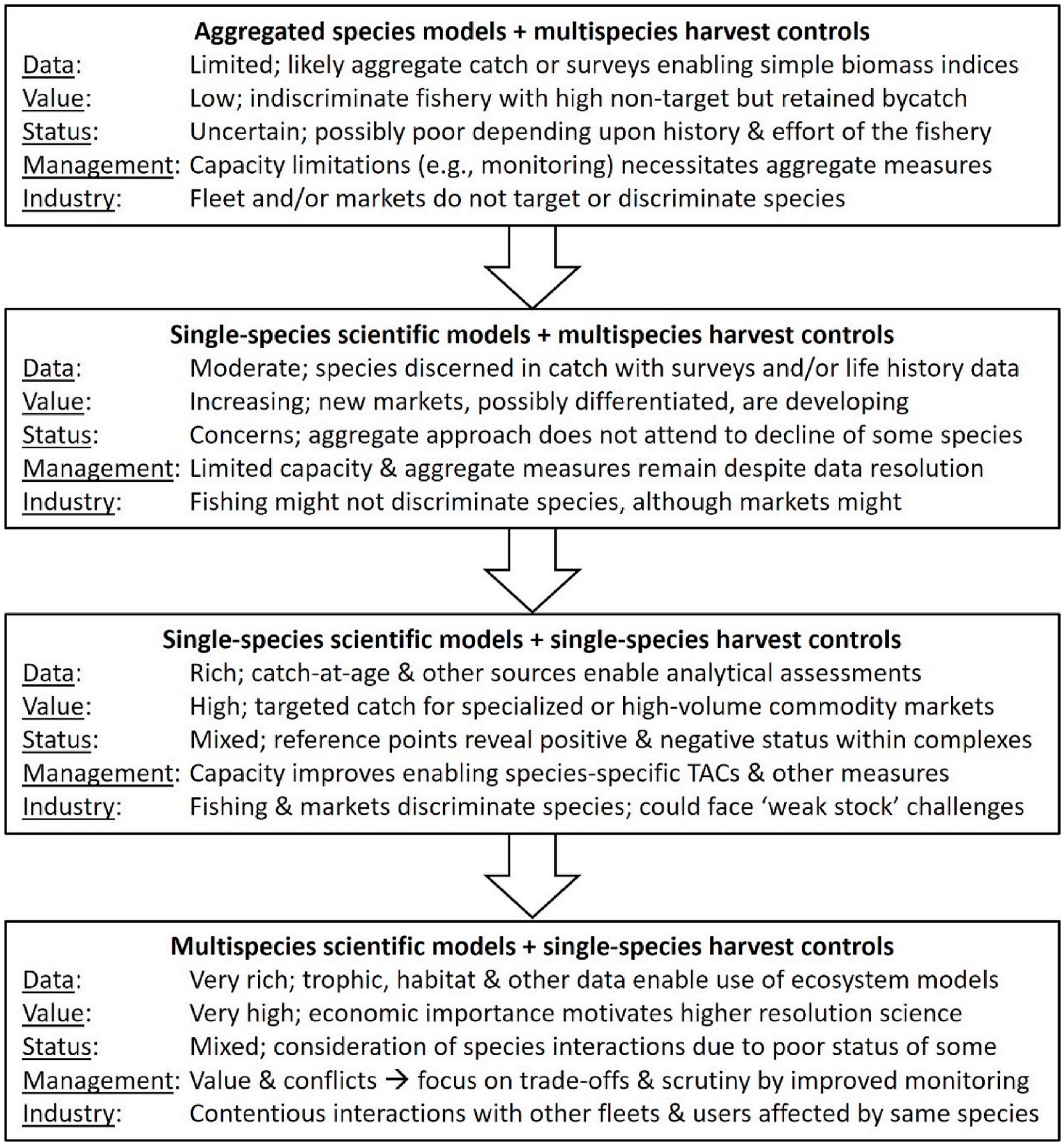

Fig. 2. Generalized spectrum of multispecies fishery management strategies defined by whether the underlying scientific models and harvest controls have single-species or multispecies focus, with common conditions associated with each strategy including the nature of available data, value of the catch, status of the stocks, management capacity and constraints, and industry objectives and constraints.

4. Multispecies scientific models + single-species harvest controls: Models consider multiple species, but the resultant harvest controls are developed for individual species. Here, the models do not simply aggregate species into a single index, but explicitly account for ecological interactions among them (i.e., predation and competition). This combination is employed in only one case study considered at the workshop, the Atlantic herring fishery in New England, U.S.A., which is the most data-rich case study considered. Adoption of this approach was motivated by controversies arising from the high economic and ecological value of the herring fishery and the herring stock for other fisheries and industries in the region. These competing values necessitated a more thorough evaluation of ecological interactions, and the resultant risks and trade-offs associated with different management alternatives.

We order the four combinations in this sequence following a general progression from data-limited models and harvest controls with low taxonomic resolution to more data-rich models and harvest controls targeted at individual species. At the time of the workshop, three of the case study fisheries were in the midst of transitions in either the underlying scientific models or nature of harvest controls, or had recently gone through such a transition (Table 2). These changes suggest that this sequence might represent a progression for some fisheries (Fig. 2), although not all fisheries will start at the same point or move through the sequence. Rather, a fishery can maintain any given combination of modeling approach and harvest controls for as long as the prevailing scientific, economic, biological, management, and operational conditions warrant.

The four case studies with aggregate models and multispecies harvest controls include two very different scenarios. In the Thailand trawl fishery and Fujian swimming crab TAC pilot, data limitations preclude assessment at the species level at present, so aggregate models and resultant harvest controls are the only feasible options. In contrast, the fisheries for deep-dwelling sharks off Southeastern Australia and on the Western Europe slope have data, life history information, or even more complex models for individual species that are used for risk evaluation. However, the proxies for abundance used to develop harvest controls are aggregate CPUE trends and aggregate swept-area biomass estimates, respectively. In both cases, management aims to have no harvest of any species in the complex, and therefore harvest controls are designed for the complex as a whole to achieve this common objective. Whereas most of the multispecies complexes in the case studies are based on some combination of common habitat use (e.g., Fig. 3A) or taxonomy and feeding ecology (e.g., Fig. 3B), these elasmobranch fisheries for which management aims to have no harvest also consider stock status (e.g., Fig. 4).

As the scientific foundation for a fishery grows, models for individual species often become more common. However, operational issues, including the ability of managers to implement and enforce harvest controls at the species level, the ability of fishers to target or differentiate species, or markets that do not discriminate among species, can mean that harvest controls are still implemented for multispecies complexes despite finer taxonomic resolution of the underlying science. Finer model resolution means the status of individual species can be evaluated and multispecies management measures can be made more stringent if warranted, but the measures might not effectively address the species of concern since they are not targeted at those species directly. For example, management of the skate complex in the Northeastern United States began in 2003 based on a finding that four of the seven species in the complex were overfished. Multispecies management has resulted in recovery of three of these species, but the thorny skate stock remains overfished due to an absence of targeted management. An

