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Adaptive fisheries responses may lead to climate maladaptation in the absence of access regulations

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Adaptive fishery responses to climate-induced changes in marine fish populations may lead to fishery maladaptation. Using a stylised bio-economic model of the global fishery, we demonstrate the importance of adaptive management regimes. We show how the losses resulting from poor access regulation increase in a fishery system negatively impacted by environmental change, and demonstrate the proportional benefits provided by management strategies that control the levels and allocation of fishing effort. Indeed, under poor to nonexistent access regulation, highly adaptive actors can generate significant bio-economic losses. This might lead to foregone benefits and cascading economic and ecological losses, whereas well-designed adaptive management regimes may enable making the most of the best, and the least of the worst, climate-induced outcomes for fisheries. These findings emphasize the need for integrated assessment approaches to the impacts of climate change on fisheries, that should incorporate not only ecological responses but also the industry and management responses.

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INTRODUCTION

A growing number of ecological studies show that climate change is likely to entail significant impacts on marine ecosystems globally, with ensuing changes in the productivity of marine fisheries[1] and in the spatial distribution of fish stocks[2,3]. Expected changes in marine animal biomasses by 2100 include declines in most oceanic areas, with strong heterogeneity across regions and species[3,4].

The discourse on the need for adaptation to climate change has increasingly occupied centre stage in relation to these major changes occurring in the fish communities exploited by commercial fisheries. Whether to benefit from or to best cope with these changes, adaptation is commonly viewed as a positive force whereas fisheries are often represented as a fairly static force in these ecological studies (e.g.[5]), with limited consideration of likely responses by economic actors (although exceptions exist such as adjusting supply and demand models to climate change[6]). Implicit in the calls for industry to develop adaptation strategies is the assumption that such adaptation would necessarily result in positive outcomes. While the study of economic adaptation in fisheries has attracted growing interest[7–9], numerical analyses of fisheries responses to climate-induced ecosystem changes remain limited.

Here, we examine the circumstances under which such responses may lead to positive or negative outcomes on both economic returns and fish stock sustainability. Our main contribution lies in showing that adaptive economic actors without adaptive management (i.e., the capacity to adjust regulations of fishing effort levels) may lead to fishery maladaptation (i.e., decreased long-term economic returns and biomass levels associated with fisheries responses).

As stressed by Papaioannou et al.[10], fisheries can respond to shifting species distributions by changing fishing grounds or target species. A number of studies have been carried out at the global level to assess the implication of those responses[5,11]. To examine the consequences of such adaptation, we built on the stylized model of the global fishery by the World Bank[12] which treated the world's marine fisheries as one single aggregate fishery and estimated substantial economic losses in the year 2012 ("the Sunken Billions", hereafter SB model) due to poor fisheries management. We developed a dynamic version of the SB model (hereafter SB-Dyn, see Methods) which includes four "métiers" representing the combinations of two species fished in two fishing regions (métiers 1–4, see Supplementary Table 1). To represent the spatial and species-specific heterogeneity in climate impacts, we assumed that ecosystem changes lead to a 25% reduction in the carrying capacity in one métier only (métier 3)[5,13]. We modelled two levels of responses to this change (see Supplementary Material for details of the model):

(i) ecological drift: the spatial distribution of the affected fish species adjusts to changes in carrying capacity and biomass density across regions;
(ii) fishing effort allocation: within management constraints, fishing activity is reallocated to métiers with highest anticipated economic margins.

We simulated the expected evolution of the fishery using the level of fishing effort of the SB model in the reference year[12], defining this level of effort as our status quo (see Supplementary Fig. 1). Next, we considered two archetypal management regimes, which differed in terms of fishery access regulation and effort limitation:

– Open Access: the fishery reverts to unrestricted entry/exit of fishing effort in all métiers, leading to a dynamic adjustment towards zero profit levels[14];
– Adaptive management for Maximum Sustainable or Economic Yield (MSY/MEY): optimal effort maximising yield or profit at steady state is calculated, then recomputed to account for ecosystem change with a lag reflecting delays in management planning and implementation.

