Supplementary information for

https://doi.org/10.1038/s44183-023-00010-0

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

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1. Supplementary methods - The model

Our stylized model builds on the stylized model of the global fishery in the World Bank's Sunken Billion Report (hereafter SBR, 2017) and relies on it for the initial conditions (Supplementary Table 1). The SBR model is mainly based on the FAO FishStat Plus estimates and on a database of landings and biomass for 147 fish stocks covering the main types of commercial fish stock around the world. To enable representing the heterogeneity of climate-induced impacts on marine ecosystems, we develop a stylised regionalised version with two sets of species and two regions, differing in their sensitivity to these impacts (only one set of species in one region is affected by a changed ecosystem). In order to capture the dynamic responses of fishing fleets to these changes, we also assume key processes driving biomass and fishing effort responses across métiers.

Following Soulié & Thébaud (2006), we describe a fishery system composed of N métiers, where each métier defines a fleet of vessels targeting a species i and operating over a region j. We assume no biological interactions between the target species. Each species i is characterised by:

- A biomass b_i;
- An intrinsic natural growth rate r_i;
- A speed with which a species can move between regions *SpeciesMobility*;

- A schooling parameter δ_i.

Parameters values are documented in Supplementary Table 1. Furthermore, each métier k is characterised by the following parameters and variables:

- A carrying capacity K_k;
- A biomass flow $Flow_k$;
- A fish price in that métier $Price_k$;
- A fishing effort targeting the species in that métier E_k;
- An effort effectiveness parameter q_k;
- A catch $Catch_k$;
- A unit cost of effort $Cost_k$.

In addition, management and fishery inertia, which control the speed of readjustment are represented by the following parameters:

- *EffortInertia,* which defines the percentage of fishing effort that can move towards a targeted fishing effort in a single time step, reflecting the speed with which this targeted effort can be reached. If *EffortInertia* is set to 0, the targeted effort is reached instantaneously. Here, we set it to 0.8. This progressive adjustment represents the time needed for policy change to translate into effective adjustments in fishing effort corresponding to the policy goals.
- z_k^{in} and z_k^{out}, two factors controlling how much effort can enter or exit a specific métier under Open Access. While the former represents the attractiveness of a métier, the latter reflects the existence of economic alternatives outside the métier considered. Here, we assume z_k^{in} and z_k^{out} are equal across all métiers (set to 0.2).
- $TE_{k\rightarrow l}$, the cost of reallocating effort from métier *k* to métier *l* under Open Access. Here, it is assumed that it is costlier to change species (0.05) than to change region (0.04).

In the rest of this description, in all equations, variables are indexed by métier. When the variable refers to species (biomass, carrying capacity, etc.), the index refers to the species in that métier.

1.1. Fish stock dynamics

The dynamic of fish stocks is modelled as follows:

$$b_k(t+1) = b_k(t) + Gr_k(t) + Flow_k(t) - Catch_k(t) \qquad \text{Eq 1}$$

where

$$Gr_k(t) = r_k b_k(t)\left(1 - \left(\frac{b_k(t)}{K_k(t)}\right)^{\gamma-1}\right) \qquad \text{Eq 2}$$

measures the instantaneous growth per unit of biomass of the species in métier *k*; and γ is the Pella-Tomlinson exponent (Fletcher, 1978).

Eq 3 measures the migration of biomass between métier *k* and other métiers *l* which share the same species.

$$Flow_k(t) = SpeciesMobility \sum_l (K_k(t)b_l(t) - K_l(t)b_k(t))/(K_k(t) + K_l(t)) \qquad \text{Eq 3}$$

Eq 4 measures the catch in métier *k* and δ is the schooling parameter (World Bank, 2017), where N^δ is a scaling term compensating for the effect of the schooling parameter when the biomass is spread over *N* métiers.

$$Catch_k(t) = N^\delta q_k E_k(t) b_k(t)^\delta \qquad \text{Eq 4}$$

We impose the further constraint

$$Catch_k(t) = \min(Catch_k(t)\,, Q_k b_k(t)\,) \qquad \text{Eq 5}$$

where Q_k is the availability factor which ensures no complete biomass depletion is possible.

