Supplementary Material

Initial BOATS model before including larval advection

The ecological module of BOATS is forced by sea surface temperature (SST) and net primary production (NPP). SST drives temperature-dependent growth and mortality of fish, while a combination of SST and NPP regulates the carrying capacity of each grid cell[1]. The time evolution *t (*s) of each fish group *k* in the biomass size spectrum ($f_k(m,t)$) follows the McKendrick-von Foerster partial differential equation:

$$\frac{\partial}{\partial t}f_k(m,t) = -\frac{\partial}{\partial m}\gamma_k(m,t)f_k(m,t) + \frac{\gamma_k(m,t)f_k(m,t)}{m} - \Lambda_k(m,t)f_k(m,t),$$

where $f_k(m,t)$ (gwB m^{-2} g^{-1}) is the normalised fish biomass in grams of wet fish biomass (*g*wB) per square metre of ocean surface per unit of the mass class *m* (g). The first term on the right-hand side describes the somatic growth of biomass into larger size classes, with $\gamma_k(m,t)$ (g s^{-1}) denoting the individual growth rate at size m and time *t.* The second term represents the increase of biomass within each size class from individual growth. The third term is the natural mortality rate $\Lambda_k(m,t)$ (s^{-1}). For all simulations, we used temporally interpolated, daily climatologies of net primary production (NPP) and sea surface temperature from Carozza et al.[1]. They extracted mean water temperatures from the euphotic zone of the World Ocean Atlas 2005[2], a database of climatological maps calculated with scientifically quality-controlled historical temperature data. To obtain NPP climatologies whilst accounting for variability in NPP models, Carozza et al.[1] averaged over three satellite-based NPP estimates[3–5].

The ecological module is coupled to a fishing module based on the Gordon-Schaefer open-access fisheries economics model[6]. The economic model relies on three economic forcings: cost of fishing per unit effort, *c*; the ex-vessel price of fish, *p*; and the catchability parameter, *q*, reflecting the technology level and ease with which fish can be caught[7]. In addition, two regulation forcings allow modelling fisheries management that steers fishing towards an agreed fishing target through various enforcement mechanisms[8]. By setting a target for fishing effort $E_{targ,k}$ (W m^{-2}) in selected cells and the enforcement strength S (≥ 0; dimensionless) for reaching this target, the regulation component allows including MPAs in BOATS. The economic-regulation module models the fishing effort E_k (W m^{-2}) on a size group k over time as:

$$\frac{d}{dt}E_k(t) = \kappa_e \frac{revenue_k - cost_k}{E_k} e^{-S} + (1 - e^{-S})\kappa_S(E_{targ,k} - E_k)$$

with κ_e (W m^{-2} \$$^{-1}$) denoting the fleet dynamics parameter, κ_S (m^2 s^{-1}) the regulation response parameter, and