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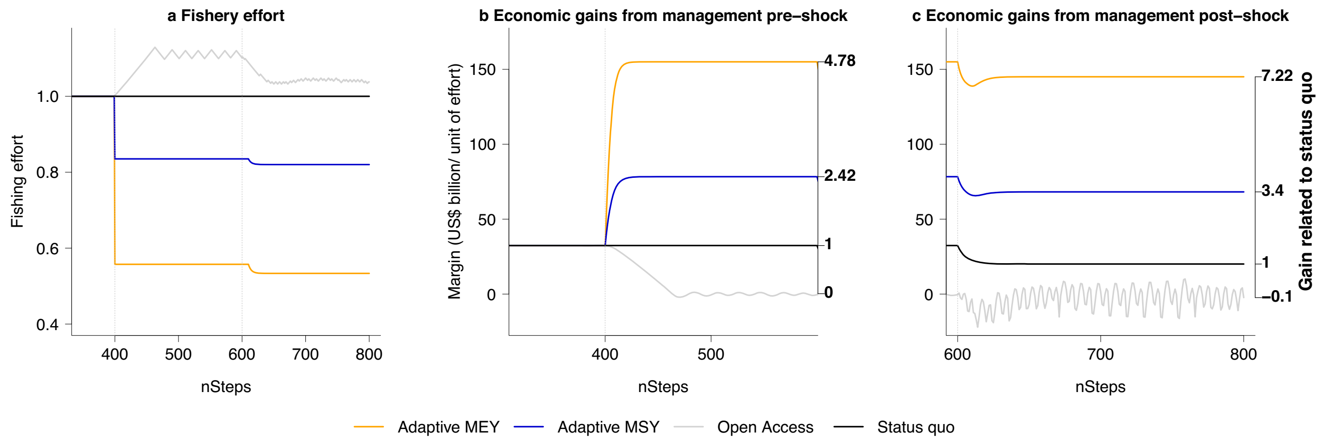

Fig. 1 Simulation outputs at the fishery scale. Trajectories for total fishery effort (**a**) and economic gains from management (**b**, **c**) are shown across management strategies. Management change occurs at time step 400, while the drop in carrying capacity in métier 3 occurs at time step 600. Margins are calculated as the ratio of net economic returns per unit of effort. Economic gains from management (the ratio of economic margins obtained under each management strategy to the margins obtained under the status quo levels of fishing effort, before and after shock) are also presented (right-hand *y*-axis in **b** and **c**).

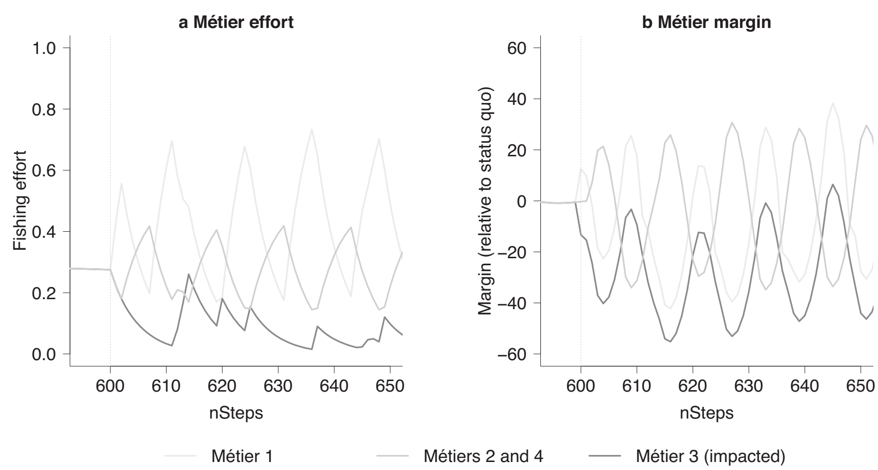

Fig. 2 Transitional responses per métier in the open-access strategy after the drop in carrying capacity in métier 3. Effort per métier (**a**) and métier margin (**b**) are relative to status quo. Fishing behaviours are similar in metiers 2 and 4.

These target effort levels were then applied with implementation inertia, reflecting lags in the economic and social response to changes in the ecosystem (see Methods).

