Impacts of climate change on marine ecosystem production in fisheries-dependent societies

The size-structured ecosystem model explicitly links primary production to fish production through predation[1]. The model incorporates two coupled size-structured functional groups that have distinct trophic properties: 'pelagic predators' and 'benthic detritivores'. Temperature acts on the feeding and intrinsic mortality rates of organisms in both communities. In the fishing scenarios fishing mortality was only applied to the pelagic community where fishing mortality rates F were equal across all sizes > 1.25 g.

A. Model Equations and Parameters[1]

Table S1. Equations for the dynamic coupled size-spectrum model.

Subscripts: P = pelagic predators, B = benthic detritivores and D=detritus.

Equations	Units
Dynamical system:	
$$\frac{\partial N_P}{\partial t} = -\frac{\partial}{\partial m}(G_P N_P) - D_P N_P$$	m^{-3} yr^{-1}g^{-1}
$$\frac{\partial N_B}{\partial t} = -\frac{\partial}{\partial m}(G_B N_B) - D_B N_B$$	m^{-3} yr^{-1}g^{-1}
Temperature effect:	
$$\tau = e^{c1 - E/(kT)}$$	
Feeding rates result from allometric search rates, prey size preference and availability across the size spectra:	
$$F_{Pi}(m,t) = \tau \omega_i A_P m^{\alpha_P} \int \phi(m/m') N_i(m',t) m' dm'$$	g yr^{-1}
$$F_B(m,t) = \tau A_B m^{\alpha_B} B_D(t)$$	
give growth rates:	
	g yr^{-1}
$$G_P(m,t) = K_P f_{PP}(m,t) + K_B f_{PB}(m,t)$$ $$G_B(m,t) = K_B f_B(m,t)$$	

Flux terms from death included:

Predation mortality yr^{-1}

$$D_{iP}(m,t) = \omega_i \, A_P \int m'^{\alpha_P} \, \varphi(m'/m) \, N_P(m',t) \, dm' \qquad \text{yr}^{-1}$$

Intrinsic and senescence mortality

$$D_{iO}(m) = \tau 0.2 m^{-0.25} + 0.2\left(m/m_s\right)^{0.3}$$

Fishing mortality yr^{-1}

$$F(m) = \begin{cases} F \, , \, m > 1.25 \\ 0 \, , \, \text{otherwise} \end{cases}$$

yr^{-1}

Total death rates were:

$$D_i(m,t) = D_{iP}(m,t) + D_{iO}(m) + F(m)$$

Table S2. Parameter definitions, values and units for the dynamic coupled size spectrum model. In cases where two values are given the first value is for pelagic predators and the second value is for benthic detritivores.

Symbol	Definition	Value	Unit
m_{min}	minimum body mass of plankton	10^{-12}	g
$m_{P,min}$	minimum body mass of pelagic predators (also of max body size of plankton)	10^{-3}	g
$m_{B,min}$	minimum body mass of benthic detritivores	$10^{-3.5}$	g
m_{max}	maximum body size in the whole system.	10^{6}	g
k	Boltzmann constant	8.62E-5	eV K^{-1}
E	activation energy	0.63	eV
$c1$	Constant	25.55	
ω	preference for prey in either the pelagic or benthic spectrum	0.5	
β	preferred predator-prey mass ratio log10(PPMR)	2.0	
σ	measure of the width of the log10 PPMR distribution	1.0	
A	pre-factor of search volume	64, 6.4	$\text{m}^3 \, \text{yr}^{-1}$
a	exponent of search volume	0.82, 0.75	
K	net growth conversion efficiency	0.2, 0.1	
z_0	pre-factor for background mortality	0.1	yr^{-1}
z_i	exponent for intrinsic background mortality	-0.25	g yr^{-1}
m_s	start size for senescence mortality	1	kg
z_s	exponent for senescence background mortality	0.3	g yr^{-1}

B. Model application and output

The model was applied to each EEZ included in the analysis using time series of outputs from a coupled physical-biogeochemical model, POLCOMS-ERSEM, combined with the dynamical processes driving growth and predation of the pelagic predators and benthic detritivores (Table S1). This framework was applied to 11 coastal and shelf sea regions, covering 30 Large Marine Ecosystems (Table S1) and including 67 marine national Exclusive Economic Zones (EEZ). The model was applied to all EEZ using the same parameter values, such that only the forcing variables differed among EEZ. For each EEZ and scenario, the model was first run to equilibrium using time-averaged input before applying the model to time-varying environmental conditions for the duration of a 10-year time slice, under each of the scenarios.