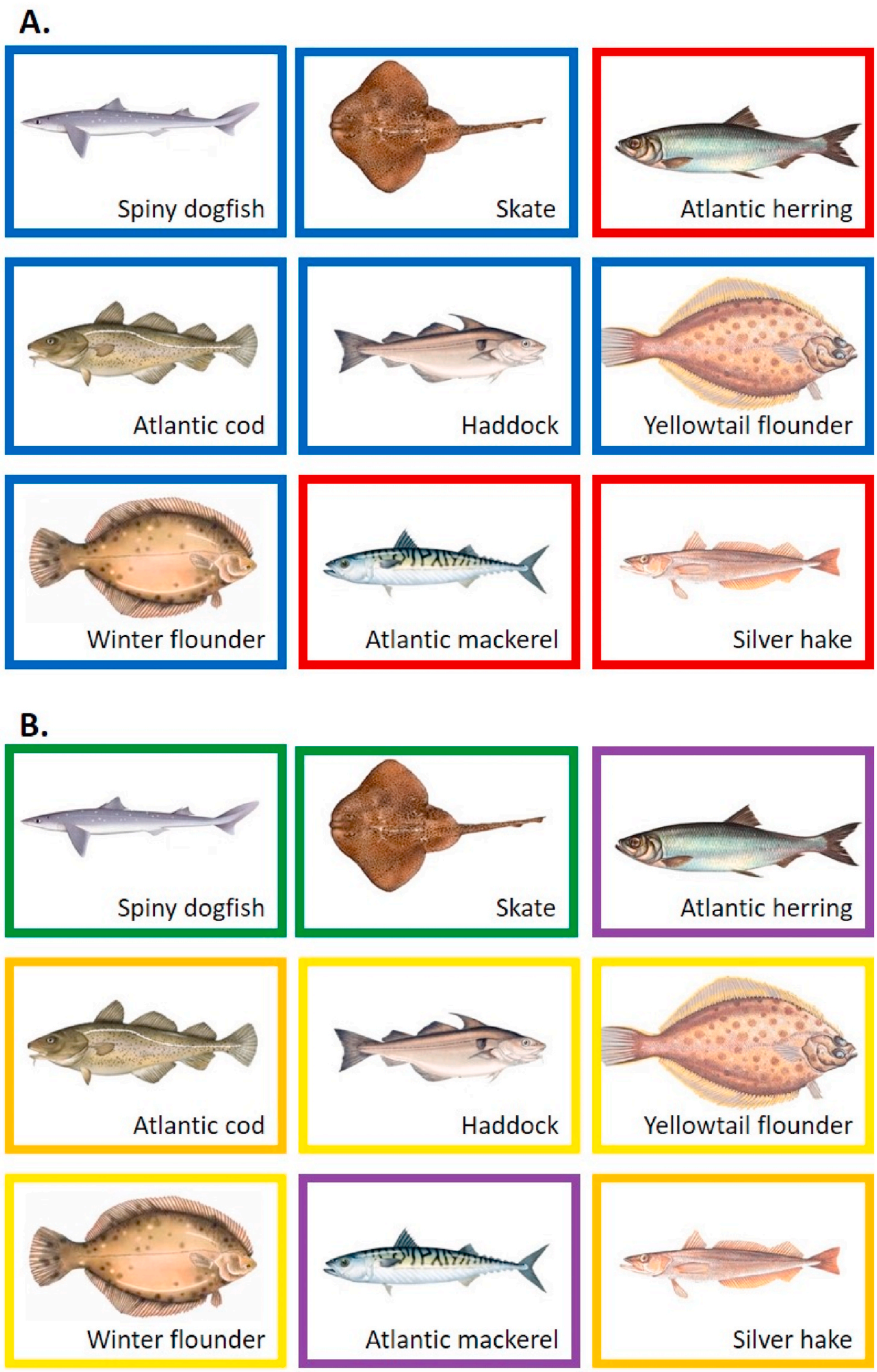

Fig. 3. Possible groupings of selected marine fish species harvested in New England, U.S.A., for multispecies management based on (A) habitat use or (B) a combination of taxonomy and feeding ecology. Groupings by habitat include a pelagic complex (red) and demersal complex (blue). Groupings by taxonomy and feeding ecology include species that are elasmobranches (green), planktivores (purple), primarily invertivores (yellow), and primarily piscivores (orange). (modified from workshop presentation by S. Gaichas). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

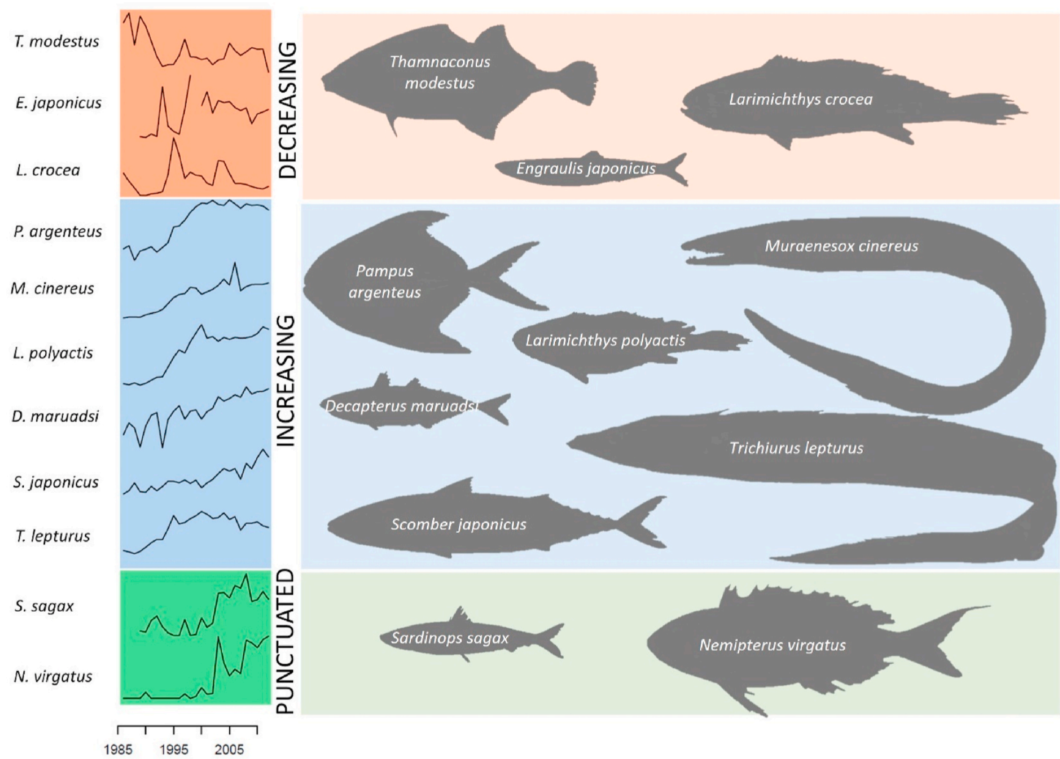

Fig. 4. Possible groupings of marine finfish species harvested in China for multispecies management based on catch trends as a proxy for stock status and dynamics. (modified from workshop presentation by C. Szuwalski; data from National Bureau of Statistics of China, 2017).

outcome such as this, as well as other biological and economic differences among the species, can motivate disaggregating the multispecies complex and implementing species-specific harvest controls (Hogan et al., 2013). This transition is currently underway for the scorpaenid complex of Southeastern Australia (Table 2).

Harvest controls for multispecies complexes among the case studies include both input controls and output controls, as well as spatial protection for the elasmobranch complexes off Southeastern Australia, in the North Sea, and on the Western Europe slope. For the three case studies that adopt single-species harvest controls in a multispecies fishery, output controls are used in all, at least for the majority of species. Input controls are used to supplement some of the single-species TACs, and as the primary harvest controls for some of the secondary species in the fishery in Southeast Australia.