1.2. Economic returns

Profits are given by:

$$\pi_k(t) = Catch_k(t)Price_k(t) - E_k(t)Cost_k \quad \text{Eq 6}$$

where $Cost_k$ is the cost per unit effort in métier *k* and fish price is given by

$$Price_k(t) = a\left(\frac{K_0}{K}\right)^d b_k(t)^d \quad \text{Eq 7}$$

where *a* is the landing price parameter and *d* is the price elasticity as a function of biomass (see Appendix B in the SBR, 2017, Homans & Wilen 2005), assuming that fish prices increase as current biomass approaches carrying capacity and provides higher quality catch. $(K_0/K)^d$ is a scaling term compensating for the effect of price elasticity when the biomass is spread over *N* métiers. K_0 is a baseline carrying capacity (here set to the carrying capacity used in the SBR, 2017), which allows us to relate fish prices between stocks/condition with different carrying capacity.

1.3. Fishing effort dynamics and management strategies

We model fishing effort dynamics under four archetypal management strategies.

1.3.a. Status quo

For this management strategy which we use as a reference, we keep fishing effort at its level in the business as usual scenario of the World Bank study throughout the simulation, such that $E_{Tot}^{ref} = 1$.

1.3.b. Open Access

This strategy mimics a generalized failure of fisheries management, which would lead to fishing effort entering or exiting the fishery according to its economic profitability. Total fishing effort $E_{Tot}^{OA}(t) = \sum_k E_k^{OA}(t)$ is determined at the fishery scale, as follows:

1) Métier margins and total margin are computed as

$$M_k(t) = \frac{Catch_k(t)Price_k - E_k^{OA}(t)Cost_k}{E_k^{OA}(t)}$$

$$M_{Tot}(t) = \frac{\pi_{Tot}(t)}{E_{Tot}^{OA}(t)} \quad \text{Eq 8}$$

Where $\pi_{Tot}(t)$ is the aggregated profit across métiers.

2) Total effort is updated as $E_{Tot}^{OA}(t+1) = E_{Tot}^{OA}(t) + z * M_{Tot}(t)$, where z= $\widetilde{z_k^{in}}$ if $M_{Tot}(t)$>0 and z= $\widetilde{z_k^{out}}$ otherwise, following (Smith, 1972).

3) Expected effort at métier level is then calculated as a function of the relative margins of each métier at the previous time step, under a myopic behavior assumption (Soulié & Thébaud, 2006):

$$E_k^{exp,OA}(t+1) = E_{Tot}^{OA}(t+1)\frac{M_k(t)}{\sum M_k(t)} \qquad \text{Eq 9}$$

If $M_k(t) < 0$ while other métiers generate positive margins, this is set to a very small positive value. Technically it should be set to zero since no vessel should have any interest to fish in a métier with negative return, as long as there is at least one other métier which can provide a positive return.

4) We define $dE_k^{exp,OA} = E_k^{exp,OA}(t+1) - E_k{}^{OA}(t)$ the effort reallocation required to match the expected relative margins in a given métier. We then compute $dE_{k\to l}^{exp,OA}$, the required effort reallocation between métiers *k* and *l*, as proportional to relative excess allocation.

5) Finally, we compute the actual effort reallocation as

$$dE_{k\to l}^{OA} = (1 - EffortInertia)dE_{k\to l}^{exp,OA}\, TE_{k\to l} \qquad \text{Eq 10}$$

where $TE_{k\to l}$ represents the cost of moving from métier *k* to *l* and *EffortInertia* is a parameter which reflects the speed with which fishing effort can adjust to the targeted effort.

1.3.c. Adaptive MSY per métier

We compute b^{MSY}, the biomass at MSY from the general form Growth = $rb - \beta b^{\gamma}$, where $\beta = \frac{r}{K^{\gamma-1}}$, as in the SBR:

$$\frac{dCatch}{db} = r - \gamma\beta {b^{MSY}}^{\gamma-1} = 0 \rightarrow b^{MSY} = \left(\frac{r}{\gamma\beta}\right)^{\frac{1}{\gamma-1}} \qquad \text{Eq 11}$$

Next, we compute MSY_k, the catch at MSY as:

$$MSY_k = rb^{MSY} - \beta b^{MSY^{\gamma}} = r\left(\frac{\gamma - 1}{\gamma}\right)\left(\frac{r}{\gamma\beta}\right)^{\frac{1}{\gamma-1}} \qquad \text{Eq 12}$$