Temporal changes in the intercept of the plankton component of size-spectrum were estimated from phytoplankton and microzooplankton biomass density from POLCOMS-ERSEM. The plankton size spectrum is described as log $N(m) = a + b$log(m) where N is abundance density per unit volume at mass, and mass is m (in grams). The intercept a of the size spectrum is determined by the temporal changes in phytoplankton and microzooplankton biomass density predicted by the POLCOMS-ERSEM models, with the consequences that higher primary production leads to size spectra with higher intercepts. Phytoplankton and microzooplankton functional groups in ERSEM are assumed to occupy size ranges. We allocated the functional groups to their relevant size ranges and combined the biomass densities of phytoplankton and microzooplankton. Assuming invariant biomass in body mass log bins and a -1 numerical density slope[2] across a size range of 10^{-14} to 10^{-4} g, we estimated the intercept. Recent work has shown that size spectrum dynamics can be influenced by the variation in intercepts, slopes and the size range of phytoplankton[3]. Our results may therefore be sensitive to these simplifying assumptions.

Other time-varying model inputs were near sea floor detritus biomass density estimates. Temperature inputs also varied in time and estimates were taken from the mixed layer depth and near sea floor vertical layers and applied to the feeding and intrinsic mortality rates for the pelagic predators and benthic detritivores, respectively.

Since temperature acts on the feeding and intrinsic mortality rates of organisms in this model, temperature affects absolute rates of biomass flux but does not affect the relative biomass at size in either community. Consequently, size spectrum slopes do not change as a function of temperature, consistent with the empirical observation that slopes are similar in environments ranging from the poles to the tropics[4]. Similarly, trophic transfer efficiency (TE) is not affected by temperature, because this depends on the exponent of the search volume *a,* the preferred predator-prey mass ratio *β*, the width of the distribution of prey mass *σ* and the net growth conversion efficiency *K*, all of which are not affected by temperature. The absence of modelled temperature effects on these parameters is consistent with the empirical observation that realized predator–prey mass ratios in fish communities do not vary systematically with temperature in the world's oceans[5] and that estimates of TE from studies of individual systems do not vary systematically with temperature[6].

In the 'pelagic predators' functional group, trophic level at size will be determined by the predator-prey mass ratio. Since *β* was assumed not to vary with temperature, consistent with an analysis of realised predator-prey mass ratios[5], the trophic level at size relationship does not vary with temperature. The 'benthic detritivores' share energy from a common pool and consequently they are assumed to feed at the same trophic level.

The total biomass density (g m^{-3}) across a size-range (m1 to m2) was computed from the numerical density at size *N(m)* at time across the body mass spectrum as[1]:

$$\int_{m1}^{m2} N(m)\, m\, dm \qquad (1)$$

The total annual catch (or 'yield', in g m^{-3} yr^{-1}) across a size-range was calculated by combining (1) with the fishing mortality rate at size $F(m)$:

$$\int_{m1}^{m2} F(m)N(m)m\,dm \qquad\qquad (2)$$

Table S3. Large Marine Ecosystems (LME, www.lme.noaa.gov) included in the analysis, with information on the primary production, surface area and 2005 fish catches. These LMEs contributed ca. 77% of the catch from all LMEs combined, and 60% of the global marine catches (data from www.seaaroundus.org).

LME	PP (mgC.m^{-2}.d^{-1})	Area (10^3.km^2)	Fish Catch 2005 (t)
East China Sea	891	1,008	3,329,876
Yellow Sea	1,613	439	2,063,739
Humboldt Current	876	2,619	9,855,464
Bay of Bengal	729	3,657	3,818,679
South China Sea	477	5,662,985	6,606,620
Sulu-Celebes Sea	573	1,016	1,111,075
Indonesian Sea	772	2,289,597	1,609,263
North Sea	1,115	690,041	1,885,726
Celtic Biscay Shelf	956	766,550	1,086,603
Canary Current	1,196	1,120	2,077,314
Norwegian Shelf	491	1,109	1,341,406
Benguela Current	1,387	1,470	1,095,408
Icelandic Shelf	551	521,237	1,312,248
Greenland Sea	477	1,176	127,504
California Current	613	2,225	728,988
Gulf of California	1,199	216	195,308
Newfoundland- Labrador	809	675	354,768
NE US Continental Shelf	1,536	308	741,834
Baltic Sea	1,910	397	702,404
Guinea Current	980	1,959	859,111
Gulf of Thailand	780	391,665	862,066
Kuroshio Current	422	1,333,074	612,605
Okhotsk Sea	815	1,627	2,662,794
Faroe Plateau	422	151	316,817
Iberian Coastal	758	301	299,644
Oyashio Region	716	664	584,048
Scotia Shelf	1,395	413	351,017
Sea of Japan/ East Sea	604	1,054	1,166,937
East Bering Sea	782	1,194	1,627,509
West Bering Sea	586	2,183	1,185,440

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- ## **Supplementary information 2: Fisheries dependency methodology**

To determine the relative 'fisheries dependency' of countries we developed three indicators to generate a score for the relative importance of fisheries in each of the 58 countries considered. Fisheries contribute to economies and societies by creating employment, adding economic value and contributing to food security[1-3]. To develop an index that would consider these three contributions we normalized each variable (i.e. employment in fisheries industries, value of fish landings, and animal protein supply), according to the relevant national scales (i.e. total economic active population, GDP and total animal protein supply, respectively).