When management adopts controls tailored to individual species, measures for one species can preclude full utilization of the TACs for other species, often referred to as the 'weak stock' or 'choke stock' problem (Dunn et al., 2013). In other words, fishers can be inhibited from harvesting their full allocation of some stocks because they lack sufficient quota allocation for other generally depleted stocks with low TACs that are caught at the same time. Therefore, transitioning from multispecies to single-species harvest controls can mean trading ecological risk for economic costs. However, single-species harvest controls can be made more permissive to alleviate economic costs, while multispecies harvest controls can be made more restrictive to mitigate ecological risk. That means decisions about risk tolerance have significant influence on the economic and ecological trade-offs associated with alternative management decisions (Crosson 2013; Dichmont et al., 2016), and not solely the decision to use either single-species or multispecies harvest controls.

Notably, in all three cases that adopt single-species models and single-species harvest controls, the single-species TACs are allocated within a rights-based management system to either individual permit holders or harvest cooperatives (Table 1). Rights-based management approaches have the potential to mitigate economic risks introduced by weak stock issues, if the allocation accounts for technical interactions and the needs of different fleets (e.g., Fig. 5). These technical interactions have been especially problematic in the North Sea groundfish fishery, where two levels of quota allocation – to individual nations by the European Commission and then to individual permit holders within each nation – introduce especially strong disparities between allocation and catch (International Council for the Exploration of the Sea [ICES], 2020). Although rights-based management can provide fishers with the ability to more effectively navigate constraining quotas by removing inefficient effort controls and enabling quota transfers (Sanchirico et al., 2006), risk-pooling (Miller and Deacon 2017), communication and coordinated harvest (Deacon et al., 2008), and other strategies, the initial allocation and total amount of available quota will still be important factors shaping weak stock problems.

For some fisheries, the implications of management decisions extend beyond the target stocks and fishers exploiting them through trophic linkages. In order to more carefully evaluate impacts on different users affected by a fishery in these cases, new scientific approaches are needed. One such example among the case studies is the Atlantic herring fishery off New England, U.S.A., which recently adopted new modeling approaches that account for ecological interactions among species. The new multispecies scientific tools are used to select a Harvest Control Rule (HCR) and develop a single-species TAC that minimize adverse impacts across a range of uses (Deroba et al., 2019; Feeney et al., 2019). The other species considered in the modeling framework are, for the most part, not harvested in the herring fishery. Instead, these are species affected by the fishery as a result of their trophic interactions with herring. This represents an indirect or extended effect of fishing, but not through direct fishing mortality. This is a different concept of multispecies management than that adopted in the other case studies, and moves more strongly in the direction of ecosystem-based management (Gaichas et al., 2016).

Species interactions are considered in the scientific approach to

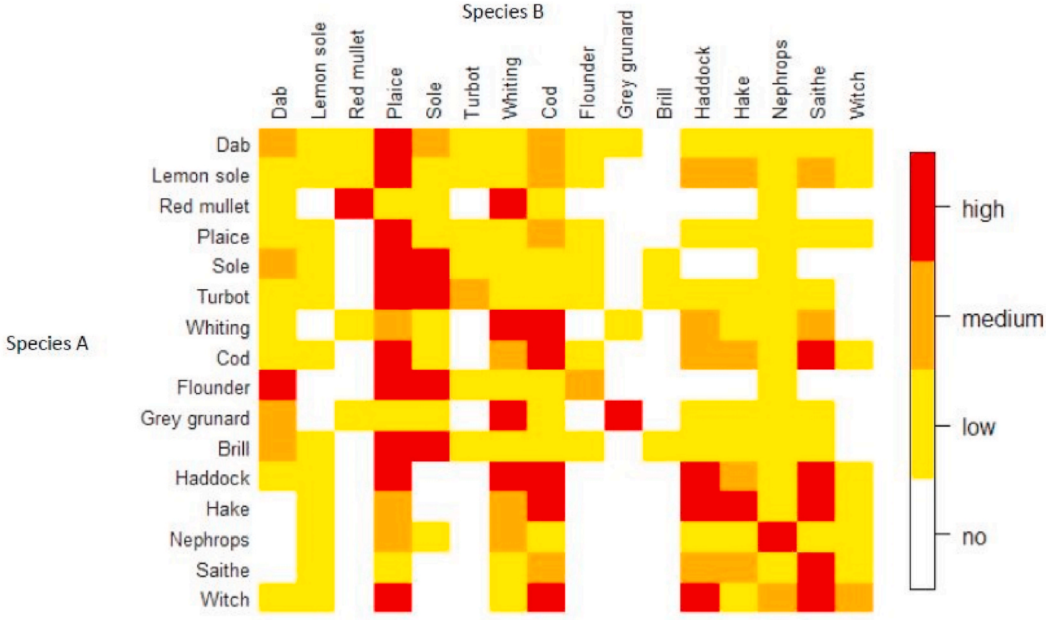

Fig. 5. Technical interactions among managed finfish in the North Sea. Colors indicate the amount of species B that is commonly caught while targeting species A. These interactions should be considered when grouping species into multispecies management complexes or allocating quotas among nations and individual permit holders to ensure that economic impacts are mitigated to the extent possible. (from International Council for the Exploration of the Sea [ICES], 2020 and workshop presentation by E. Peñas). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Atlantic herring management through a two-stage modeling framework involving both an age-structured stock assessment model that accounts for predation in estimates of natural mortality, and an MSE model to compare performance of HCRs. Therefore, this is an incredibly data-rich case study, an investment motivated by the very complex array of high-value uses connected to the herring fishery. These include the herring fishery itself, the lucrative lobster fishery for which herring is the primary bait, and other valuable commercial fisheries, sport fisheries, and wildlife tourism (i.e., whale watching and birding) that are dependent upon predators of herring. Understanding complex interactions across

