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Towards resilience-based management of marine capture fisheries

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ABSTRACT

The world faces major risks in ensuring the sustainability and on-going socio-economic benefits from its marine capture fisheries (MCFs). Key drivers of risks for MCFs include: overharvesting, bycatch, illegal fishing, habitat loss and damage, climate change, and marine pollution. These risks threaten the livelihoods of the hundreds of millions of households and the nutrition of billions of people who depend on fish as a key source of protein. Resilience-based management offers an approach to respond to risks. Here, we review how might resilience contribute to the sustainability of fish stocks and evaluate the implications for net economic returns under alternative management strategies. Our focus is in three parts. First, we review: (1) rights-based management; (2) marine protected areas; and (3) ecosystem-based management. Second, we discuss how resilience-based management complements existing management approaches and describe the findings of emerging resilience research in four different fisheries. Third, we highlight the knowledge gaps and practice gaps that emerge from the review.

1. Introduction

The world is an increasing ‘riskier’ place as it approaches some key planetary boundaries (Steffen et al., 2015) and tipping points (McKay et al., 2022). This has important implications about how to manage natural resources such as freshwater, forests, and the world’s oceans. In terms of marine capture fisheries (MCFs), key planetary risks include changes to: sea-surface temperatures, direction and intensity of ocean currents, salinity, sea-level rise, and precipitation.

We contend that resilience-based management approaches offer a significant improvement to how marine capture fisheries (MCFs) are managed in a ‘riskier’ world, especially for fish stocks that are already overexploited biologically. Risks are, typically manifested by negative shocks that affect habitats, diversity, and abundance of fisheries populations. These shocks exist in a world of peaking global marine fish catches (FAO, 2020), marine pollution, observable declines in marine biodiversity, impaired ecosystem services, and changes to marine habitats (UN 2021). These risks not only affect marine species and habitats but threaten the livelihoods of the hundreds of millions of fishers, and their families, and the nutrition of billions of people who depend on fish as a key source of protein.

There is a large and rich literature in the marine and fisheries science about the risks to marine capture fisheries, including pioneering contributions by Walters and Hilborn (1976), Kirkwood (1993), Butterworth and Punt (1999),

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among others. This risk research has led to innovative ways to manage fisheries including, but not limited to: the precautionary principle (González-Laxe, 2005); management strategy evaluation (Punt, 2010); robust decision-making (Regan et al., 2005); active adaptive management (McCarthy and Possingham, 2007); ecosystem-based management (Curtin and Prellezo, 2010); and the use of marine protected areas (Grafton et al., 2005a,b; Humphreys and Clark, 2020). Despite these approaches, there remain important knowledge gaps about how show fishery managers respond to risks, especially in relation socio-economics outcomes.

We focus on the economics of risk and resilience in MCFs and do not review the vast science literature on risk and uncertainty (Ludwig et al., 1993) that spans many disciplines and practices. Instead, our resilience framing is based on the work of Grafton et al. (2019) which, itself, builds on the pioneering work of Holling (1973), among others. Our focus is on a socio-ecological understanding of resilience that, in this context, is about the ability of a MCFs to 'bounce back' or to recover following negative shocks. Specifically, we define and measure resilience with three separate metrics in relation to desired MCF system performance: (1) the time it takes to recover to a neighbourhood of its former state (recovery time); (2) the ability to withstand a negative shock without changing its underlining system behaviour (resistance); and (3) the probability of *not* crossing an undesirable threshold in which the system behaviour is irretrievably changed (robustness).

We review how resilience-based approaches to fisheries management contribute to sustainability of fish stocks and the implications for net economic returns. First, we highlight some of the key findings in the socio-economics literature on MCF relevant to resilience. Second, we review the key findings of a special issue on resilience in MCFs in *Economic Analysis & Policy*. Third, we provide our own insights about both knowledge and practice gaps.

2. Overview of the key economics literature on marine capture fisheries

Much of the risk literature has considered negative shocks in relation to harvesting of fish (Ludwig et al., 1993), but increasing attention is being given to indirect drivers such as climate change and marine pollution (UN 2021). A key focus in this risk literature for MCFs is the effects of negative shocks on the net economic benefits under alternative management scenarios and system states (Grafton et al., 2000b). Here, we briefly review three key management approaches that, in part, were developed to respond to risks facing MCFs: (1) rights-based management (RBM); (2) marine protected areas (MPAs); and (3) ecosystem-based management (EBM).