By using $\beta = \frac{r}{K^{\gamma-1}}$, as in the SBR, $Catch^{MSY}$ can be written as:

$$MSY_k = r_k K_k \left(\frac{\gamma - 1}{\gamma}\right)\gamma^{\frac{1}{1-\gamma}} \qquad \text{Eq 13}$$

Finally, we compute effort at MSY as

$$E^{MSY} = \frac{MSY_k}{qb^{MSY^{\delta}}} \rightarrow E^{MSY} = \frac{r_k}{q_k}\left(\frac{\gamma-1}{\gamma}\right) {K_k}^{1-\beta}\gamma^{\frac{1-\beta}{\gamma-1}} \qquad \text{Eq 14}$$

The change in management is assumed to occur at time step 400 of the simulation. Implementation inertia is assumed, with a cap set on the percentage of effort adjustment that is applied at each time step:

$$dE_k^{MSY}(t) = E_k^{MSY} - E_k(t) \qquad \text{Eq 15}$$

$$E_k(t+1) = E_k(t) + (1 - EffortInertia) * dE_k^{MSY}(t) \qquad \text{Eq 16}$$

The MSY fishing effort target is recomputed at time step 600 (see section 2. Calibration and Simulations) to account for changed conditions in the fishery (i.e., drop in the carrying capacity for métier 3).

1.3.d. Adaptive MEY per métier

We compute the effort at MEY, E^{MEY} from the general form $rb - \beta b^{\gamma} = Eqb^{\delta}$

$$E^{MEY} = \frac{r}{q} b^{1-\delta}\left(1 - \frac{\beta}{r} b^{\gamma-1}\right) \qquad \text{Eq 17}$$

Again using $\beta = \frac{\alpha}{K^{\gamma-1}}$

$$E^{MEY} = \frac{r}{q} b^{1-\delta}\left(1 - \left(\frac{b}{K}\right)^{\gamma-1}\right) \qquad \text{Eq 18}$$

Profit is given by:

$$\pi = PriceEqb^{\delta} - cE \qquad \text{Eq 19}$$

Using Eq 7, and replacing Eq 7 in Eq 19, we have:

$$\pi = arb^{1+d} - r\beta b^{\gamma+d} - \frac{c}{q}rb^{1-\delta} + \frac{c}{q}\ \beta b^{\gamma-\delta} \qquad \text{Eq 20}$$

again using $\beta = \frac{r}{K^{\gamma-1}}$ leads to

$$\pi = r(1 - (\tfrac{b}{K})^{\gamma-1})(rb^{1+d} \text{-} \tfrac{cb^{1-\delta}}{q}) \qquad \text{Eq 21}$$

And

$$E^{MEY} = \frac{r}{q}b^{1-\delta}\left(1 - \left(\frac{b}{K}\right)^{\gamma-1}\right) \qquad \text{Eq 22}$$

Next, we look for maximum profit with respect to b, by solving for $\frac{d\pi}{db} = 0$, leading to

$$arb^{d}\left((d+1) - (\gamma \mp d)\left(\tfrac{b}{K}\right)^{\gamma-1}\right) - \tfrac{c}{q}rb^{-\delta}\left(1 - \delta - (\gamma - \delta)\left(\tfrac{b}{K}\right)^{\gamma-1}\right) = 0 \qquad \text{Eq 23}$$

Eq 23 is then solved numerically. Since it can display multiple extrema, care must be taken to ensure that the solution found is a global maximum.

MEY fishing effort is first computed at time step 400 of the simulation (with similar progressive adjustment as in Eq 15 and 16), and then kept constant until the drop in carrying capacity. It is recomputed at time step 600 to account for changed conditions in the fishery (i.e., assuming a drop in the carrying capacity for métier 3).

2. Supplementary methods - Simulations

Simulations run for 400 time steps without any change in fishing effort ($E_{Tot}^{ref} = 1$) to allow the population to come into equilibrium. Management archetypes are implemented at time step 400, and the changes in steady states of the fishery are computed over the following 200 time steps. We then introduce a 25% reduction in carrying capacity in métier 3 (from 245 to 183.75 million tons). Fishing effort levels are 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.