RESULTS

Impacts at the fishery scale

Figure 1 presents the changes in total fishing effort and average economic margins (defined as the ratio of net economic returns per unit of effort) at the fishery scale, associated with moving from the status quo to each of the management regimes (from time step 400), without climate-induced impacts (to time step 600). As expected, improved management entails reduced levels of fishing effort (−16% for MSY and −44% for MEY), and higher economic productivity (+242% for MSY and +478% for MEY), while a shift to Open Access entails an average 11% increase in fishing effort and a drop to zero average margins, as well as variability in the fishery status (see Supplementary Fig. 2 and Supplementary Table 2 for the corresponding biomass and profit levels in the fishery).

We used these stylized reference situations of the global fishery to examine the potential implications of our hypothetical climate-induced ecological change (from time step 600 in Fig. 1), depending on the archetypal management strategy in place at the time when this change occurs.

Simulation results clearly show that the benefits of improved management (as compared to the status quo) increase in a fishery faced with such a change. Indeed, with the onset of climate effects and as compared to the status quo, annual margins increase by +722% under MEY management and by 340% under MSY management. Corresponding effort levels are adjusted slightly downwards (−18% under MSY management and –47% under MEY management) to cope with the drop in carrying capacity (see Supplementary Fig. 2 and Supplementary Table 3 for the corresponding biomass and profit levels in the fishery affected by ecosystem change). This benefit partially derives from the assumption made in the SB model that higher average price can be achieved under MEY due to a larger stock biomass[12] (See Supplementary Methods for the price assumption explanation and Supplementary Fig. 3).

Responses under Open Access at the métier scale

In contrast, under Open Access, where fishers are assumed to be able to freely adapt in the absence of any effort constraints, climate-induced ecosystem change entails a stronger reduction in average total fishing effort, which still remains above its status quo reference level. In addition, the change in carrying capacity leads to further destabilization of the fishery, with significant impacts in terms of economic performance (Fig. 1). This is due to the dynamic

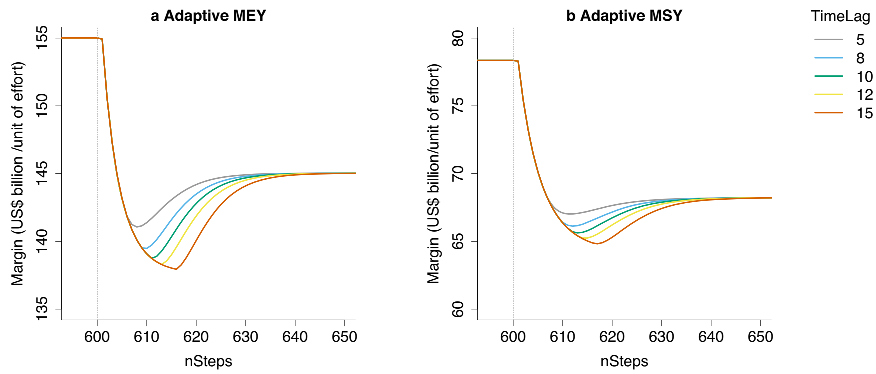

Fig. 3 Sensitivity of economic margins at the fishery scale with time lag (management adaptation) varying between 5 and 15 years. Trajectories for margins are given under MEY (**a**) and MSY (**b**) strategies. The drop in carrying capacity in métier 3 occurs at time step 600.

reallocation of fishing effort, which takes place in response to short-term changes in the relative margins across métiers (Fig. 2). Due to the drop in its carrying capacity, métier 3 becomes less attractive to fishers than métiers 1, 2 and 4, leading to effort flowing towards these alternative activities, as well as fishing effort exiting and/or entering the fishery in response to overall fishery performance. This affects the relative biomass densities across métiers, in turn affecting relative margins, and leading to unstable conditions throughout the simulation. This instability is driven by short-term changes in the relative economic attractiveness of the different métiers, which may transitionally present positive or negative margins, despite the overall biomass reduction entailed by ecosystem change (Supplementary Table 3).

Impacts of management adaptation delays on economic margins

The sensitivity of economic margins at the fishery scale was explored with shorter and longer time lags in implementing adapted MEY and MSY strategies (i.e. with shorter or longer delays for management to establish adapted target effort levels). The drop in carrying capacity leads to a transition phase (around 50 time steps in our simulations), before a stable state is reached in our stylized model of the fishery. The longer management takes to set a new target effort (e.g., 15 time steps, orange curves in Fig. 3), the lower the margins will be during the transition phase and the greater the cumulative losses will be, following the environmental change. Given economic returns are greater under the MEY than under MSY strategy, the interim losses associated with delayed management adaptation are also expected to be greater under a MEY strategy.