2.1. Rights-based management (RBM)

Of particular importance to economists (Grafton et al., 2006b, pp. 1–23) is the maximum economic yield (MEY) of an MCF; the harvest level, and associated biomass, that maximises the discounted net benefits of harvesting (Clark, 1973; Grafton et al., 2010a,b; Squires and Vestergaard, 2016). The MEY concept has been extended to encompass 'dynamic-MEY' which considers not only the desired harvest or biomass at a point in time, or at an equilibrium, but also the optimising strategies and trajectories, while accounting for shocks, to arrive at the optimal (harvest and biomass) level (Grafton et al., 2012). A key finding of this literature is that, with static technology and purely private (rivalrous) inputs, the stock levels that maximise dynamic-MEY are larger than with the maximum sustainable yield (MSY); a traditional goal of fisheries management. The 'conservation bias' of dynamic-MEY target, however, depends on harvesting costs increasing in a non-linear way with declines in the biomass (Grafton et al., 2007). This can be undermined, however, by fish harvesting technology and other public (non-rivalrous) inputs that reduce the dependency of harvesting costs to changes and decrease the incentive for larger fish stocks (Squires and Vestergaard, 2013, 2018).

RBM, or incentive-based approaches to fisheries management (Grafton et al., 2006a), were developed to respond to low or declining net returns from fishing. Low or declining net economic returns in MCFs is explained by traditional input controls on fishers that leave unaffected the incentive to 'race to fish'. As a result, if fishers can substitute to non-regulated fishing inputs, fishing effort continues to grow (Squires, 1987). Where there is also a limit on the total allowable catch (TAC), as there is in many MCFs in input-controlled fisheries, fishers race against each other for a share of the catch before the total harvest limit is reached. This, in turn, increases fishing capacity but fails to increase the total harvest or revenues and increases costs. Input controls also, typically, can contribute to more complex and more expensive governance in MCFs (Maguire, 2003).

RBM offers an alternative by providing fishers with the rights to fish or to territorial rights to fish. Harvesting rights, if properly enforced, should encourage fishers to harvest their fixed catch at lowest cost, and to increase the value of landings through better handling and care of fish. When such rights are transferable, more profitable fishers can also harvest a greater share of the TAC (Grafton et al., 2000a) that, in turn, can increase productivity (Fox et al., 2003) and reduce harvesting overcapacity (Dupont et al., 2005). Another advantage is that RBM can potentially reduce the demand for information by fisheries managers (Arnason, 1990).

RBM is, however, not without challenges that include: inequities in the original allocation of harvesting rights; incentives to increase discarding at fish at sea so as to avoid exceeding individual harvesting rights (Arnason, 1994); and the potential to increase market power if there are inadequate limits on the proportion of harvesting rights owned by individual entities. The incentives provided by RBM are also only in relation to market values and, typically, do not provide incentives for fishers to conserve non-market values.