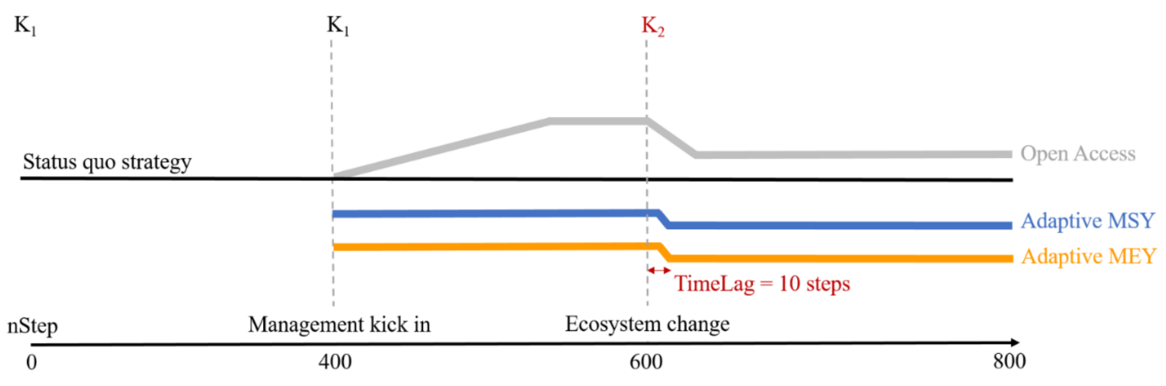
Supplementary Table 1 | Parameter values for simulation of dynamics of the fishery. All parameters except those related to métier breakdown and system inertia are taken from the SBR which uses 2012 as the reference year.

Métier	**Units**	**Symbol**	**Métier 1**	**Métier 2**	**Métier 3**	**Métier 4**
Region			Region a		Region b	
Species			Species 1	Species 2	Species 1	Species 2
Biological parameters						
Carrying capacity	Million tons	K_k	245	245	245→ 183.75	245
Starting biomass	Million tons	b	53.5			
Growth rate	n.a.	r	1.644			
Pella Tomlinson exponent	n.a.	γ	1.188			
Schooling exponent	n.a.	δ	0.71			
Species mobility	n.a.	$SpeciesMobility$	1			
Economic parameters						
Cost per unit of effort	US$ billion	$Cost$	97.422			
Effort effectiveness parameter	n.a.	q	1.76			
Landing price	n.a.	a	0.387			
Price elasticity	n.a.	d	0.22			
Inertia parameters						
Effort Inertia	n.a.	$EffortInertia$	0.8			
Cost of changing regions	n.a.	$TE_{k \to l}$	0.04			
Cost of changing species	n.a.	$TE_{k \to l}$	0.05			
Factor controlling effort entry	n.a.	Z_{in}	0.2			
Factor controlling effort exit	n.a.	Z_{out}	0.2			

Comparisons of long-term steady state outputs between management strategies include biomass, catch, effort, profit and margin metrics estimated at both the fishery and the métier levels. In addition, we evaluate the net present values (NPVs) of economic returns at the fishery scale for different discount rates over a period of 20 time steps after the ecosystem change, and compare this to the outcomes which would occur without this change:

$$NPV = \sum_{1}^{T=20} \frac{\pi(t)}{(1+d)^t} \quad \text{Eq 24}$$

with $\pi(t)$, the total profit at step t (t ∈ [1,20]) and d is a discount rate ranging from 0 to 5% (following observations that individuals appear to use a moderate discount rate ~2.5% for time horizons around twenty years, and a higher discount rate, up to 5%, for shorter times horizons; Heal 1998).



Supplementary Figure 1 | Simulation sequence and adjustment of fishing effort.