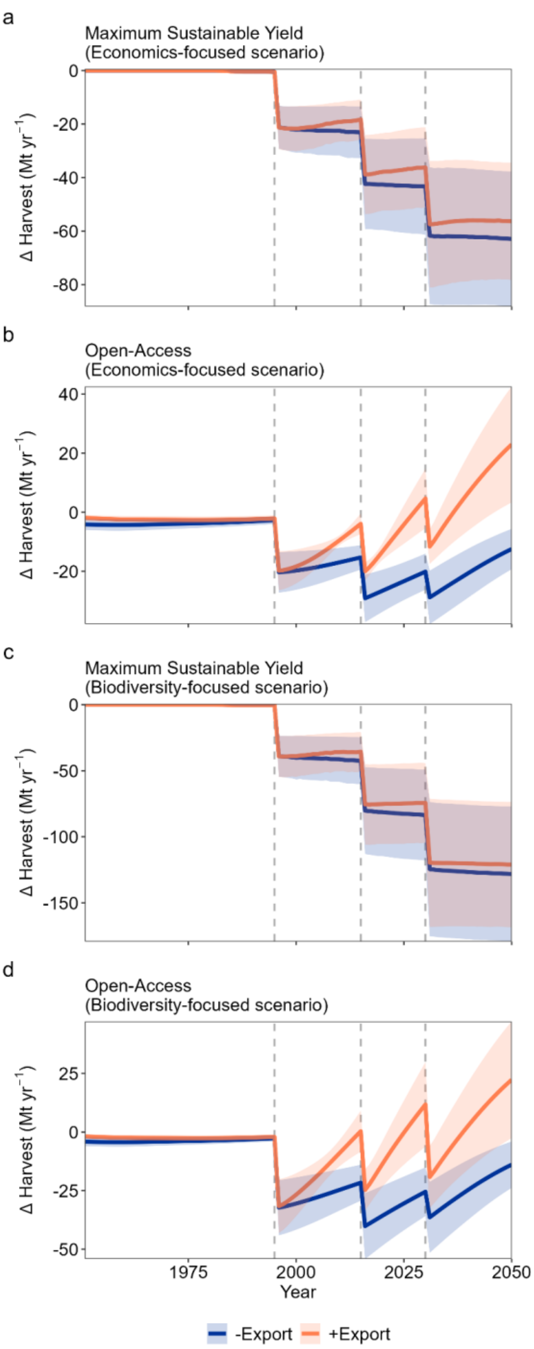
$$revenue_k = p_k q_k E_k B_k,$$

$$cost_k = c_k E_k$$

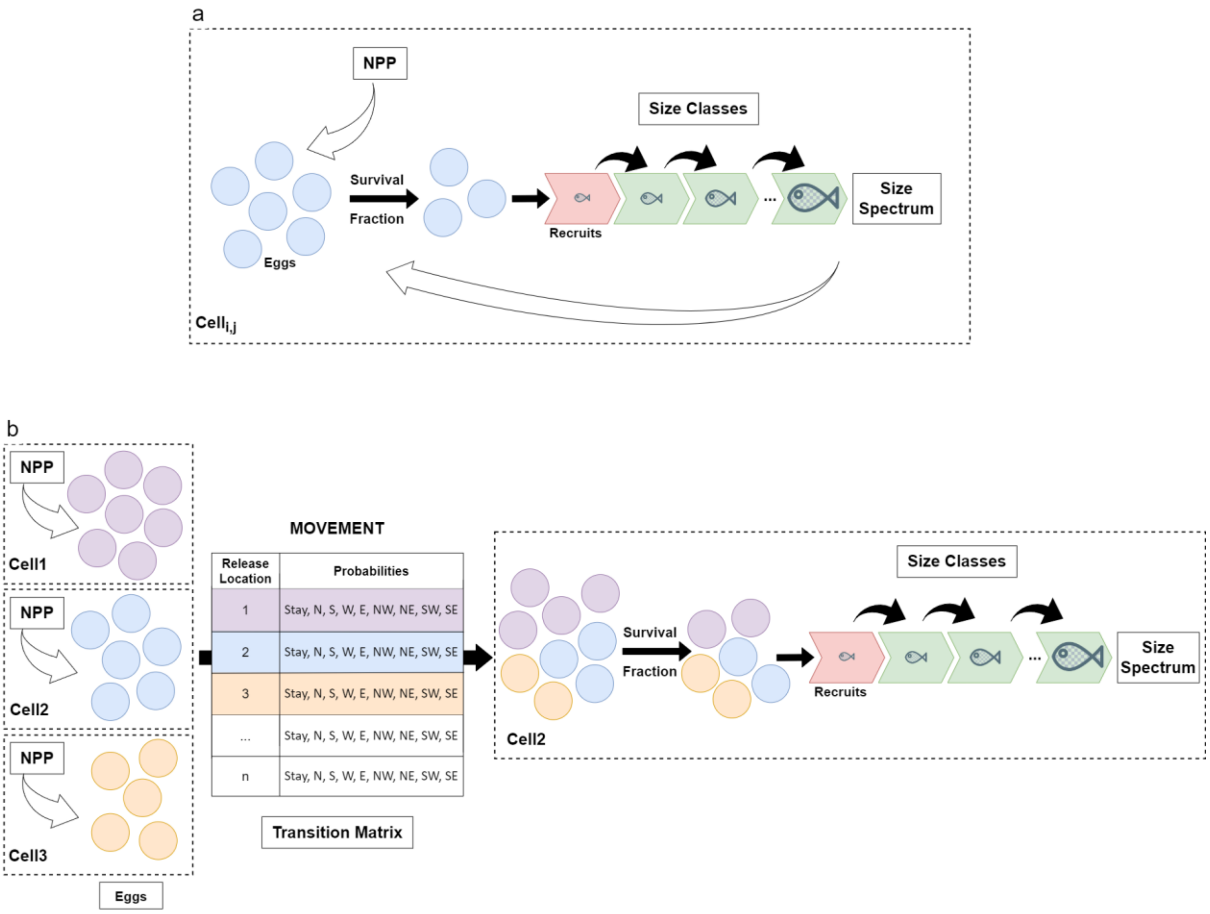
where p_k (\$ gwB^{-1}) is the ex-vessel price of fish, q_k the catchability parameter (m^2 W^{-1} s^{-1}), B_k (gwB) the selectable biomass of size group k, and c_k (\$ W^{-1} s^{-1}) the cost of fishing per unit effort.