	Indicator	Year and source of data
Employment dependency	People working in marine fisheries (including indirect employment) (A) as % of total economic active population (B)	A[3]: baseline 2003 A[4]: variable >2000 B[5]: Average 2002-2006
Economic dependency	Value of marine fish landings (C) as % of GDP (D)	C[6]: Average 2002-2006 D[7]: Average 2002-2006.
Food security dependency	fish protein intake (E)/ total animal protein intake (F) _____ total animal protein intake/required animal prot. intake (G)	E[4]: Average 2002-2006 F[4]: Average 2002-2006 G[8]: not applicable

For each indicator the resulting values were indexed providing a score of the countries´ relative dependence on fisheries in terms of employment, economy and food security. The overall dependency score was determined by taking the average of the three indexed scores.

We produced relative rather than absolute values because the accuracy of data derived from government and/or FAO sourced fisheries statistics is not sufficiently high to justify absolute dependency figures. Had this been possible we could have use potential changes in marine catches (our index of exposure to climate change) to calculate changes incurred in fisheries contributions to employment, economy and food security. The difficulty in using absolute figures, especially with regard to small scale fisheries, has been pointed out before (e.g.[3,9]). In

the context of high data uncertainty, using relative dependency scores is therefore more appropriate.

Detailed notes per indicator

Fisheries Employment

There is a notorious lack of sophisticated data on fisheries related employment. Available databases are either relying on data provided by member countries (e.g.[4,7]) which typically leads to an underestimation of employment, or are based on extrapolations of coastal populations[3,10]. Teh and Sumaila (2013) compensate for the underestimation of small scale fisheries, but their data appear to overestimate employment by up to an order of magnitude if comparing to some detailed country studies[12], and occasionally exceeds the total economically-active population (e.g. Guinee-Bissau). We therefore decided to take the average value of the FAO country profile data (low estimate) and the data by Teh and Sumaila (2013) (high estimate).

Value of marine landings

Marine fish landings were derived from the online EEZ database provided by the Sea Around Us project (http://www.seaaroundus.org). Average values for the period 2002-2006 were used, to counter interannual variability. We included the total value of all marine fish production taken from EEZs considered, including any fish taken by foreign fleets, assuming that these foreign fleet generally (but not always) provide financial compensation to their host countries. As climate change projections were based on the EEZ territories belonging to the mainland of a country, overseas territories were excluded.

Food security

The contribution of fisheries to food security was calculated following the methodology used by Hughes et al (2012)[11]. In the context of this paper, a country can be considered highly dependent on marine fisheries in terms of food security, if a high proportion of its animal protein intake is derived from fish ánd if animal protein consumption is low compared to a reference

point (indicating an overall inadequate diet). We consider that animal protein provides a good proxy for sources of important dietary fatty acids, such as omega 3 and omega 6.

$$Dep(FS) = \frac{\text{importance of fish consumption to animal protein intake}}{\text{Animal protein intake relative to threshold}}$$

$$Dep(FS) = \frac{\text{fish protein intake/total animal protein intake}}{\text{total animal proteinintake/required animal protein intake}}$$

For fish protein intake and total animal protein intake, the 2002-2006 average was derived from FAO food balance sheets[4]. We used a minimum requirement of 36gr animal protein per capita day for an average adult (Akpan et al., 2013).

There are two limitations to this calculation. The first is that FAO food balance sheets calculate apparent fish consumption on the basis of fish availability for food consumption, which is the result of total fish production, minus production not used for direct food consumption, minus fish exports plus imports. The FAO balance sheets tend to heavily underestimate fish landings of small scale fisheries in developing countries[12] resulting in an underestimation of fish availability, and consumption by the poor, leading to under-estimates of fisheries dependency in countries with substantial artisanal fisheries. The second problem is that we cannot specify the specific contribution of the EEZ to a countries food security but rather rely on total consumption (which includes imports and aquaculture production). In the future it should be possible to assess the importance of fisheries in the adjacent EEZ to food security in a particular country by collecting disaggregated data for fish exports by source (marine, inland, aquaculture).

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