3. Supplementary Results

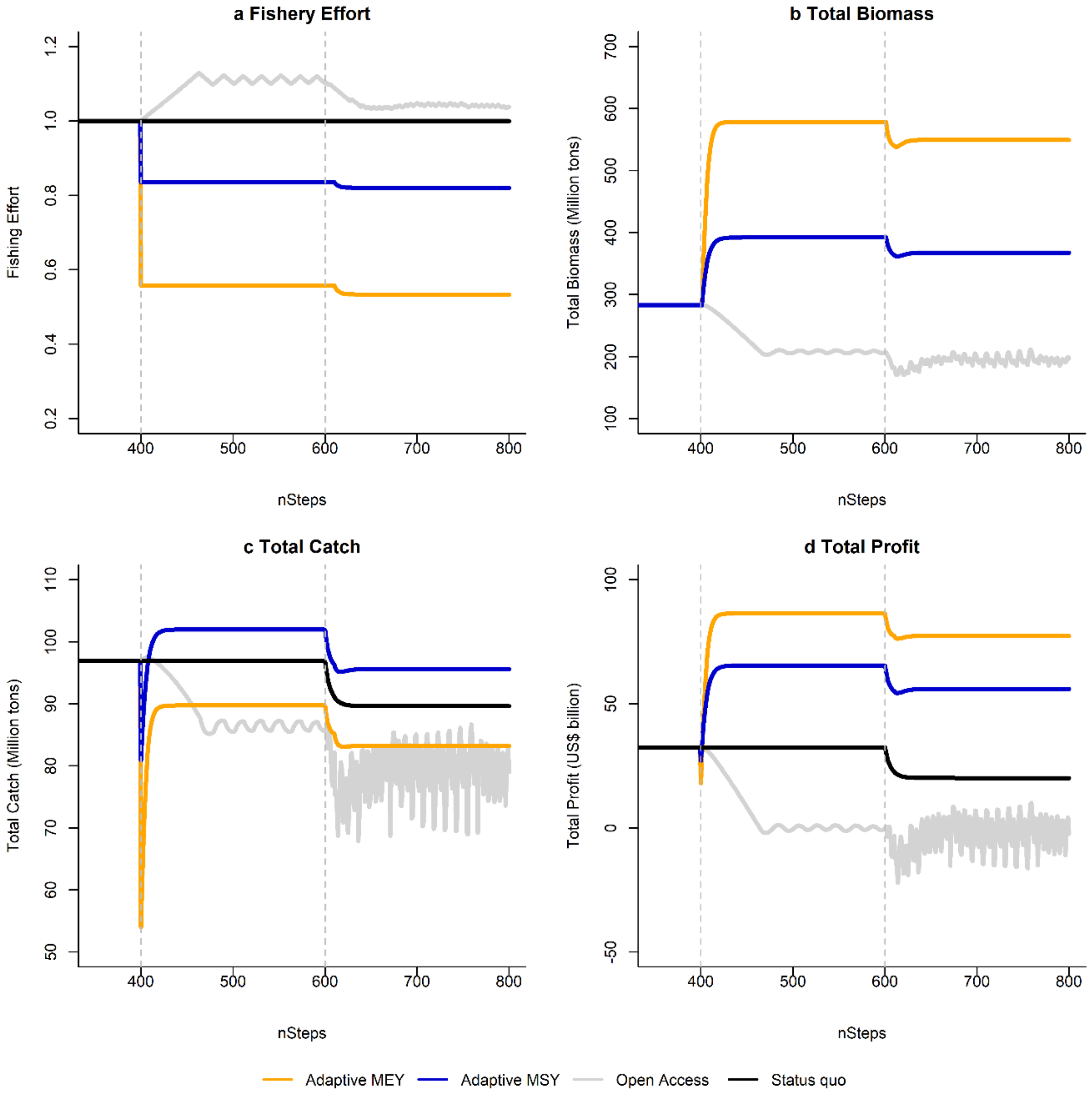
Supplementary Table 2 | Total biomass, total effort, total catch, total profit and average margin at the fishery scale across management strategies once steady state is reached, before the drop in carrying capacity. Values can be compared to the SBR outputs indicated in italics. Open Access values are the mean across observations representing 100 years at MEY/MSY management strategy steady state.

Strategy	Total Biomass (Million tons)	Total Effort (Standard Unit)	Total Catch (Million tons)	Total Profit (US$ billion)	Average Margin (US$ billion/ standard unit of effort)
MEY	578.47	0.56	89.73	86.41	155.01
MEY-SBR	*578.60*	*0.56*	*89.70*	*86.30*	*154.90*
MSY	391.98	0.84	101.98	65.44	78.35
MSY-SBR	*392.20*		*102.00*		
Open Access	207.83	1.11	86.40	0.013	0.012
Status Quo	283.00	1.00	96.89	32.41	32.41

Management for MEY leads to higher levels of fish biomass (578.47 million tons), than for MSY (391.98 million tons) or Open Access (207.81 million tons, Supplementary Table 2 and Supplementary Fig. 2). Steady state annual landings at MEY (89.73 million tons) are lower than for MSY (101.98 million tons) or Open Access (86.40 million tons), while profits are greater for MEY (US $ 86.41 billion) than for MSY (US $ 65.44 billion), while Open Access leads to minimal levels of annual profits (on average US $ 0.013 ± 0.75 billion, variation due to the instability of the fishery under this strategy).

