Supplementary Information for

Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change

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28 **Supplementary Methods**

29 **Ecosystem model selection**. We used six published and peer-reviewed global fisheries and

30 marine ecosystem models (MEMs) that participated in the first round of the Fisheries and Marine

31 Ecosystem Model Intercomparison Project (Fish-MIP, Table S1, 1-11). These six MEMs varied

32 considerably in basic model structure and underlying assumptions, taxonomic scope and key

33 ecological processes included, and their representation of species, functional groups, size classes

34 and the proportion of commercial to non-commercial taxa (Tables S1 and S2). Together, this

35 heterogeneity reflects the diversity of model structures, parameterizations, scopes and purposes,

36 meaning that our ensemble is more likely to include a greater number of relevant processes in the

37 ocean than any single model.

38   The MEMs also varied in their representation of fishing, with some models only

39 representing an unfished ocean (Macroecological) while others were able to incorporate fishing

40 effort (BOATS, EcoOcean) or fishing mortality (DBEM, DPBM, APECOSM) as forcing

41 variables, but so far only few models can incorporate feedbacks from the biological to social and

42 economic systems. For example, BOATS uses an interactive bioeconomic model to determine

43 spatial and temporal changes in fishing effort (2, 3), and EcoOcean uses a spatially-explicit

44 fishing dynamics model to simulate spatial patterns of imposed fishing effort (7). Due to these

45 inherent differences, we could not standardize fishing scenarios across MEMs and therefore

46 assessed the climate-change effect in an unfished compared to a fished ocean in a subset of

47 MEMs (see below).

48   In addition to our own empirical model validation (see below), the performance of

49 individual MEMs has been previously compared with various observed spatial or temporal catch

50 or biomass data (Fig. S3), and with ecological data from observations or experiments at different

stages of model development. Model outputs from BOATS were compared to global historical

time series of catch data from the Sea Around Us Project (SAUP, http://www.seaaroundus.org/),

including unreported catches, and trends in the biomass of assessed stocks relative to their

unexploited biomass (B/B_0) from the RAM Legacy stock assessment database

(http://ramlegacy.org/) (2, 3, Fig. S3A and B). Moreover, parameter sensitivity was extensively

tested with temperature and NPP to optimize the model's ability to reproduce historical patterns

of fish catch from SAUP and RAM (12). Model outputs from EcoOcean were compared to

historic time series of catch data from SAUP (7, Fig. S3C), and to catches for major functional

groups and large marine ecosystems (LMEs) from SAUP in the 1950s (not shown) and 2000s

(shown in Fig. S3D; 7). For DBEM, the mean state projected catch potential among large marine

ecosystems (LMEs) was significantly correlated with observed catch data from SAUP (Fig.

S3E), and this was robust to different underlying calculations for the carrying capacity of each

grid cell (13). Also, the rate of range shifts projected by DBEM correlated significantly with

observed range shifts in the North Sea and Bering Sea (13), and the predicted growth and body

size parameters (that contribute to the calculation of biomass and catch potential) were also well

correlated with observations (13). Moreover, the sensitivity of the model outputs was tested with

different ocean variables, with temperature being the main driver, followed by NPP and then

oxygen, particularly in tropical ecosystems (14). For DPBM, previous work at the scale of

regional seas (5) compared modelled catches (based on a fishing mortality rate of 0.8 yr^{-1} that

produced maximum equilibrium catches) to reported landings (excluding discards) from the

Food and Agriculture Organization (FAO) in 11 regional domains based on 78 Exclusive

Economic Zones (EEZ) (Fig. S3F). Additionally, modelled fish and benthic community size

spectra and species averaged size-specific growth rates were consistent with previous empirical

74   observations for EEZs and in the North Sea (5, 15). Model outputs from APECOSM were

75   compared to biological observations at all stages of model development (e.g. growth,

76   ingestion/assimilation, reproductive outputs, maintenance, development, size at maturity, aging

77   mortality; 16). Vertical distributions in APECOSM were assessed using acoustic observations

78   (using data in 17), and horizontal and size-distributions using fisheries data for large sizes (18)

79   and MAREDAT for small ones (19). Also, observed and predicted catches were compared for

80   skipjack tuna fisheries in Indian Ocean across different schools with good correlation (18, Fig.