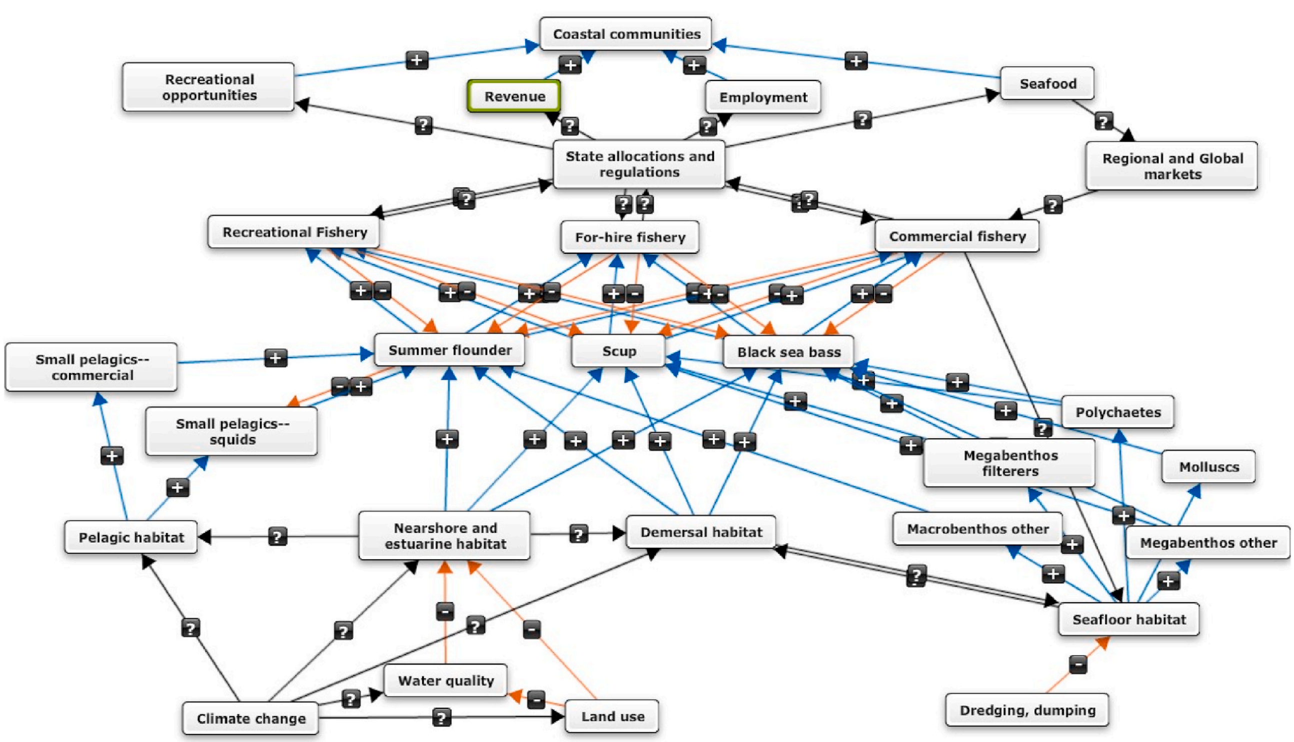

Fig. 6. Example of a conceptual model of interactions among marine organisms and human uses for the Mid-Atlantic region, U.S.A. These interactions should be considered when grouping species into multispecies management complexes or allocating quotas among jurisdictions, fishing fleets, individuals permit holders, or other entities to ensure that adverse ecological and economic impacts are mitigated to the extent possible. (from workshop presentation by S. Gaichas, based on the conceptual model described by DePiper et al., 2021).

an ecosystem and competing human uses is critical to resolving conflicts and ensuring that a range of ecosystem services and socio-economic values can be generated in ways that are sustainable, equitable, and efficient (e.g., Fig. 6; also see White et al., 2012 for an illustrative analysis of cross-industry trade-offs).

4. Multispecies TACs in the Fujian swimming crab fishery

The primary aim of the international workshop was to examine approaches for managing multispecies fisheries that might be applicable in China to meet new national policy objectives, including but not limited to setting multispecies TACs. The case studies considered in the workshop spanned a range of ecological, economic, and governance contexts, which resulted in different management approaches being adopted within each fishery. Similarly, despite some shared attributes among the many fisheries in China, multispecies fisheries across the country exhibit important differences in the number of species harvested, their value, the number and types of gears used, the status of stocks and the ecosystem, the scientific and governance capacity at the local and provincial scales, and other factors. Therefore, the applicability of approaches used in the case studies will vary among Chinese fisheries. Because the workshop was particularly motivated by China's first multispecies TAC pilot project in the Fujian swimming crab fishery, here we consider the suitability of a multispecies TAC approach for the fishery in light of its attributes and the lessons illuminated by the case studies.

Multispecies TACs like those adopted by the Fujian swimming crab pilot seem to be relatively rare in fisheries management. Among the 13 case studies considered, only three – skates in New England, skates and rays in the North Sea, and scorpaenids in Southeast Australia – are truly managed at scale by multispecies TACs. Deep-water sharks on the Western Europe Slope and off Southeast Australia are managed by multispecies TACs that are effectively zero, with spatial closures and effort restrictions implemented to minimize or eliminate harvest. Furthermore, management of the scorpaenid complex of Southeast Australia is transitioning to single-species harvest controls due to concerns that the multispecies approach is not providing sufficient protection of all stocks in the complex. Three other case study fisheries that use multispecies harvest controls – Northern Australia reef fish, Northern Australia prawn, and Thailand trawl – do not use TACs but rather various effort controls targeted at multispecies complexes. Still, all of these case studies illustrate considerations that can inform management of the Fujian swimming crab fishery.

The paucity of case studies in management by multispecies TACs and supportive technical guidance might have hindered application of this approach in settings where it can be effective, but this does not mean that the approach is not more widely applicable. The Fujian swimming crab pilot therefore presents another rare but informative case study. The pilot used a multispecies TAC for four co-occurring swimming crab species (*Monomia haanii, Portunus trituberculatus, P. sanguinolentus, P. pelagicus*) harvested by a study fleet of 106 fishing vessels in a defined pilot area (Fig. 7). These vessels use a single gear type (pots) and fish during an August to April season outside of China's annual summer fishing moratorium. A critical question is whether Fujian will be able to scale up its pilot project and apply TAC management to all areas and gears in the swimming crab fishery? The fishery is unique among the case studies considered in that it does not have the high level of species diversity in the catch of the Northern Australia reef fish and Thailand trawl fisheries, and does not target long-lived and risk-prone finfish or elasmobranches like most of the others that employ either single-species or multispecies TACs. Therefore, management by multispecies TACs in the Fujian swimming crab fishery might be more practicable.

The case study that might be most similar to the Fujian swimming crab fishery among those considered is the Northern Australia prawn fishery. The prawn fishery targets a modest number of species (seven prawn species in Northern Australia versus four crab species in Fujian) that are also crustaceans with similar longevity (<2 years), and inhabit similar soft-sediment habitats in relatively shallow waters (Dichmont

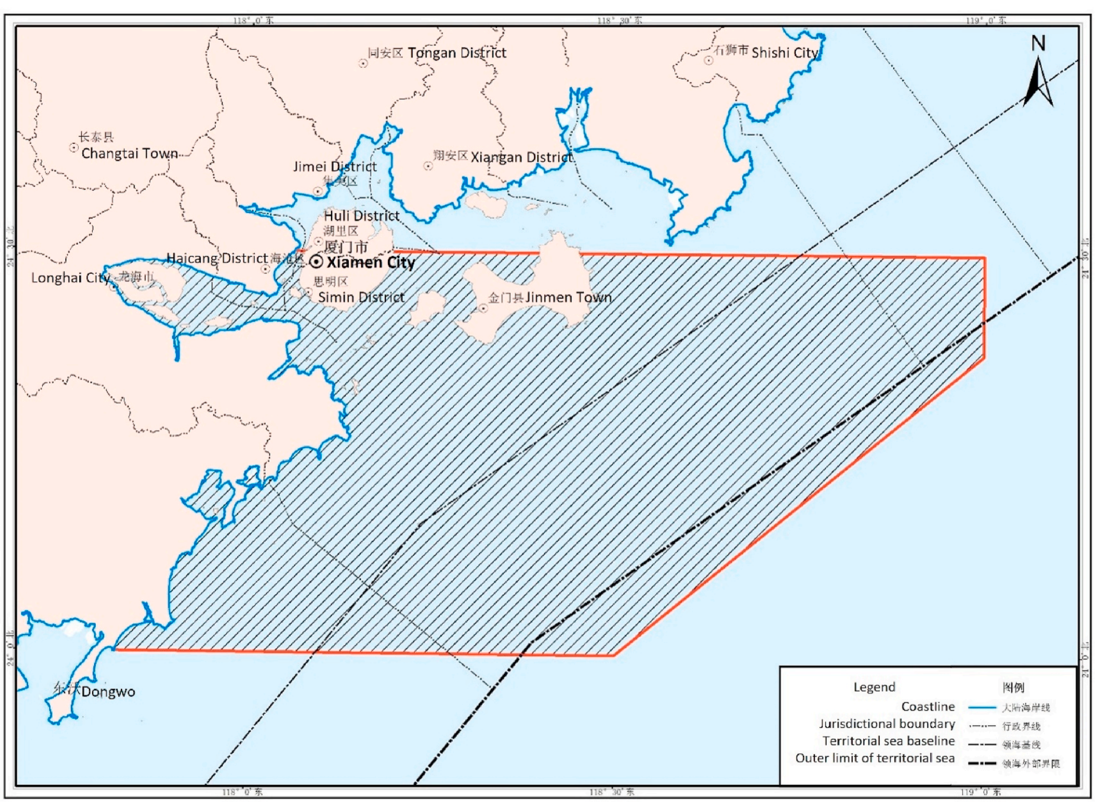

Fig. 7. The study area for the multispecies swimming crab TAC pilot project in Fujian province (modified from workshop presentation by C. Shen).