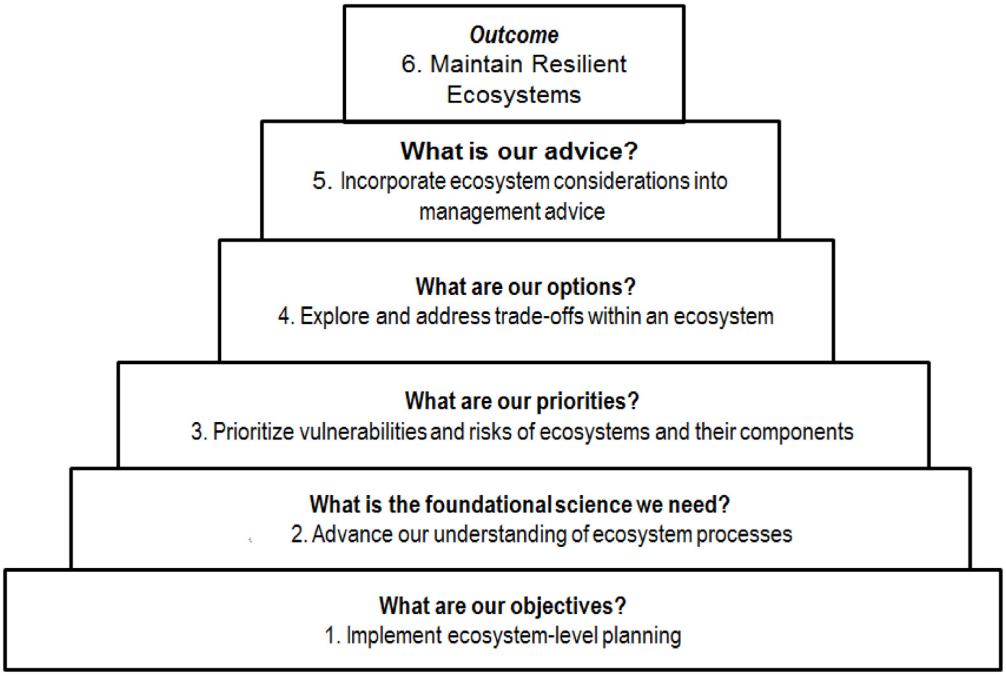

Fig. 1. Key Steps in Ecosystem-based Management in Marine Capture Fisheries.
Source: NOAA (2016, p. 4).

2.2. Marine protected areas (MPAs)

In response to fisheries management failures to control harvest or to deliver potential benefits from MCFs, alternative management options have been developed. MPAs is an approach that can provide a range of possible benefits, especially to adjacent MCFs (Roberts et al., 2001) that include: (1) increase the spawning biomass—especially with overexploited stocks; (2) increased robustness by ensuring a given proportion of the population persists; and (3) potentially lower management costs relative to traditional fisheries regulations (Polacheck, 1990).

Other potential benefits identified in the MPA literature include: improved habitat (Roberts and Sargant, 2002); enhanced conserved ecosystem structure, function and integrity; non-consumptive opportunities (Bhat, 2003); and species diversity (Halpern, 2003). Whether these benefits are realised in practice, however, depends on the size, location and permitted uses within MPAs. The economic benefits of MPAs may also be enhanced if MCFs are also managed with the use of dynamic-MEY as a target to complement MPAs (Yamazaki et al., 2014).

Hannesson (1998, 2002), however, highlights that, under given circumstances, MPAs may have limited effect as they only contribute to transferring the fishing pressure elsewhere. This is especially problematic for highly mobile fish stocks when there is open access outside the MPA, including the high seas.

2.3. Ecosystem-based management (EBM)

A key approach to responding to risks in MCFs has been ecosystem-based management (EBM) which, at its core, seeks to integrate the social, ecological, and economic, to understand causes and drivers of ecosystem changes (NOAA 2022). The management approach is illustrated in Fig. 1.

An important outcome of the approach is to maintain resilient marine ecosystems. Rather than a stand-alone approach to managing MCFs, EBM complements and stands alongside existing fisheries management. Its value add is to have a 'systems understanding' of natural and human-based impacts on MCFs and an adaptive approach to management to better deliver on multiple societal outcomes.

3. Special issue on resilience in marine capture fisheries

A special issue on resilience of marine capture fisheries in the journal *Economic Analysis and Policy* offers insights into the strategies that fishery managers in MCFs can employ when responding to risks. This special issue includes four independent, but related contributions on resilience in MCFs that we separately review.

3.1. Optimisation of economic performance and stock resilience in marine capture fisheries

This research by Chu et al. (2022) compares resilience, as measured by recovery time and robustness and economic performance, in the Northern Australia's sandfish (*Haluthria sabra*) fishery under alternative harvest control rules. Their analysis responds to three key questions: (i) what is the fish biomass level, and corresponding harvest, that maximises economic performance? (ii) what is the likelihood of fish biomass falling below a critical target threshold? and (iii) what is the expected recovery time for fish biomass to reach a desired target level?

The modelling results of Chu et al. (2022) show that a dynamic-MEY harvest control rule generates a higher net economic surplus and greater stock resilience than any other harvest control rule. Its better economic performance and resilience in this fishery is because it generates lower harvest when the stock level is at lower levels but results in higher harvests at higher stock levels. At least for the Australian sandfish fishery, there is not necessarily a trade-off between the goal of higher net economic returns and the resilience of the fish stock. That is, a dynamic-MEY harvest control rule results in both a higher net economic surplus and a speedier and robust stock recovery from low stock levels than the widely used MSY harvest control rules. Importantly, their approach can be applied to any MCF where there are sufficient data for calibration.