81   S3G). The Macroecological model (4) exclusively represents an unexploited ocean and can

82   therefore not be compared to observed global catch or biomass data; however, comparisons

83   could be done for some regions, such as the North Sea, where very comprehensive biomass data

84   exist for non-fished as well as fished species. Here, the median predicted biomass estimate for

85   fish size classes >100g was 8.3 million tonnes, which compared well with detailed empirical

86   estimates of 8.6-13.1, 10.0, 3.8-7.5 million tonnes from 3 independent studies (4). Moreover,

87   almost all parameterization in the Macroecological model was based on empirical analysis and

88   the underlying functional processes are well supported by many empirical and experimental

89   studies (4).

90

91   **Climate-change scenarios**. All MEMs were forced with the same standardized set of outputs

92   from Earth-system models (ESMs) derived from the Coupled Model Inter-comparison Project

93   Phase 5 (CMIP5 database: http://cmip-pcmdi.llnl.gov/cmip5/). We selected NOAA's

94   Geophysical Fluid Dynamics Laboratory Climate Model (GFDL-ESM2M, 20) and the Institute

95   Pierre Simon Laplace Climate Model (IPSL-CM5A-LR, 21) because they generated all

96   necessary physical and biogeochemical outputs needed to run our global marine MEMs,

97   particularly the monthly depth-resolved biogeochemical fields of different size groups of

98   phytoplankton and zooplankton concentration and productivity (1). While several other ESMs

99   are available in CMIP5, they did not generate or save all variables required by our MEMs. The

100   two selected ESMs spanned the range of projections from all CMIP5 models with GFDL-

101   ESM2M being at the lower end and IPSL-CM5A-LR at the higher end of projected future

102   changes in SST and NPP (Fig. S1), while other variables, including phytoplankton and

103   zooplankton biomass (Fig. S2) as well as pH and O_2 concentrations were more similar among all

104   CMIP5 models (22). Therefore, global annual mean trends of these two ESMs should reflect the

105   multi-model mean and range of a broad set of CMIP5 models (1, 22).

106   Each ESM was run for each of four Representative Concentration Pathways (RCPs)

107   representing a standard set of IPCC informed emission scenarios, ensuring that starting

108   conditions, historical trends, and projections are consistent across models and sectors. RCP2.6

109   represents a strong mitigation scenario characterized by an emission pathway leading to very low

110   greenhouse gas (GHG) levels by 2100 (23). RCP4.5 and RCP6.0 represent stabilization emission

111   scenarios, requiring a stabilization in radiative forcing after 2100, without exceeding the target

112   value of 4.5 W m^{-2} for RCP4.5 and 6.0 W m^{-2} for RCP6.0 (24). RCP8.5 represents a business-as-

113   usual scenario characterized by increasing GHG emissions over time leading to high GHG

114   emissions in 2100 (25).

115

116   **Standardized model inputs and outputs**. The fundamental goal of Fish-MIP is to compare the

117   response of a wide range of MEMs to common external forcings, namely standardized climate-

118   change scenarios. Standardized physical and biogeochemical variables from the 2 ESMs and 4

119   RCPs were derived on a 1×1-degree global grid for a historical (1970-2005) and a future period

120   (2006-2100) to be used as climate input data in our MEMs (Table S2). Physical variables

121   included current velocities, water temperature, salinity, dissolved oxygen concentration, pH,

122   mixed-layer depth and ice coverage. Biogeochemical variables included large and small

123   phytoplankton and zooplankton concentrations and productivity. All variables were summarized

124   as monthly, depth-resolved values and then further aggregated or integrated to suit the input

125   requirements for each MEM, such as providing values for surface, bottom or depth-integrated

126   layers (Table S2). For more details on input variable selection and requirements of each

127   ecosystem model see ref. (1).