et al., 2006; Lin et al., 2021). The prawn fishery is managed by a tradeable effort system, which is facilitated by the fishery using a single gear type and having effective catch reporting and monitoring. Also, the fishery is supported by a strong scientific foundation based on a bio-economic model that combines stock assessment models with profit estimation toward the goal of achieving Maximum Economic Yield (Kompas et al., 2010) supplemented by broader understanding of ecosystem dynamics (Dambacher et al., 2015). Swimming crabs in Fujian are caught by three gear types – pots, gillnets, and trawls – which would complicate development of a single tradable effort system. Of course, separate systems could be developed and implemented for fleets using different gears. However, tradable effort systems require estimating the quantitative relationship between effort and fishing mortality, an extra analytical step that is not required when managing by TACs. That added analytical demand would present a challenge for the fishery, which operates with limited data and without a stock assessment at present (although a stock assessment and bio-economic model are currently in development; Boenish et al., 2021a). The Fujian swimming crab fishery is also similar to the New England skates fishery and North Sea skates and rays fishery in terms of the number of species in the complex, biological similarity among those species, diversity of gears used, and data-limited assessment frameworks. Like these elasmobranch fisheries, a multispecies TAC approach might be workable in the Fujian swimming crab fishery.

One factor that could compromise the effectiveness of management by a multispecies TAC is the price disparity among the species in the swimming crab complex. Differences in economic value among species in several of the multispecies fisheries considered in the workshop has been an important factor underlying differences in targeting, scientific investment, stock status, and management. The red swimming crab *M. haanii* comprises the majority of the catch in the Fujian fishery (Lin et al., 2021), but the blue swimming crab *P. pelagicus* is the most valuable species. Prices of blue swimming crabs can reach nearly double that of red swimming crabs in international commodity markets (Huffman 2018). Catch in the pilot project did not reach the TAC, there is market demand for all of the crabs landed, and quotas are not allocated to individual vessels. Therefore, discarding has not been practiced, as is the case in nearly all Chinese fisheries (Szuwalski et al. 2017, 2020). However, if changes in the TAC or catch bring the two closer to one another, and especially if quotas are enforced at the level of individual vessels, the fleet might begin targeting blue swimming crab, which could impose disproportionate fishing mortality on the stock. Also, high-grading could become an issue, with red swimming crab and other species discarded to maximize the proportion of blue swimming crab landed under the multispecies TAC (Batsleer et al., 2015). This could introduce undocumented fishing mortality on the discarded species, especially given the limited at-sea monitoring in the fishery at present, which would compromise scientific assessments (Rudd and Branch 2017).

On the other hand, key biological factors could reduce risks introduced if targeting, high-grading, and discarding become factors in the fishery. Swimming crabs are short-lived and productive species (Lee and Hsu 2003; Lin et al., 2021), and therefore have higher potential to exploit varied ecological niches, adapt to climate change and other ecosystem alterations, and recover from overfishing that could result from differential targeting or discarding (Boenish et al., 2021b). This is in contrast to the life history traits of skates, rays, and scorpaenids that comprise the multispecies TACs in other case studies. Also, decapod crustaceans are fairly robust and can have high post-release survival rates from traps or pots (Tallack 2007; Butcher et al., 2012), similar to skates and rays discarded from trawls (Mandelman et al., 2013). In fact, an important management strategy in many crustacean fisheries is the required release of egg-bearing, or 'berried', females. This strategy, which has been one important contributor to the success of the American lobster fishery in the United States and might help buffer that fishery from adverse effects of climate change (Le Bris et al., 2018), relies on high post-release survival. In China, the nationwide summer fishing moratorium currently provides protection from fishing mortality for egg-bearing females during that period, but at least *M. haanii* females bear eggs at many times of year outside of the moratorium (Lin et al., 2021).

Crabs caught by gillnets and especially trawls, on the other hand, would likely experience lower survival rates, which would limit the effectiveness of management by multispecies TACs if management and market factors increased targeting, high-grading, and discarding from those gears. These factors underscore the importance of effective at-sea monitoring in the implementation of TAC management to ensure that all catch is accounted for, and also to improve scientific assessments and shape fishing behavior (Kritzer 2020). Furthermore, improving the scientific foundation for management will be most effectively accomplished by integrated systems that combine at-sea monitoring and other types of fishery-dependent and fishery-independent monitoring (Boenish et al., 2020), and fishery scientists and managers are working to build those systems. Of course, sound science is a necessary but not sufficient requirement for effective fishery management, and systems for participatory decision-making, enforcement, accountability, and the institutional capacity to carry out these functions are also required as well (Barner et la. 2015; Bundy et al., 2016; Melnychuk et al., 2016; Mora et al., 2009). Building institutional capacity in a collaborative manner among different levels of government, affected industries, technical experts, and other stakeholders is a key objective of pilot projects in China (Kuhn 2016), so Fujian in already on this pathway.

All in all, despite the challenges imposed by multiple gears, price disparities, science and monitoring deficiencies, and institutional capacity, multispecies TACs could be workable at scale in the Fujian swimming crab fishery, at least for the pot sector. Facilitating this approach are the modest number of species with relatively similar biology and productive life history traits, high post-release survival should discarding become a factor, and broad market demand for all species that should reduce, although probably not eliminate, high-grading. Moreover, the pilot project has begun fostering the improvements in science, monitoring, and institutional capacity needed for effective implementation of a TAC management program. Other fisheries in China with different attributes might be more suitable for different approaches illustrated by the case studies, such as single-species TACs, effort controls, spatial measures, or combinations of these tools. The preceding evaluation of the suitability of multispecies TACs for the Fujian swimming crab fishery illustrates the types of questions to ask and how the answers might be interpreted. Also, the most appropriate management strategy might change through time as scientific, governance, economic, and operational attributes of the fishery change (Fig. 2).

5. Summary and conclusions

The appropriate multispecies management strategy for a given fishery will depend upon a variety factors, including its scientific foundation, economic value of the catch, status of the stocks, management capacity and institutional structure, and history and operational attributes of the fleet (Fig. 2). Harvest controls that aggregate multiple species into single measures, whether TACs or other approaches (Liu et al., 2016), have the advantage of more modest scientific and management needs than single-species approaches. These multispecies harvest controls can be effective as long as biological factors, such as late maturation or slow growth, or economic factors, especially market value, do not introduce excessive risks of overfishing for certain species. High risk of overfishing can in turn incur high biological, ecological, and economic risks for the fishery. When those risks are high, species-specific harvest controls might be warranted, although these introduce new challenges for science, management, and fishing fleets. For species that are depleted, vulnerable, relatively sessile, and of limited economic importance to the fishing fleets, robust spatial protection through well-designed marine reserves might achieve biomass conservation comparable to harvest controls, thereby alleviating some of the costs and challenges associated with weak stock management (Hastings et al., 2017).