3.2. Resilience management for coastal fisheries facing global changes and uncertainties

This research by Cuilleret et al. (2022) focuses on multi-species MCFs in French Guiana and compares resilience outcomes under three alternative harvesting strategies; (1) dynamic-MEY; (2) MSY; and (3) No harvesting with 'Business as Usual', as based on historical trends. An interesting feature of their modelling is to account for projected climate change (RCP 2.6 and 8.5) through changes in sea surface temperatures.

The results of Cuilleret et al. (2022) were developed using a viability approach (Béné and Doyen, 2018) and show that both dynamic-MEY and MSY harvest strategies are more resilient than business as usual. Further, they find that dynamic-MEY and MSY strategies generate similar recovery time and resistance measures of resilience. Importantly, their methods can be readily applied in multi-species MCFs to compare alternative harvesting strategies across three key measures of resilience: recovery time, resistance, and robustness.

3.3. Negative shocks in an age-structure bioeconomic model and how to deal with them

In this research by Ni et al. (2022) applied an age-structured model to a fishery subject to negative shocks in recruitment and somatic growth. The optimal fishing strategy turns out to be pulse fishing. In their analysis, the period and magnitude of the shocks are varied in order to investigate how optimal management adjusts, and also what factors trigger pulses in the fishing pattern.

The main finding is that two principles should govern. First, harvest when the number of small cohorts is at its minimum. Second, harvest when shocks to growth have the least impact on the weight distribution of the stock. In addition, they find that both harvest and profitability (net present value) change almost linearly with the average impact of the shocks.

3.4. Stock crash and recovery in the norwegian spring spawning herring fishery

This research by Hannesson (2022) examines one of the most well-known stock collapses in modern fisheries that occurred in the late 1960s with the Norwegian spring spawn herring fishery. Previous studies of this fishery have attributed its collapse to overharvesting due to the absence, at the time of the collapse, of adequate harvesting controls (Gullestad et al., 2018). After estimating a stock-recruitment relationship (Ricker, 1975) for this fishery, Hannesson investigated its resilience, as measured by recovery time, to alternative levels of harvesting and states of the world.

Key results by Hannesson (2022) include: (1) the importance of the harvesting technology in contributing to stock collapse in the absence of adequate harvesting controls; (2) the long recovery time, up to 65 years, of the fish stocks to recover following its collapse; (3) the high variability in the recovery of the fish stock that may arise from random fluctuations in recruitment into the fishery; and (4) how mismeasurement of stock size (Hilborn, 2020) can contribute to overharvesting and less than desirable stock size. Importantly, a key implication, at least for this fishery, is that randomness in terms of recruitment can be an important explanation for resilience, as measured by recovery time.

4. Knowledge and practice gaps in marine capture fisheries

Knowledge gaps relate to what is unknown or uncertain in relation to resilience and MCFs while practice gaps refer to impediments in implementation of best practice or existing knowledge and evidence. Practice gaps occur because of hysteresis and inertia in terms of fisheries management and have several possible causes including, but not limited to: (1) technical and capacity constraints of fisheries researchers and managers; (2) management systems that are adapted to particular knowledge systems and, thus, may be difficult or time consuming to change; and (3) updating management processes can be costly such that, if management performance is judged 'acceptable', there may be little or no incentive for change.