128   First, we used a no-fishing scenario across all six MEMs to isolate the climate-change effect

129   on fish or animal biomass. In a subset of three MEMs we also used a simple fishing scenario

130   based on observed or estimated time-varying data on fishing effort, mortality or exploitation

131   rates (depending on model requirements) for the historical period (1970-2005) and then kept

132   constant at 2005 levels for the future period (2005-2100) (1). Thereby, each model relied on its

133   own mechanism for incorporating fishing data (1). Dynamic projections of future fishing

134   pressure were not used because appropriate temporally- and spatially-explicit scenarios of future

135   fishing pressure are not yet available (1), although we do acknowledge that fishing pressure will

136   change over the projection period. Recently, future fishing scenarios have been developed

137   conceptually based on the IPCC's Shared Socio-economic Pathways (SSPs) (26). Once

138   translated into quantitative form, these should be available for future efforts to project changes in

139   fish and fisheries.

140   All MEMs were required to produce a set of standardized outputs that could be directly

141   compared and combined into ensemble projections (1). For this study, we selected three outputs:

142   (i) total consumer biomass density (g C m^{-2}) representing all animals, size classes or trophic

143 groups in each model, (ii) biomass density of all animals, size classes or trophic groups >10 cm

144 (g C m^{-2}), and (iii) biomass density of all animals, size classes or trophic groups >30 cm (g C m^{-2}

145). Since the taxonomic scope differs among models, we used the terms 'total animal biomass',

146 'animals >10 cm' and 'animals >30 cm', respectively, for simplification. All data reported in this

147 paper are archived and publicly available at http://doi.org/10.5880/PIK.2018.005.

148

149 **Simulations**. Several limitations resulted in not all MEMs being able to run the full set of 16

150 simulations from 2 ESMs, 4 RCPs and 2 fishing scenarios for total animal biomass, biomass of

151 animals >10 cm and >30 cm. We therefore decided to use comparable subsets of available

152 MEM-ESM combinations to answer different questions. ESM limitations included the

153 unavailable monthly, depth- and size-resolved biogeochemical data in GFDL-ESM2M (not run

154 in APECOSM, DPBM); MEM limitations included substantial simulation run time in some

155 MEMs (e.g. DBEM did not run all RCPs; DPBM and APECOSM did not perform fishing runs),

156 the lack of size class differentiation (e.g. DBEM), and the inability to incorporate fishing (e.g.

157 Macroecological). Therefore, all six MEMs used the IPSL-CM5A-LR no-fishing runs and four

158 used the GFDL-ESM2M no-fishing runs for RCP2.6 and 8.5 (n = 10), and five and three MEMs,

159 respectively, for RCP4.5 and 6.0 (n = 8; Table S3). A subset of three MEMs (BOATS,

160 EcoOcean, DBEM) was used for fishing runs with inputs from both ESMs for RCP2.6 and 8.5 (n

161 = 6). All six MEMs projected total animal biomass, and five MEMs animal biomass >10 cm and

162 >30 cm (Table S3). However, since DBEM represents all commercial fish and invertebrate

163 species covering the full size spectrum, we used DBEM outputs for all three size groups, but

164 cross-checked results with and without DBEM as a sensitivity analysis.

165

166 **Analyses and model validation**. Because the six MEMs include different species, size classes

167 and trophic groups, their output for absolute biomass density varied across models. We therefore

168 calculated time series of relative change in animal biomass defined as percent (%) relative to

169 1990-99 for each simulation. This reference period was chosen as representing the last decade of

170 the 20th century, which was later compared to 2090-99 as the last decade of the 21st century.

171 The different time series of relative change were then averaged into a multi-model mean

172 change, and variability among models was described with the standard deviation (SD) around the

173 mean (Fig. 1*A*, Fig. S5) as well as with box and whisker plots (Fig. 1*C*). To summarize the

174 results across simulations and size groups, we also calculated the % change in 2090-99 relative

175 to 1990-99 (Table S3).