The optimal strategy in many cases is likely to include a portfolio of approaches tailored to the unique properties of different species and complexes in the fishery, and those approaches might change as the fishery evolves. The Southeast Australia shark and scale-fish fishery provides an especially good example of a portfolio of approaches applied in a single fishery (Table 1) and their evolution (Table 2). Rapid assessment tools such as Productivity-Susceptibility Analysis (PSA) can help evaluate risks and determine the appropriate approach for different species, especially in high diversity and data-limited contexts (e.g., Puga et al., 2018). MSE can also be a powerful tool to gauge the expected performance of different portfolios of management approaches and select the most cost-effective option (Punt et al., 2014). As China and other nations continue working to build fisheries management systems that strive to balance ecological, economic, and social objectives (Cao et al., 2017), meeting the challenges presented by multispecies fisheries will be critical in light of the implications for biodiversity conservation. Fortunately, international experience presents a broad and growing portfolio of approaches and lessons to draw upon and evolve, which can help China effectively shape and implement its fishery sector goals under the 14th Five-Year Plan.

CRediT authorship contribution statement

Jacob P. Kritzer: Conceptualization, Investigation, Supervision, Project administration, Funding acquisition, Visualization, Writing – original draft, Writing – review &amp editing, Writing – original draft. **T.A.N.G. Yi:** Conceptualization, Investigation, Supervision, Project administration, Funding acquisition, Visualization. **C.H.E.N. Yong:** Conceptualization, Investigation, Supervision, Project administration, Funding acquisition. **Chris Costello:** Conceptualization, Investigation, Funding acquisition. **Sarah Gaichas:** Conceptualization, Investigation, Visualization. **Tom Nies:** Conceptualization, Investigation. **Ernesto Peñas:** Conceptualization, Investigation, Visualization. **Keith Sainsbury:** Conceptualization, Investigation. **S.H.E.N. Changchun:** Conceptualization, Investigation, Visualization. **Cody Szuwalski:** Conceptualization, Investigation, Funding acquisition, Visualization. **Z.H.U. Wenbin:** Conceptualization, Investigation, Funding acquisition.

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References

Australian Fisheries Management Agency [AFMA]. (2021b). Southern and eastern scalefish and shark fishery. Retrieved from https://www.afma.gov.au/fisheries/southern-eastern-scalefish-shark-fishery. (Accessed 8 November 2021).

Australian Fisheries Management Agency [AFMS]. (2021a). Northern prawn fishery. Retrieved from https://www.afma.gov.au/fisheries/northern-prawn-fishery. (Accessed 8 November 2021).

Banks, T., Richard, C., Ping, L., & Zhaoli, Y. (2003). Community-based grassland management in Western China. *Mountain Research and Development, 23*, 132–140.

Barner, A. K., Lubchenco, J., Costello, C., Gaines, S. D., Leland, A., Jenks, B., Murawski, S., Schwaab, E., & Spring, M. (2015). Solutions for recovering and sustaining the bounty of the ocean: Combining fishery reforms, rights-based fisheries management, and marine reserves. *Oceanography, 28*, 252–263. https://doi.org/10.5670/oceanog.2015.51

Batsleer, J., Hamon, K. G., van Overzee, H. M. J., Rijnsdorp, A. D., & Poos, J. J. (2015). High-grading and over-quota discarding in mixed fisheries. *Reviews in Fish Biology and Fisheries, 25*, 715–736. https://doi.org/10.1007/s11160-015-9403-0

Battista, W., Tourgee, A., Wu, C., & Fujita, R. (2017). How to achieve conservation outcomes at scale: An evaluation of scaling principles. *Front. Mar. Sci., 3*. https://doi.org/10.3389/fmars.2016.00278

Boenish, R., Lin, B., Kritzer, J. P., Wilberg, M. J., Shen, C., Jiang, Y., & Liu, M. (2021a). A bioeconomic approach towards improved fishery management of *Monomia haanii* in the southern Taiwan Strait, China. *Fisheries Research, 240*, 105969. https://doi.org/10.1016/j.fishres.2021.105969

Boenish, R., Kritzer, J. P., Kleisner, K., Steneck, R., Werner, K. M., Zhu, W., Schram, F., Rader, D., Cheung, W., Ingles, J., Tian, Y., & Mimikakis, J. (2021b). The global rise of crustacean fisheries. *Frontiers in Ecology and the Environment*. https://doi.org/10.1002/fee.2431

Boenish, R., Willard, D., Kritzer, J. P., & Reardon, K. (2020). Fisheries monitoring: Perspectives from the United States. *Fish. Aquacult., 5*, 131–138. https://doi.org/10.1016/j.aaf.2019.10.002

Bundy, A., Chuenpagdee, R., Boldt, J. L., Borges, M. D., Camara, M. L., Coll, M., Diallo, I., Fox, C., Fulton, E. A., Gazihan, A., Jarre, A., Jouffre, D., Kleisner, K. M., Knight, B., Link, J., Matiku, P. P., Masski, H., Moutopoulos, D. K., Piroddi, C., … Shin, Y. (2016). Strong fisheries management and governance positively impact ecosystem status. *Fish and Fisheries*. https://doi.org/10.1111/faf.12184

Butcher, P. A., Leland, J. C., Broadhurst, M. K., Paterson, B. D., & Mayer, D. G. (2012). Giant mud crab (Scylla serrata): Relative efficiencies of common baited traps and impacts on discards. *ICES Journal of Marine Science, 69*, 1511–1522. https://doi.org/10.1093/icesjms/fss109

Cao, L., Chen, Y., Dong, S., Hanson, A., Huang, B., Leadbitter, D., Little, D. C., Pikitch, E. K., Qiu, Y., Sadovy de Mitcheson, Y., Sumaila, U. R., Williams, M., Xue, G., Ye, Y., Zhang, W., Zhou, Y., Zhuang, P., & Naylor, R. L. (2017). Opportunity for marine fisheries reform in China. *Proceedings of the National Academy of Sciences, 114*, 435–442. https://doi.org/10.1073/pnas.1616583114

Central Committee of the Communist Party of China [Central Committee]. (2016). *The 13th five-year plan for economic and social development of the People's Republic of China (2016-2020)*. Beijing: Central Compilation and Translation Press.

Costello, C. (2017). Fish harder; catch more? *Proceedings of the National Academy of Sciences, 114*, 1442–1444. https://doi.org/10.1073/pnas.1620731114

Council of the European Union [CEU]. (2016). Council regulation (EU) 2016/2285 of 12 December 2016 fixing for 2017 and 2018 the fishing opportunities for Union fishing vessels for certain deep-sea fish stocks and amending Council Regulation (EU) 2016/72. *Off. J. Eur. Union, L344*, 32–45.

Crosson, S. (2013). The impact of empowering scientific advisory committees to constrain catch limits in US fisheries. *Science and Public Policy, 40*, 261–273. https://doig.org/10.1093/scipol/scs104.