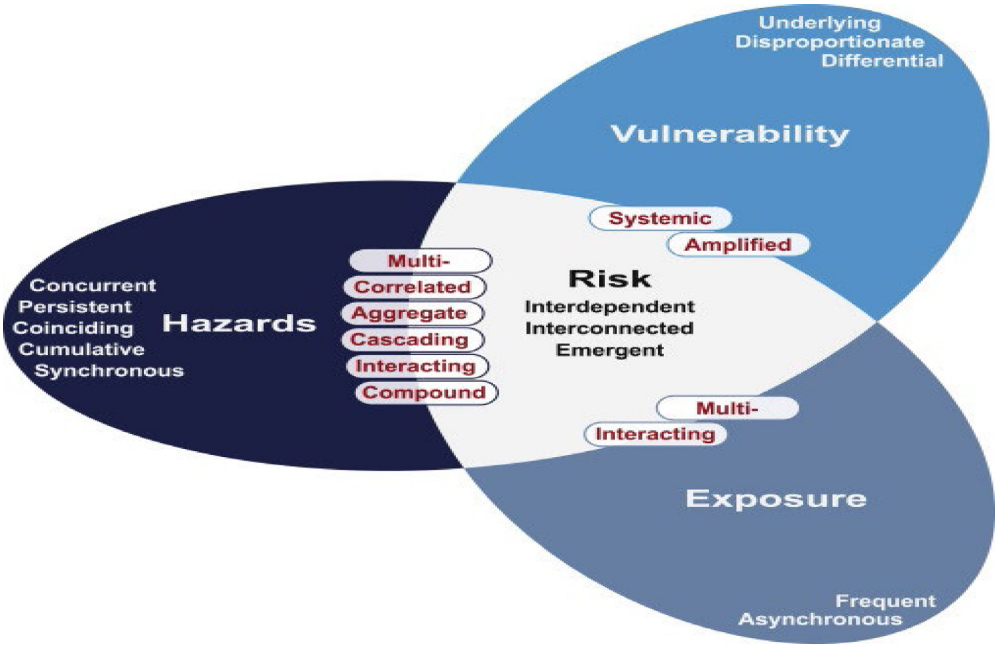

Fig. 2. Multiple Possible Risks in Marine Capture Fisheries.
Source: Simpson et al. (2021, p. 492).

4.1. Knowledge gaps

Operationalising resilience in MCFs requires a common understanding of what to manage (stocks, harvests, habitats, fishers, etc.) and what to manage *for* (sustainability, catches, diversity, employment, economic rent, etc.). Typically, managers have multiple, sometimes competing, goals which makes effective resilience management in MCFs a challenge.

To effectively implement resilience, MCF managers need to respond to a series of key questions (Grafton et al., 2019), namely: resilience for whom (e.g., for fish or fishers?); resilience of what (e.g., stocks or habitats?); resilience to what (e.g., climate change? ENSO events? or overharvesting? management system?); and resilience over what timeframe (e.g., current fishing season or next decade?). Responding to these key questions about resilience acknowledges both existing knowledge and decision gaps and creates a research agenda and strategies that focus on, 'what to do?'.

At the core of the knowledge gaps in MCFs is risk which, in turn, is determined by hazard (potential loss), vulnerability (susceptibility to loss) and exposure of a human population to the loss (see Fig. 2). Simpson et al. (2021) identify multiple risks, three of which are particularly relevant to MCFs: (1) cascading risk, where a trigger of one risk, such as an increase in sea surface temperature, cascades across multiple marine systems; (2) interconnected risk, whereby the connections across socio-economic-technological-environmental systems lead to unforeseen risks that affect multiple systems, such as improvements in harvesting technology; and (3) systemic or networked risks, such that overfishing on one species may trigger large-scale changes to the performance of an entire food web and marine system.

Some of the knowledge gaps around risks are unknowable. Nevertheless, modelling of the performance of alternative management strategies under a range of possible scenarios provide important insights about what strategies are preferred, and under what conditions (Grafton and Little, 2017). For instance, Little and Grafton (2015) developed iso-resilience curves of equal speed of recovery in terms of the quantity and quality of connections of a fish meta-population. They used their analysis to calculate trade-offs while accounting for risks.

Models of harvesting, stocks, and fishers' performance, as developed in the papers discussed in Section 3, explicitly consider risks. Such modelling is needed to develop adaptive strategies and to evaluate alternative strategies in multiple possible states of the world (Yamazaki et al., 2009).