176 Given the differences in MEM structure and characterization of fishing (see above) we could

177 not standardize the fishing scenarios and did not compare the magnitude of the fishing effects

178 across models. Instead we compared the relative difference in the climate effect (RCP8.5 vs RCP

179 2.6) in a fished and an unfished ocean. To do so, we calculated ((RCP8.5-RCP2.6)/RCP2.6)

180 within each MEM in the 2090s and over time which was then compared across MEMs (Fig. 1*D*,

181 Fig. S6*A*).

182 Next, we compared the variability of results due to the different ESMs and MEMs (Fig. 1*E*).

183 For ESM variability, we calculated the standard deviation for individual MEM results for

184 simulations run with the IPSL-CM5A-LR compared to the GFDL-ESM2M (for all MEMs run

185 with both forcings, n = 4). For MEM variability, we calculated the standard deviation of results

186 across all MEMs for IPSL-CM5A-LR (n = 6) and GFDL-ESM2M (n = 4) which were then

187 combined. These calculations were performed separately for the different RCPs and size groups

188 in an unfished ocean (Fig. 1*E*).

189   To validate our ensemble model projections with empirical data, we compared our multi-

190   model mean historical biomass trend of animals >10cm (for better comparison with assessed fish

191   stocks) with biomass trends of assessed fish stocks in (i) a fished and (ii) an unfished situation

192   from 1970-2005. For the fished situation, we compared our multi-model mean of all MEM-ESM

193   combination with fishing (n = 6) to the observed biomass of assessed exploited fish stocks

194   relative to their biomass at MSY (B/B_{MSY}) from a database of 331 stocks from ref (27) (Fig. S4).

195   For the unfished situation, we compared our multi-model mean of all MEM-ESM combination

196   without fishing (n = 10) to the temperature-dependent hindcasts of maximum sustainable yield

197   (MSY) for 235 stocks from ref (28) that are independent of the effects of fishing (Fig. 2). In

198   addition to displaying the corresponding temporal trends, we also calculated linear regressions of

199   projected biomass vs MSY in corresponding years, and found that the models explain a large

200   fraction of the observed variance without fishing (R^2 = 0.44, Fig. 2) and an even larger fraction

201   with fishing (R^2 = 0.96, Fig. S4). Importantly the linear regression fits with the ensemble mean

202   were generally better than those with individual MEM-ESM combinations, with R^2 ranging from

203   0.13-0.43 without fishing (except for BOATS-IPSL, R^2 = 0.47) and from 0.80-0.94 with fishing.

204   This suggests that the ensemble mean is generally better at representing empirical observations

205   than all but one individual MEMs.

206   To compare the magnitude of biomass declines across trophic levels and evaluate a trophic

207   amplification effect (29), we calculated the mean and standard deviation of the relative change

208   (2090s vs 1990s) in net primary production (NPP), total phytoplankton and total zooplankton

209   biomass (both small and large) across the 2 ESMs (n = 2) for each of the 4 RCPs. We then

210   compared these mean biomass changes to those for higher trophic levels (Fig. 3) represented by

211   total animal biomass (which does not include zooplankton) across all MEM-ESM combinations

212   (n = 10 for RCP2.6 and 8.5, n = 8 for RCP 4.5 and 6.0).

213   To relate the magnitude of change in total animal biomass (Fig. 4) and biomass of animals

214   >10 cm and >30 cm (Fig. S7) to changes in global air temperature since pre-industrial times, we

215   obtained global air temperature timeseries from 1861-2100 for both ESMs from the CMIP5

216   archive. We calculated the average pre-industrial temperature over the period 1861-1870, and

217   then calculated subsequent changes in air temperature relative to this reference period. We then

218   plotted the % change in total global animal biomass vs. the change in global air temperature

219   across the historical and future period including all RCPs in an unfished ocean (Fig. 4). This was

220   repeated for animals >10 cm and >30 cm (Fig. S7). To assess how this relationship might change

221   in a fished ocean, we plotted the difference in % biomass change (RCP8.5 vs RCP2.6) in a fished

222   versus unfished ocean over the difference in global surface air temperature between RCP8.5 vs

223   RCP2.6 in any given year (Fig. S6*B*). The resulting positive relationship shows that as warming

224   increases, the reduction in simulated biomass is slightly less in a fished compared to an unfished

225   ocean.