Supplementary Table 3 | Total biomass, total effort, total catch, total profit and average margin at the fishery scale across management strategies after the drop in carrying capacity and once steady state is reached. Percent changes (%) were calculated relative to the situation where fisheries are managed before the drop in carrying capacity (i.e., Supplementary Table 2). Open Access values are the mean across observations representing 100 years at MEY/MSY management strategy steady state.

Strategy	Total Biomass (Million tons)	Total Effort (Standard Unit)	Total Catch (Million tons)	Total Profit (US$ billion)	Average Margin (US$ billion/ standard unit of effort)
MEY	549.43 (-5.02%)	0.53 (-4.29%)	83.20 (-7.28%)	77.38 (-10.45%)	145.03 (-6.44%)
MSY	367.48 (-6.25%)	0.82 (-1.79%)	95.61 (-6.25%)	55.95 (-14.50%)	68.22 (-12.93%)
Open Access	194.87 (-6.23%)	1.04 (-6.31%)	79.22 (-8.31%)	-2.01 (-201,100%)	-1.92 (-110,445%)
Status Quo	254.39 (-10.11%)	1.00 (0%)	89.63 (-7.50%)	20.08 (-38.06%)	20.08 (-38.06%)



Supplementary Figure 2 | Trajectories for total effort, total biomass, total catch, and total profit at the fishery scale across the alternative management strategies. Management change occurs at time step 400 while the carrying capacity decreases in métier 3 at time step 600.

We first examine the implications of a change from the SBR status quo to each management regime, without climate-induced change (time step 400 in Supplementary Fig. 2). Management for MEY leads to higher levels of fish biomass (578.47 million tons), than for MSY (391.98 million tons) or Open Access (207.83 million tons). Global annual landings at MEY (89.71 million tons) are lower than for MSY (101.98 million tons) or Open Access (86.40 million tons), while profits are greater for MEY (US $ 86.41 billion) than for MSY (US $ 65.44 billion), while Open Access leads to null average annual profits.