4.2. Practice gaps

Impacts of changes in technology and climate and insufficient knowledge of, and data for, marine ecosystems create important practice gaps in managing that account for socio-ecological resiliency. EBM is the next step forward for fisheries management, particularly in high-income countries. Currently, however, model and data limitations preclude use of ecosystem-based models with quantitative targets for catch, effort, and ecosystem impacts of sufficient certainty (for all three types of risk) underpinning practicable ecosystems-based fisheries management. Until the latter is rectified, single-species stock assessments and management, qualified by bycatch and habitat impacts, and also management strategy evaluation, will likely remain the focus of conservation and management. Neither single-species stock assessments nor ecosystem models currently explicitly consider socio-ecological resiliency (i.e., incorporates the socio-economic or ecosystem), but management strategy evaluation increasingly does (though often incompletely for socio-economic systems). Single-species assessments do consider risk for overfishing and overfished stocks, often through formal assessments, within this single-species stock paradigm.

In the absence of ecosystem-based fisheries management, the less demanding ecosystem approach ecosystems approach to fisheries (EAF) is appropriate (Staples and Funge-Smith, 2009). EAF can be viewed as an extension of single-species management with concerns for bycatch and habitat impacts and less demanding than EBM. That is, EAF gives greater weight to uncertainty than conventional management, is oriented to action in the absence of full scientific certainty and is able to incorporate socio-ecological resiliency in 'thinking', if not always in formal modelling. In short, management strategy evaluation and the ecosystem approach to fisheries are good candidates to more explicitly and formally incorporate resiliency concepts, whether formally or through 'resiliency thinking, especially in high-income countries.

Sound MCF practices (based upon current practices) are largely understood in high-income country fisheries, but are far less understood in low- and middle-income countries. In these latter countries, MCFs are often intertwined with the complex and difficult issues of economic development and poverty eradication, knowledge gaps about complex, multispecies, tropical ecosystems, limited resources available for data collection, stock assessments, and fisheries management. The combination of all these constraints creates considerable risk and uncertainty (especially interconnected risk) not faced by high-income country fisheries.

Low-income fisheries face much greater risks to their resiliency than those of high-income countries that, typically, have greater management capacities. This is because formal, quantitative incorporation of socio-ecological resiliency faces impediments in low- and middle-income fisheries. In turn, this provides potential opportunities for explicitly adding in 'resiliency thinking' to fisheries management. While data are often limited in low-income fisheries, their less extensive management institutions, paradoxically, may offer greater opportunities to incorporate 'resiliency thinking' because fewer current established practices and institutions inhibit new management approaches and practices.

Broad qualitative impacts of climate change are increasingly understood, but quantitative short-, medium, and long-term impacts are sufficiently imprecise and risky to preclude their direct, formal incorporation into stock assessments, management, or management strategy evaluation. Instead, often the most reliable information that is provided is indicators that can be used to qualitatively adjust and supplement the abundance, availability, and location of stocks and resulting target catch or effort or to inform management strategy evaluation or the ecosystem approach to fisheries. Changes in technology, such as information and communication technology (e.g., fish finding devices, GPS) or fish aggregating devices (with embodied technology to assess stocks), can rapidly increase effective fishing effort (Squires et al., 2003) thereby increasing risks to stocks and habitats. Resilience thinking offers a framework to consider and to respond to these risks.

5. Conclusions

On-going global biodiversity losses, including in marine environments, and faster than projected climate change, is creating a more uncertain world. This poses critical risks for important natural capital stocks, such as marine capture fisheries, that are an important protein source for many hundreds of millions and provide livelihoods for tens of millions of people.

One response to increasing risks in fisheries management is to incorporate new findings from 'resilience thinking' and practice. We contend that emerging research in terms of socio-ecological resilience and marine capture fisheries provide valuable frameworks to guide managers in the setting of their harvest controls. These 'resilience methods' are, generally, applicable to any fishery where there is sufficient data available and offer the potential to transform and improve the practice of fisheries management.

While every fishery is different, insights from the emerging socio-economics resilience literature include: (1) the importance of managing marine capture fisheries to ensure acceptable levels of resilience (recovery time, resistance and robustness); (2) the complementarities, rather than trade-offs, between managing for resilience and to maximise net economic returns; (3) the need to consider multiple shocks directly, such as from overharvesting and indirectly, such as from climate change, when comparing alternative harvesting strategies; (4) the importance of considering random effects in management strategies; (5) the value of pulse fishing, closures, marine protected areas and ecosystem-based management as approaches to promote resilience in the presence of negative shocks; and (6) no management strategy performs the best in all possible states of the world.

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