226   To visualize spatial patterns of change globally, we mapped the relative (%) change in 2090-

227   99 compared to 1990-99 for the multi-model mean and standard deviation of total animal

228   biomass on a 1×1-degree grid across all MEM-ESM-combinations for RCP2.6 and RCP8.5 in an

229   unfished ocean (Fig. 5). We also mapped the multi-model mean +1SD and -1SD (Fig. S8) to

230   visually display the full range of minimum to maximum potential changes. As an additional

231   measure of robustness, we mapped the percentage of MEMs agreeing on the direction of change

232   (22), where 100% means full model agreement and 50% represents an even split. Next, to

233   compare the climate effect in a fished and an unfished ocean spatially (Fig. S9), we mapped the

234   multi-model mean relative difference (%) in biomass change (RCP8.5 vs RCP2.6) in 2090-2099

235   in a fished and in an unfished ocean based on the three MEMs that performed fishing runs

236   (BOATS, DBEM, EcoOcean). To evaluate the spatial variability due to ESM selection in an

237   unfished ocean (Fig. S10), we also mapped the multi-model mean biomass change and standard

238   deviation across all MEMs for the IPSL-CM5A-LR and the GFDL-ESM2M separately. Lastly,

239   we mapped relative changes in total animal biomass for each MEM for IPSL-CM5A-LR and

240   GFDL-ESM2M under RCP2.6 and RCP8.5 in an unfished ocean (Fig. S11).

241

Table S1. Description of the basic features and key references of each of the six global fisheries and marine ecosystem models. For more detail see ref. (1).

Model name	Basic model structure	Taxonomic scope	Key ecological processes	Spatial & temporal resolution	Vertical resolution	Key references
BiOeconomic mArine Trophic Size-spectrum (BOATS)	Size-structure model that uses macroecological theory and empirical metabolic constraints to calculate the production of commercially-harvested fish across multiple size spectra. Directly coupled to a dynamic fisheries economic model at the grid scale.	3 'superspecies' (small, medium, large) defined by their asymptotic mass, with 50 size classes each, representing all commercial fish.	Applies empirical parameterizations to describe phytoplankton community structure, trophic transfer of primary production from phytoplankton to fish, fish growth rates, natural mortality of fish, stock- and environment-dependent recruitment. Animal movement is not included. Predator-prey relationships are not resolved.	1×1-degree grid Monthly mean timestep	None (2-dimensional domain).	2-3
Macroecological Model	Static size-structure model that uses minimal input parameters together with ecological and metabolic scaling theory to calculate mean size composition and abundance of marine animals (including fish).	180 body mass classes, species are not resolved.	Simple characterization of marine ecosystems in terms of body mass distribution and marine animal abundance based on estimates of predator-prey mass ratios, transfer efficiency and changing metabolic demands with body mass and temperature. Animal movement is not included.	1×1-degree grid Annual mean timestep	Single vertical (surface-integrated) layer.	4
Dynamic Pelagic Benthic Model (DPBM)	Dynamic size- and trait-based model that incorporates a pelagic predator size-spectrum with a benthic detritivore size-spectrum.	1 pelagic predator and 1 benthic detritivore size spectrum, with 100 size classes each.	Individual processes of predation, food-dependent growth, natural mortality, and reproduction give rise to emergent size spectra for each functional group (pelagic predator and benthic detritivore).	1×1-degree grid Monthly mean timestep	2 vertical layers (sea surface and sea floor). No vertical transport or movement.	5