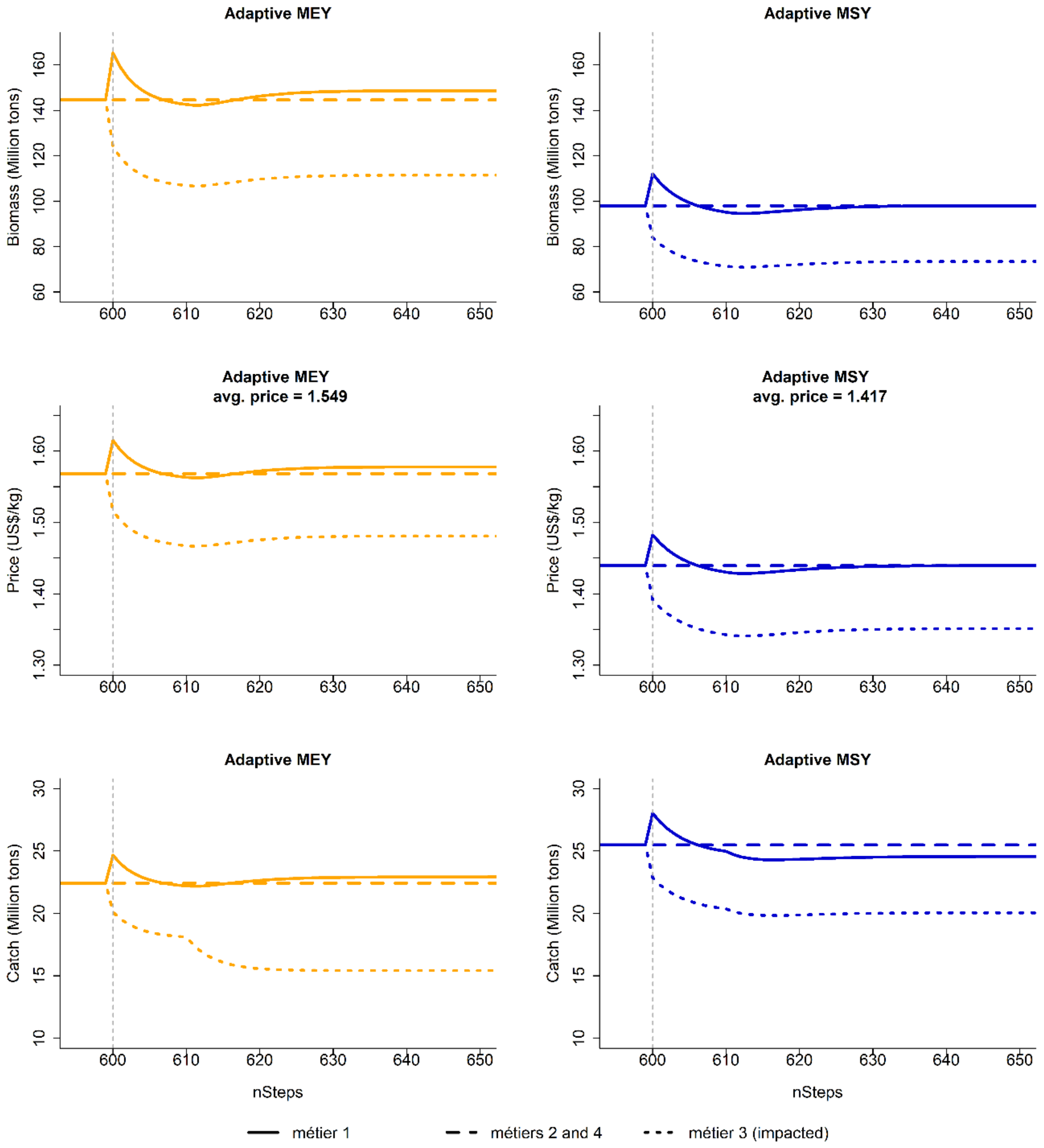
Following the drop in carrying capacity (time step 600), the relative performance of the MEY and MSY management strategies does not change and comparing outcomes in terms of total annual profits to those under status quo effort shows that improved management provide benefits in the face of climate change. For example, the gain in total annual profits in the global fishery under MEY rises from US $ 54 billion to US $ 57.3 billion under climate change (compare Supplementary Tables 2 and 3, 86.41-32.41 and 77.38-20.08, respectively).

In contrast, under Open Access, climate-induced ecosystem change entails a stronger reduction in average total fishing effort. In addition, the change in carrying capacity leads to further destabilization of the fishery, with significant impacts in terms of economic performance (Supplementary Fig. 2, grey lines).

Sensitivity analyses show that results are fairly robust to variations in key model parameters. The quicker the Open Access expected effort level is reached (i.e., the lower the coefficient *EffortInertia*), the higher the cost. If the expected effort is reached instantaneously (*EffortInertia* = 0) losses equal to -2.92 US$ billion (Supplementary Table 4). The more responsive the fishery is in the Open Access strategy (i.e., the larger the coefficients Z_{in} and Z_{out}), the more unstable the fishery is and the higher the costs of not having effective management. If Z_{out} is reduced by 75% in two metiers only, assuming exiting a metier is difficult due to limited alternatives, the cost is even higher.