Parameter Optimization and Uncertainty Estimation

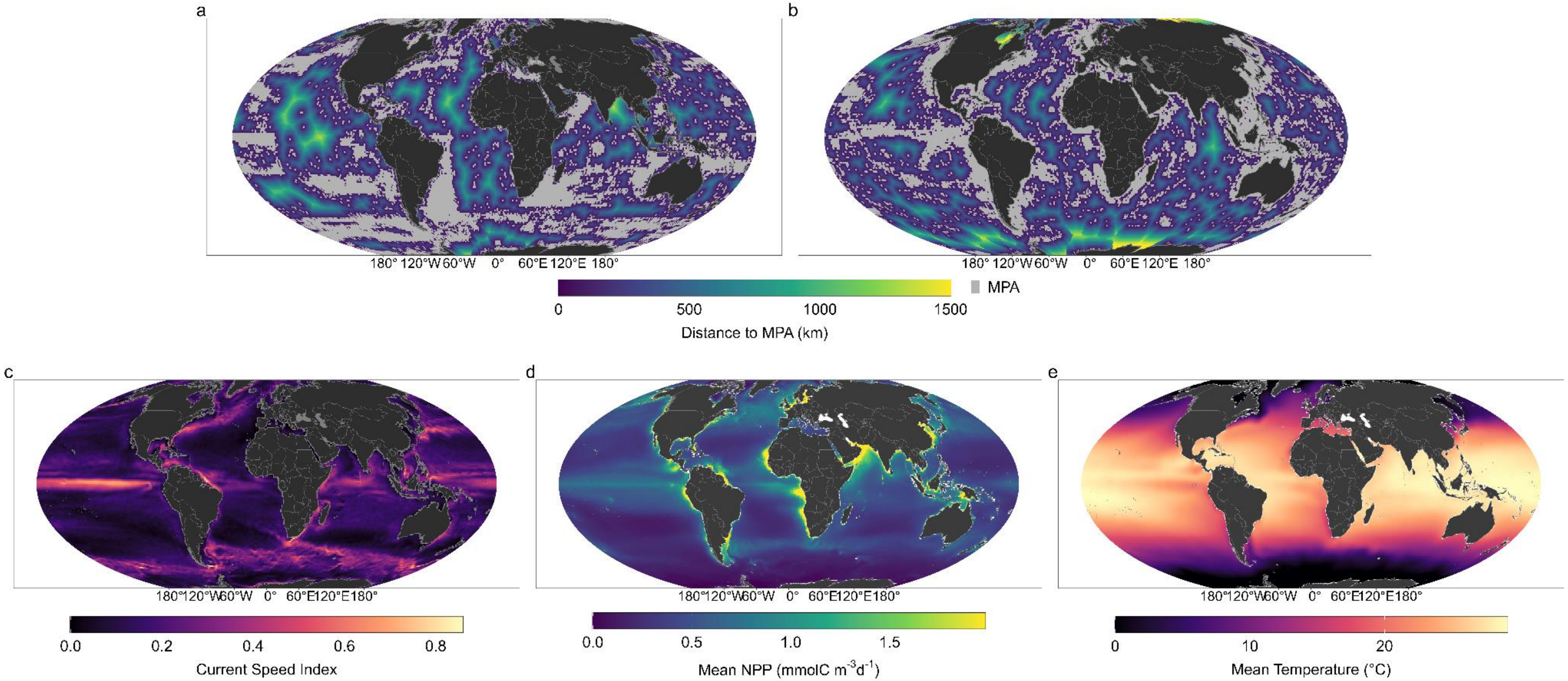
Model parameter values used in the five model ensemble members (Supp. Table 1) were estimated previously by Galbraith et al.[9] by employing a Monte Carlo approach spanning the range of uncertainty in the ecological and economic parameters. This involved generating 10,000 random values from the probability distributions of statistically-estimated ranges of values for all uncertain parameters. Estimated ranges were either taken directly from the literature or assumed using a uniform probability distribution given informed parameter choices taken from previous work without statistical estimates. Five parameter ensembles that span a wide range of possible parameter values (while still complying with the model evaluation criteria; see Carozza et al.[7] for details) were used for simulations, generating the mean value and uncertainty ranges shown in Figures 1-2 in the main text.



Supplementary Figure 1. Annual time-series of fish harvest difference under a Maximum sustainable Yield (a, c) or an Open-Access (b, f) fishing strategy based on an economics-focused (a, b) or biodiversity-focused (c, d) 30×30 scenario. a-d. Total fish harvest difference between the simulations with and without MPAs either with (orange) or without (blue) larval export. Shaded regions represent +/-SD. Dashed lines represent when an additional 10% of MPAs were implemented.