|					
Dynamic Bioclimate Envelope Model (DBEM)	Species distribution model based on bioclimatic envelopes (niche) defined for each species. Simulates changes in species abundance and carrying capacity under environmental change. Carrying capacity is a function of the environment and species' habitat preferences.	892 commercial fish and invertebrate species.	Population dynamics are dependent of habitat suitability and movement of adult species driven by a gradient of habitat suitability and population density. Larval dispersal is driven by currents and temperature. Growth, reproduction, and natural mortality are dependent on oxygen, pH, and temperature.	0.5×0.5-degree grid Annual mean ocean conditions	Vertical layers (sea surface and bottom) defined by species niche preferences.	6
EcoOcean	Trophodynamic model based on species interactions and energy transfer across trophic levels. Ecosim-with-Ecopath (EwE) framework designed to evaluate the impacts of fisheries and climate change on marine resources and ecosystems.	51 trophic biomass groups, including all trophic level and taxonomic groups (marine mammals, birds, fish, invertebrates, primary producers and bacteria).	Combines a food web model comprising a mass-balance component (Ecopath; input: biomass, production/biomass ratio, consumption/biomass ratio, diet composition, catches), a temporal dynamic predator-prey component (Ecosim), and a spatio-temporal dynamic component which is a function of grid cell specific habitat attributes i.e. pH, water depth, temperature, and bottom type (Ecospace).	1×1-degree grid Monthly mean timestep	Vertical layers defined by food web interactions and habitat preferences, vertical movement and transportation through establishment of trophic links and generation and consumption of dead organic matter linking pelagic organisms to demersal and benthic organisms.	7-8
Apex Predators ECOSystem Model (APECOSM)	Composite (hybrid) model. 3D dynamic energy budget Eulerian model of size-structured marine populations and communities, based on individual environmentally driven bioenergetics, trophic interactions and behaviors, that are upscaled to populations and communities.	Explicit size-based communities including 3 communities (epipelagic, migratory, mesopelagic); 95 species length classes and 100 size classes.	Size-based predation, food- and temperature-driven growth, reproduction and senescence. Includes environmental impacts on vertical and horizontal movements and schooling.	1×1-degree grid Monthly mean timestep	3D explicit vertical movement considered.	9-11

Table S2. Overview of layer configuration and selected forcing variables used in the marine ecosystem models included in the ensemble projections. Forcing variables were provided by the two Earth-system models GFDL-ESM2M (1×1-degree grid cell, 50 depth levels) and IPSL-CM5A-LR (1×1-degree grid cell, 31 depth levels). Layers included surface, bottom, depth-integrated surface to bottom, or depth resolved, depending on each ecosystem model's requirements. For more detail see ref. (1).

Model name	Depth integration	Current speed	Sea temperature	Dissolved oxygen concentration	NPP - primary organic carbon production	Phytoplankton carbon concentration	Zooplankton carbon concentration	pH	Salinity	Total alkalinity	Ice coverage	Mixed layer depth
BOATS	Integrated over full water column	-	Upper ocean temperature (average of upper 75m)	-	Depth integrated primary production (full water column)	-	-	-	-	-	-	-
Macro-ecological model	Integrated over full water column	-	Sea surface temperature (0-200m)	-	Depth integrated primary production (assumed to be allocated to the mixed layer depth or euphotic depth if deeper)	Large/small phytoplankton	-	-	-	-	-	Areas shallower than mixed layer depth (or euphotic depth if deeper) treated as productive zone
DPBM	2 layers, surface (0-100m) and bottom	-	Sea surface and sea bottom temperature	-	Depth integrated primary production	Large/small phytoplankton	-	-	-	-	-	Mixed layer depth included

DBEM	Vertical dimension dependent on species specific min/max depth limits	Zonal and meridional velocity	Sea surface and sea bottom temperature	Dissolved oxygen included	Depth integrated primary production	Large/small phytoplankton	-	Sea surface pH	Sea surface and sea bottom salinity	-	Ice coverage incl.	-
EcoOcean	Vertical dimension dependent on depth distribution from species/ functional groups	-	Sea surface (150 m)	-	-	Large/small phytoplankton	Large/small zooplankton	-	-	-	Ice coverage included (not floating ice)	-
APECOSM	3D depth-resolved	Zonal, meridional and vertical velocity	Vertically (3D) resolved sea temperature	Dissolved oxygen included	-	Large/small phytoplankton	Large/small zooplankton	pH included	-	Turbulent mixing included	Ice coverage included	-