DISCUSSION

Although based on a highly stylized representation of the global fishery, our results demonstrate that the benefits of adequate access regulation, highlighted in the SB study, could be even greater in a context where fisheries are negatively affected by climate-induced ecosystem changes. In such a context, the MEY management strategy would provide for the greatest adaptation benefits. On the other hand, letting fishers adapt in response to economic incentives, with limited to no regulation of access, even where some inertia exists as reported in the literature[15], is likely to lead to fishery maladaptation, unstable conditions for both the fishing industry and the fish stocks, and significant economic losses. With a 2.5% discount rate, the impact on cumulative returns over a 20-year period, relative to pre-shock conditions, is 25% larger under Open Access than under MEY (see Supplementary Fig. 4 and Supplementary Table 3). This impact increases with decreasing levels of inertia in effort response (Supplementary Table 4). These results clearly point to the need to better understand the adaptation of fisheries systems to climate change[7,8,11,16]. Besides, one of the key dimensions illustrated in our results is the capacity to adapt management targets to changes in environmental conditions. Greater adaptive capacity for management can significantly reduce the transitional costs of adjusting to the new carrying capacity of the system. This economic advantage of a quick response will be even greater under MEY strategies than under MSY strategies.

Accounting for fishery and management adaptation following decreased productivity or carrying capacity of harvested resources is likely to allow better anticipation of the effective consequences of climate change on marine fish stocks and their associated fisheries. Similar conclusions would also apply to cases where climate-induced ecological changes increase the carrying capacity of fish species. An example of this is boarfish (*Capros aper*), the abundance of which increased exponentially between 1980s and 2000s in the Bay of Biscay, likely due to changes in environmental conditions[17]. In the mid-2000s, the landings of this species followed suit, but a catch limit was only introduced in 2011 and the stock status remains undefined[18]. Indeed, delays in the capacity to integrate changed bio-economic conditions in management support are an important question for further research.

Our stylized model of course ignores the broader social costs and equity considerations that will inevitably result from significant changes in carrying capacity of fisheries systems following ecosystem responses to climate change. In this model, the costs associated with a drop in carrying capacity, as well as the benefits from effective management, are considered at an aggregate level, independent of how they are spread across actors within and beyond the fishery. In principle, when access regulation is assumed, nothing would prevent participants remaining in the fishery from sharing the benefits derived from fishing with a larger number of stakeholders, potentially addressing the economic and social consequences of a reduction in employment and other livelihood benefits. The model simply enables us to assess how alternative management targets for fishing effort are likely to lead to different levels of wealth, independent of how such wealth is shared.

Further analyses of the distributional consequences of adapting to climate change in fisheries requires extending the approach. Although theoretical bioeconomic models have long been recognized and used to derive optimal harvesting trajectories, these models need further development to capture socio-cultural and livelihood dimensions, and account for broader social costs and alternative approaches to equitably allocating benefits. Some have tried to estimate optimal yield achieving maximum returns to society by considering the trade-offs between the benefits to industry, fish consumers and conservation of biodiversity[19]. Others have attempted to frame the desirable operating space for "Pretty Good Social Yield" in multi-species fishery systems, which requires agreeing on the multiple short-term and long-term objectives that can be pursued by fisheries management[20]. Eco-viability approaches, seeking to include social viability constraints, alongside ecological and economic constraints, have also been proposed to address the trade-offs associated with alternative management strategies for marine fisheries[21].

Many different dimensions of fisheries management could be considered in reflecting on the potential benefits of managing fisheries for climate change. In this study, we build on the SB model and focus on the potential benefits of adopting MSY or MEY strategies, which imply the existence of regulations restricting access to fisheries resources to selected fishers, as contrasted with situations of Open Access. While Open Access incentivizes excess investment and leads to poor outcomes at the fishery level, rights-based fisheries management (RBFM) tackles the negative impacts of open access fishing. One useful form of RBFM is the implementation of individual catch shares in fisheries managed under Total Allowable Catches[22]. Another example is Territorial User Rights for Fisheries (TURFs), where collective groups of fishers are granted exclusive access to harvest resources within a geographically defined area. TURFs have the potential to mitigate the Open Access rent dissipation and to generate economic value and wealth because the group will seek to maximize returns from the access rights by acting as a single unit diminishing total fishing effort[23,24]. Users can decide to fish at MEY, and are able to decide when to fish according to the consequences of these decisions on markets and revenues. Future work could adapt the model developed here, where some TURF users stop fishing and shared benefit rules are established. Implications of such management strategies could then be discussed in terms of equity outcomes, as well as incentives.