Dambacher, J. M., Rothlisberg, P. C., & Loneragan, N. R. (2015). Qualitative mathematical models to support ecosystem-based management of Australia's Northern Prawn Fishery. *Ecological Applications, 25*, 278–298. https://doi.org/10.1890/13-2030.1.sm

Deacon, R. T., Parker, D. P., & Costello, C. J. (2008). Improving efficiency by assigning harvest rights to fishery cooperative: Evidence from the chignik salmon co-op. *Arizona Law Review, 50*, 479–510.

Deng, H., Huang, J., Xu, Z., & Rozelle, S. (2010). Policy support and emerging farmer professional cooperatives in China. *China Economic Review, 21*, 495–507. https://doi.org/10.1016/j.chieco.2010.04.009

Department of Fisheries-Thailand [DoF-Thailand]. (2015). *Marine fisheries management plan of Thailand: A national policy for marine fisheries management*. Thailand: Ministry of Agriculture and Cooperatives.

Department of Fisheries-Western Australia [DoF-WA]. (2016). *North Coast demersal scalefish resource draft harvest strategy*. Government of Western Australia. Fisheries Management Paper no. 278.

DePiper, G., Gaichas, S., Muffley, B., Ardini, G., Brust, J., Coakley, J., Dancy, K., Elliott, G. W., Leaning, D. C., Lipton, D., McNamee, J., Perretti, C., Rootes-Murdy, K., & Wilberg, M. J. (2021). Learning by doing: Collaborative conceptual modelling as a path forward in ecosystem-based management. *ICES Journal of Marine Science, 78*, 1217–1228. https://doi.org/10.1093/icesjms/fsab054

Deroba, J. J., Gaichas, S. K., Lee, M., Feeney, R. G., Boelke, D., & Irwin, B. J. (2019). The dream and the reality: Meeting decision-making time frames while incorporating ecosystem and economic models into management strategy evaluation. *Canadian Journal of Fisheries and Aquatic Sciences, 76*, 1112–1133. https://doi.org/10.1139/cjfas-2018-0128

Dichmont, C. M., Deng, A., Punt, A. E., Venables, W., & Haddon, M. (2006). Management strategies for short-lived species: The case of Australia's northern prawn fishery 1. Accounting for multiple species, spatial structure and implementation uncertainty when evaluating risk. *Fisheries Research, 82*, 204–220. https://doi.org/10.1016/j.fishres.2006.06.010

Dichmont, C. M., Punt, A. E., Dowling, N., de Oliviera, J. A. A., Little, L. R., Sporcic, M., Fulton, E. A., Gorton, R., Klaer, N., Haddon, M., & Smith, D. (2016). Is risk consistent across tier-based harvest control rule management systems? A comparison of four case-studies. *Fish and Fisheries, 17*, 731–747. https://doi.org/10.1111/faf.12142

Dong, J., Xue, G., Dong, M., & Xu, X. (2015). Energy-saving power generation dispatching in China: Regulations, pilot projects and policy recommendations – a review. *Renewable and Sustainable Energy Reviews, 43*, 1285–1300. https://doi.org/10.1016/j.rser.2014.11.037

Dunn, D. C., Boustany, A. M., Roberts, J. J., Brazer, E., Sanderson, M., Gardner, B., & Halpin, P. N. (2013). Empirical move-on rules to inform fishing strategies: A new England case study. *Fish and Fisheries, 15*, 359–375. https://doi.org/10.1111/faf.12019

European Parliament & Council of the European Union [EP&CEU]. (2018). Regulation (EU) 2018/973 of the European Parliament and of the Council of 4 July 2018 establishing a multiannual plan for demersal stocks in the North Sea and the fisheries exploiting those stocks, specifying details of the implementation of the landing obligation in the North Sea and repealing Council Regulations (EC) No 676/2007 and (EC) No 1342/2008. *Off. J. Eur. Union, L179*, 1–13.

Feeney, R. G., Boelke, D. V., Deroba, J. J., Gaichas, S., Irwin, B. J., & Lee, M. (2019). Integrating management strategy evaluation into fisheries management: Advancing best practices for stakeholder inclusion based on an MSE for northeast US atlantic herring. *Canadian Journal of Fisheries and Aquatic Sciences, 76*, 1103–1111. https://doi.org/10.1139/cjfas-2018-0125

Gaichas, S. K., Fogarty, M., Fay, G., Gamble, R., Lucey, S., & Smith, L. (2016). Combining stock, multispecies, and ecosystem level fishery objectives within an operational management procedure: Simulations to start the conversation. *ICES Journal of Marine Science, 74*, 552–565. https://doi.org/10.1093/icesjms/fsw119

Gaichas, S., Gamble, R., Fogarty, M., Benoît, H., Essington, T., Fu, C., Koen-Alonso, M., & Link, J. (2012). Assembly rules for aggregate-species production models: Simulations in support of management strategy evaluation. *Marine Ecology Progress Series, 459*, 275–292. https://doi.org/10.3354/meps09650

Hastings, A., Gaines, S. D., & Costello, C. (2017). Marine reserves solve an important bycatch problem in fisheries. *Proceedings of the National Academy of Sciences, 114*, 8927–8934. https://doi.org/10.1073/pnas.1705169114

Heilmann, S. (2008). Policy experimentation in China's economic rise. *Studies in Comparative International Development, 43*, 1–26. https://doi.org/10.1007/s12116-007-9014-4

Hogan, F., Cadrin, S., & Haygood, A. (2013). Fishery management complexes: An impediment or aid to sustainable harvest? A discussion based on the Northeast skate complex. *North American Journal of Fisheries Management, 33*, 406–421. https://doi.org/10.1080/02755947.2013.763873

Huang, S., & He, Y. (2019). Management of China's capture fisheries: Review and prospect. *Aquacult. Fish., 4*, 173–182. https://doi.org/10.1016/j.aaf.2019.05.004

Huffman, J. (2018). Blue swimming crab prices still high, but wholesalers fear adding inventory. Retrieved from https://www.undercurrentnews.com/2018/08/07/blue-swimming-crab-prices-still-high-but-wholesalers-fear-adding-inventory/. (Accessed 16 November 2019).

International Council for the Exploration of the Sea [ICES]. (2020). ICES working group on the assessments of demersal stocks in the North Sea and Skagerrak (WGNSSK). *ICES Sci. Rep., 2*, 1249. https://doi.org/10.17895/ices.pub.6092

Kompas, T., Dichmont, C. M., Punt, A. E., Deng, A., Che, T. N., Bishop, J., Gooday, P., Ye, Y., & Zhou, S. (2010). Maximizing profits and conserving stocks in the Australian northern prawn fishery. *Agric. Resour. Econ., 54*, 281–299. https://doi.org/10.1111/j.1467-8489.2010.00493.x

Kritzer, J. P. (2020). Influences of at-sea fishery monitoring on science, management, and fleet dynamics. *Aquacult. Fish., 5*, 107–112. https://doi.org/10.1016/j.aaf.2019.11.005

Kuhn, B. (2016). Collaborative governance for sustainable development in China. *Open Journal of Political Science, 6*, 433–453. https://doi.org/10.4236/ojps.2016.64037

Le Bris, A., Mills, K. E., Wahle, R. A., Chen, Y., Alexander, M. A., Allyn, A. J., Schuetz, J. G., Scott, J. D., & Pershing, A. J. (2018). Climate vulnerability and resilience in the most valuable North American fishery. *Proceedings of the National Academy of Sciences, 8*, 1831–1836. https://doi.org/10.1073/pnas.1711122115