Supplementary Figure 2. Schematic of BOATS steps from egg production to the size spectrum before and after implementing egg/larval advection. a. Before implementing advection, all grid cells were independent. Egg production was influenced by NPP in a cell and the number of reproductive adults. Eggs were subject to a survival fraction, determining the fraction of eggs turning into recruits. **b.** After implementing advection, egg production still depended on NPP and the number of reproductive adults in a cell (not depicted here). However, eggs were also moved to neighbouring cells based on advection probabilities in the transition matrix. Subsequent steps were the same as in the version of BOATS without advection.



Supplementary Figure 3. Predictors created for the Generalised Linear Model. a. Distance to the closest MPA for the economics-focused MPAs scenario. **b.** Distance to the closest MPA for the biodiversity-focused MPAs scenario. **c.** Current speed index as the probability to move into an adjacent grid cell within 24 h. **d.** Yearly mean net primary production**. e.** Yearly mean temperature.

Supplementary Table 1. BOATS simulations run to assess whether larval export can offset lost fishing after MPA implementation.

Simulation	Advection	Fishing Strategy	MPA Scenario	Ensemble
1 (spin-up)	Not included	No harvest	None	5
2 (spin-up)	Included	No harvest	None	5
3 (m_0mpa_0oa)	Not included	Open access	None	5
4 (m_1mpa_0oa)	Included	Open access	None	5
5 (m_0mpa_1oa)	Not included	Open access	Economics-focused	5
6 (m_1mpa_1oa)	Included	Open access	Economics-focused	5
7 (m_0mpa_2oa)	Not included	Open access	Biodiversity-focused	5
8 (m_1mpa_2oa)	Included	Open access	Biodiversity-focused	5
9 (m_0mpa_0msy)	Not included	MSY	None	5
10 (m_1mpa_0msy)	Included	MSY	None	5
11 (m_0mpa_1msy)	Not included	MSY	Economics-focused	5
12 (m_1mpa_1msy)	Included	MSY	Economics-focused	5
13 (m_0mpa_2msy)	Not included	MSY	Biodiversity-focused	5
14 (m_1mpa_2msy)	Included	MSY	Biodiversity-focused	5

Supplementary Table 2. Summary of the Generalised Linear Model with Additional Harvest as the response.

	Estimate	T Value	Statistic	P Value
(Intercept)	-1.883	0.047	-40.016	< 0.0001
ns(moveInd, DF)1	0.315	0.024	12.878	< 0.0001
ns(moveInd, DF)2	0.512	0.024	21.157	< 0.0001
ns(moveInd, DF)3	0.807	0.058	14.028	< 0.0001
ns(moveInd, DF)4	0.933	0.036	25.732	< 0.0001
regOpen-Access	1.017	0.056	18.303	< 0.0001
ns(distance, DF)1	-3.515	0.032	-108.388	< 0.0001
ns(distance, DF)2	-2.117	0.029	-73.022	< 0.0001
ns(distance, DF)3	-4.484	0.075	-59.804	< 0.0001
ns(distance, DF)4	-2.221	0.027	-83.369	< 0.0001
ns(npp_ed, DF)1	-0.108	0.032	-3.401	0.001
ns(npp_ed, DF)2	0.867	0.041	21.325	< 0.0001
ns(npp_ed, DF)3	1.664	0.075	22.212	< 0.0001
ns(npp_ed, DF)4	2.497	0.072	34.559	< 0.0001
ns(temp, DF)1	0.925	0.023	41.024	< 0.0001
ns(temp, DF)2	0.145	0.018	7.917	< 0.0001
ns(temp, DF)3	-0.323	0.042	-7.686	< 0.0001
ns(temp, DF)4	0.135	0.017	7.887	< 0.0001
mpabiodiversity	0.044	0.006	6.911	< 0.0001
regOpen-Access:ns(distance, DF)1	-1.239	0.045	-27.331	< 0.0001
regOpen-Access:ns(distance, DF)2	-0.845	0.041	-20.781	< 0.0001
regOpen-Access:ns(distance, DF)3	-1.021	0.105	-9.722	< 0.0001
regOpen-Access:ns(distance, DF)4	-0.994	0.037	-26.577	< 0.0001
regOpen-Access:ns(npp_ed, DF)1	0.029	0.033	0.869	0.385
regOpen-Access:ns(npp_ed, DF)2	1.201	0.054	22.043	< 0.0001
regOpen-Access:ns(npp_ed, DF)3	0.436	0.09	4.845	< 0.0001
regOpen-Access:ns(npp_ed, DF)4	0.209	0.1	2.081	0.037

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