This study builds on a rich literature aimed at understanding the implications of climate change at the global ecosystem and fisheries landings levels[1,5], at the industry and fleet dynamics levels[10,25], and at the institutional level[8,9,13]. Conceptual modelling frameworks integrating these different levels of impacts, such as the one developed here, can help provide an integrated prospective on these impacts. Our results contribute to a better understanding of the mechanisms and consequences of adaptation, beyond its narrative attractiveness, and point to the fundamental need to better understand how economic incentives and management institutions interact in determining fishery responses to climate-induced ecosystem changes. The drivers of these responses could then be incorporated into assessments, models and scenarios supporting management.

METHODS

The fishing effort dynamics model

We modelled a stylized fishery system composed of four métiers, where each métier defines a fleet of vessels targeting one of two species and operating over one of two regions (only one set of species in one region is affected by a changed ecosystem). The model was calibrated using information and assumptions from the SB report[11] regarding the distribution of fish biomass, fishing effort, catch and landings of a global aggregate fishery (see parameter values for simulation of dynamics of the fishery in Supplementary Table 1).

The model was run for 400 time steps assuming no change in fishing effort (i.e. the business as usual scenario in the SB report) to allow the fish stocks to come into equilibrium, this steady state providing our status quo situation for the fishery. Archetypal management regimes were implemented at time step 400, with fishing effort per métier set according to the management target (MSY or MEY) or left to vary in response to economic incentives.

We then examined the impacts on the fishery of a 25% reduction[5,12] in carrying capacity in one of the four métier from time step 600 (from 245 to 183.75 million tons in métier 3 as a result of climate change). Fishing effort levels were adjusted according to each management strategy, assuming a lag of 10 time steps is required for MEY and MSY management strategies to account for the new carrying capacity in setting the target effort levels[7] (see Supplementary Fig. 1 for the simulation sequence). In addition to this lag, implementation inertia was included in the model for all management strategies, with a cap on the percentage of fishing effort adjustment that can be applied at each time step (set at 20%). This progressive adjustment represents the time needed for policy change to translate into effective adjustments in fishing effort corresponding to the policy goals. This effort inertia parameter was calibrated to reduce unrealistic system fluctuations. Similar inertia was assumed under Open Access in the capacity for effort to respond to changed incentives in entry/exit decisions per métier, as well as costs affecting the attractiveness of changing métiers, with the assumption that it is costlier to change species (gear polyvalence) than to change region (relocation)—see supplementary methods.

Sensitivity analyses

Sensitivity analyses were carried out on the impacts of reduced (−20%) or increased (+20%) levels of change in carrying capacity, in implementation inertia, and in effort response under Open Access, as well as shorter or longer time lags and results were not qualitatively affected (Fig. 3 and Supplementary Table 4).

To analyse the impact of climate-induced ecosystem change on the performance of management strategies, outcomes in terms of total fish biomass, total catch, total effort, total profit and average margin at steady state were computed, relative to those observed under status quo levels of fishing effort (Supplementary Fig. 2). We also evaluated the net present value (NPV) of cumulative annual net returns over a 20-year transition period, for different discount rates (from 0 to 5%)[26], with and without the impacts of climate change (see Supplementary methods and Supplementary Fig. 4).

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

DATA AVAILABILITY

The data supporting the findings of this study are provided in the article and its Supplementary Information and will be available from the corresponding author on reasonable request.

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AUTHOR CONTRIBUTIONS

O.T. and F.B. conceived the study concept; All authors contributed to the study design; J.B. carried out the formal analyses and interpretation under the supervision of F.B. and O.T.; J.B., F.B. and O.T. contributed to discussions and modelling insights and wrote the article.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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