Lee, H., & Hsu, C. (2003). Population biology of the swimming crab *Portunus sanguinolentus* in the waters off Northern Taiwan. *Journal of Crustacean Biology, 23*, 691–699. https://doi.org/10.1651/C-2358

Lin, B., Boenish, R., Kritzer, J. P., Jiang, Y., Wang, S., & Liu, M. (2021). Reproductive dynamics of a swimming crab (*Monomia haanii*) in the world's crab basket. *Fisheries Research, 236*. https://doi.org/10.1016/j.fishres.2020.105828

Liu, O. R., Thomas, L. R., Clemence, M., Fujita, R., Kritzer, J. P., McDonald, G., & Szuwalski, C. (2016). An evaluation of harvest control methods for fishery management. *Rev. Fish. Sci. Aquacult., 24*, 244–263. https://doi.org/10.1080/23308249.2016.1161002

Mandelman, J. W., Cicia, A. M., Ingram, G. W., Jr., Driggers, W. B., III, Coutre, K. M., & Sulikowski, J. A. (2013). Short-term post-release mortality of skates (family Rajidae) discarded in a western North Atlantic commercial otter trawl fishery. *Fisheries Research, 139*, 76–84. https://doi.org/10.1016/j.fishres.2012.09.020

Mangin, T., Costello, C., Anderson, J., Arnason, R., Elliott, M., Gaines, S. D., Hilborn, R., Peterson, E., & Sumaila, R. (2018). Are fishery management upgrades worth the cost? *PLoS One, 13*, Article e0204258. https://doi.org/10.1371/journal.pone.0204258

Melnychuk, M. C., Essington, T. E., Branch, T. A., Heppell, S. S., Jensen, O. P., Link, J. S., Martell, S. J. D., Parma, A. M., Pope, J. G., & Smith, A. D. M. (2012). Can catch shares better track management targets? *Fish and Fisheries, 13*, 267–290. https://doi.org/10.1111/j.1467-2979.2011.00429.x

Melnychuk, M. C., Peterson, E., Elliott, M., & Hilborn, R. (2016). Fisheries management impacts on target species status. *Proceedings of the National Academy of Sciences, 114*, 178–183. https://doi.org/10.1073/pnas.1609915114

Miller, S. J., & Deacon, R. T. (2017). Protecting marine ecosystems: Regulation versus market incentives. *Marine Resource Economics, 32*, 83–107. https://doi.org/10.1086/689214

Ministry of Agriculture and Rural Affairs of the PRC [MARA]. (2017). *Notice issued by the Chinese Ministry of Agriculture on further strengthening the management of domestic fishing vessels to implement harvest control of marine fishery resources*. Retrieved from http://www.moa.gov.cn/govpublic/YYJ/201701/t20170120_5460583.htm. (Accessed 22 December 2020).

Mora, C., Myers, R. A., Coll, M., Libralto, S., Pitcher, T. J., Sumaila, U. R., Zeller, D., Watson, R., Gastron, K. J., & Worm, B. (2009). Management effectiveness of the world's marine fisheries. *PLoS Biology, 7*, Article e1000131. https://doi.org/10.1371/journal.pbio.1000131

National Bureau of Statistics of China. (2017). *China statistical yearbook 2017*. Beijing: China Statistics Press.

New England Fishery Management Council [NEFMC]. (2021a). Northeast multispecies (groundfish). Retrieved from https://www.nefmc.org/management-plans/northeast-multispecies. (Accessed 8 November 2021).

New England Fishery Management Council [NEFMC]. (2021b). Atlantic herring. Retrieved from https://www.nefmc.org/management-plans/herring. (Accessed 8 November 2021).

New England Fishery Management Council [NEFMC]. (2021c). Skates. Retrieved from https://www.nefmc.org/management-plans/skates. (Accessed 8 November 2021).

Puga, R., Valle, S., Kritzer, J. P., Delgado, G., de Leon, M. E., Giminez, E., Ramos, I., Moreno, O., & Karr, K. A. (2018). Variability of nearshore tropical finfish in Cuba: Implications for scientific and management planning. *Bulletin of Marine Science, 94*. https://doi.org/10.5343/bms.2016.1127

Punt, A. E., Butterworth, D. S., de Moor, C. L., De Oliveira, J. A. A., & Haddon, M. (2014). Management strategy evaluation: Best practices. *Fish and Fisheries, 17*, 303–334. https://doi.org/10.1111/faf.12104

Quynh, C. N. T., Schilizzi, S., Hailu, A., & Iftekhar, S. (2017). Territorial use rights for fisheries (TURFs): State of the art and the road ahead. *Marine Policy, 75*, 41–52. https://doi.org/10.1016/j.marpol.2016.10.004

Rudd, M. B., & Branch, T. A. (2017). Does unreported catch lead to overfishing? *Fish and Fisheries, 18*, 313–323. https://doi.org/10.1111/faf.12181

Sanchirico, J. N., Holland, D., Quigley, K., & Fina, M. (2006). Catch-quota balancing in multispecies individual fishing quotas. *Marine Policy, 30*, 767–785. https://doi.org/10.1016/j.marpol.2006.02.002

Scientific, Technical and Economic Committee for Fisheries [STECF]. (2017). *Long-term management of skates and rays (STECF-17-21)*. Luxembourg: Publications Office of the European Union. https://doi.org/10.2760/44133. JRC109366.

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

Shu, S., Tang, Y., Chang, B., Zhu, W., & Chen, Y. (2020). Evolution of marine fisheries management in China from 1949 to 2019: How did China get here and where does China go next? *Fish and Fisheries, 21*, 435–452. https://doi.org/10.1111/faf.12439

Szuwalski, C. S., Burgess, M. G., Costello, C., & Gaines, S. D. (2017). High fishery catches through trophic cascades in China. *Proceedings of the National Academy of Sciences, 114*, 717–721. https://doi.org/10.1073/pnas.1612722114

Szuwalski, C., Jin, X., Shan, X., & Clavelle, T. (2020). Marine seafood production via intense exploitation and cultivation in China: Costs, benefits, and risks. *PLoS One, 15*, Article e0227106. https://doi.org/10.1371/journal.pone.0227106

Tallack, S. M. L. (2007). Escape ring selectivity, bycatch, and discard survivability in the New England fishery for deep-water red crab, *Chacean quinquedens*. *ICES Journal of Marine Science, 64*, 1579–1586. https://doi.org/10.1093/icesjms/fsm107

Walters, C., & Parma, A. M. (1996). Fixed exploitation rate strategies for coping with effects of climate change. *Canadian Journal of Fisheries and Aquatic Sciences, 53*, 148–158. https://doi.org/10.1139/cjfas-53-1-148

White, C., Halpern, B. S., & Kappel, C. V. (2012). Ecosystem service tradeoff analysis reveals the value of marine spatial planning for multiple ocean uses. *Proceedings of the National Academy of Sciences, 109*, 4696–4701. https://doi.org/10.1073/pnas.1114215109

Xinhua News Agency. (2021). *Outline of the People's Republic of China 14th five-year plan for national economic and social development and long-range objectives for 2035. Translation by Center for Security and Emerging Technology*. Washington, D.C: Georgetown University.

You, X., & Kobayashi, Y. (2009). The new cooperative medical scheme in China. *Health Policy, 91*, 1–9. https://doi.org/10.1016/j.healthpol.2008.11.012