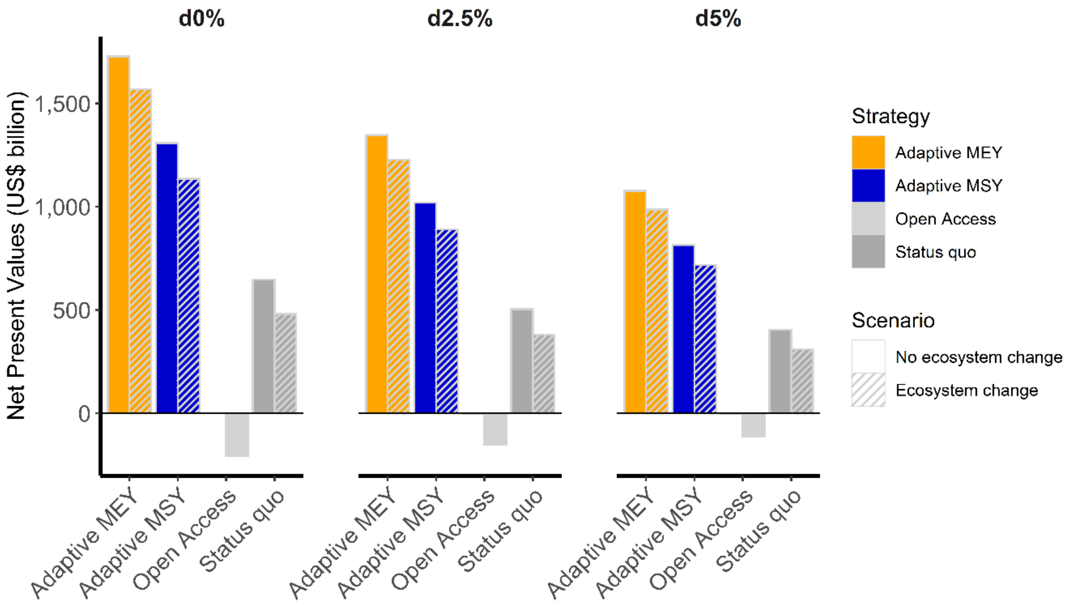
Supplementary Table 4 | Sensitivity of average margin and total effort to increasing or decreasing key parameters (Damage impact, Effort inertia, Z_{in} and Z_{out}) at the fishery scale and across management strategies once steady state is reached following the drop in carrying capacity. Values in italics represent management gains related to the status quo. Open Access values are the mean across observations representing 100 years at MEY/MSY management strategy steady state.

		Damage impact (0.25)		1-Effort inertia (0.2)				Z_{in} and Z_{out} (0.2)		
		-20% (0.2)	+20% (0.3)	-100% (0)	-20% (0.16)	+20% (0.24)	+400% (1)	-75% two metiers Z_{out} (0.05)	-20% (0.16)	+20% (0.24)
Average Margin (US$ billion/effort)	MEY	146.68 *6.52*	143.61 *8.10*	137.65 *6.86*						
	MSY	70.24 *3.12*	66.21 *3.74*	64.25 *3.20*						
	Open Access	-1.62 *-0.07*	-2.02 *-0.11*	0.07 *0.00*	-1.02 *-0.05*	-2.14 *-0.11*	-2.92 *-1.05*	-3.92 *-0.20*	-0.86 *-0.04*	-1.91 *-0.10*
	Status Quo	22.48	17.72	20.08						
Total Effort	MEY	0.54 *0.54*	0.53 *0.53*	0.56 *0.56*						
	MSY	0.82 *0.82*	0.82 *0.82*	0.84 *0.84*						
	Open Access	1.05 *1.05*	1.03 *1.03*	1.07 *1.07*	1.04 *1.04*	1.04 *1.04*	1.05 *1.05*	1.05 *1.05*	1.04 *1.04*	1.04 *1.04*
	Status Quo	1.00	1.00	1.00						



Supplementary Figure 3 | Biomass, price and catch per métier under the alternative management strategies: adaptive MEY (orange) and adaptive MSY (dark blue). Average prices correspond to the mean across métier values at stable state (nStep = 800).

The price function used in the SBR model assumes that as fish stock increases, catch comprise more valuable species and larger individuals, leading to higher average price (Eq. 7). This assumption conduces to an interesting result: with lower fishing effort in the system under MEY management, the biomass to carrying capacity ratio is higher attracting greater prices. This response may ease the absorption of the effects of a drop in carrying capacity under MEY management strategy.



Supplementary Figure 4 | Cumulative returns at the fishery scale under alternative fisheries management strategies over the transition period of 20 time steps. The net present values are calculated using three discount rates (i.e., 0%, 2.5%, 5%). Stripped bars represent cumulative returns under climate-induced carrying capacity change.

With a zero discount rate, cumulative net returns over the 20-year period without climate-induced impacts on the fishery range from US $ 1,728.24 for MEY management to US $ 0.57 billion for Open Access. The climate-induced drop in carrying capacity entails reduced net returns: US $ -158.87 billion under MEY management (with total net returns still maintained at relatively high levels), and US $ -205.5 billion under Open Access (with total net returns becoming negative). As expected, total net returns as well as the difference in net returns across management strategies, with and without climate change impacts, decreases with increasing discount rates.

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