Table S3. Summary of results across all marine ecosystem models (MEMs), Earth-system models (ESMs), emission scenarios (RCPs) and fishing scenarios. Shown is the projected percent (%) change in biomass in 2090-2099 relative to 1990-1999 for total animal biomass and animals >10 cm and >30 cm. Also shown are the mean, standard deviation (SD), and sample size (n) for the full set of available MEM-ESM combinations (n = 10), a reduced set 1 balancing the two ESMs (n = 8), a reduced set 2 balancing the ESMs and RCPs (n = 6), a reduced set 3 balancing the no-fishing and fishing runs (n = 6), and reduced set 4 with the same as set 3 but without DBEM for comparison (n = 4). Note that for DBEM, which does not differentiate between size groups but represents the full size range of commercial fish and invertebrates, we assumed the same relative biomass changes in all size groups.

| Percent biomass change (2090-2099 relative to 1990-1999)		total		>10cm		>30cm		total		>10cm		>30cm	
		no fishing		no fishing		no fishing		fishing		fishing		fishing	
Model name	RCP	GFDL	IPSL	GFDL	IPSL	GFDL	IPSL	GFDL	IPSL	GFDL	IPSL	GFDL	IPSL
BOATS	2.6	-5.29	-10.26	-5.29	-10.26	-4.54	-9.67	-66.99	-25.62	-66.99	-25.62	-84.66	-69.22
	4.5	-8.68	-17.83	-8.68	-17.83	-8.37	-17.75	-67.26	-31.22	-67.26	-31.22	-84.49	-71.12
	6.0	-9.75	-20.47	-9.75	-20.47	-9.28	-20.48	-67.64	-33.11	-67.64	-33.11	-84.64	-72.15
	8.5	-15.07	-31.68	-15.07	-31.68	-14.59	-32.47	-68.50	-41.15	-68.50	-41.15	-84.74	-74.71
EcoOcean	2.6	0.23	-2.65	0.57	-4.12	3.55	6.25	-0.76	-3.91	2.99	-5.33	-16.90	-20.24
	4.5	0.07	-6.16	1.66	-6.51	4.45	3.93	-0.90	-7.21	4.41	-6.05	-17.11	-21.81
	6.0	0.07	-7.93	1.53	-8.07	5.51	2.20	-0.83	-9.02	4.35	-7.85	-17.83	-24.21
	8.5	-0.73	-13.60	6.41	-8.81	8.18	-5.28	-1.53	-14.20	10.00	-4.62	-19.54	-30.73
Macroecological	2.6	-4.39	-10.44	-4.39	-10.44	-4.39	-10.44						
	4.5	-7.16	-17.12	-7.16	-17.12	-7.16	-17.12						
	6.0	-9.27	-21.17	-9.27	-21.17	-9.27	-21.17						
	8.5	-15.48	-34.31	-15.48	-34.31	-15.48	-34.31						
APECOSM	2.6		-3.25		-3.54		-3.09						
	4.5		-4.88		-4.23		-3.44						
	6.0		-6.70		-6.45		-5.94						
	8.5		-10.74		-9.63		-9.01						
DBPM	2.6		-4.30		-5.08		-3.63						
	4.5		-6.92		-8.76		-7.61						
	6.0		-7.61		-11.18		-10.20						
	8.5		-12.06		-20.61		-21.68						
DBEM	2.6	-1.23	-6.71	-1.23	-6.71	-1.23	-6.71	-2.87	-10.04	-2.87	-10.04	-2.87	-10.04
	8.5	-10.29	-28.48	-10.29	-28.48	-10.29	-28.48	-11.05	-28.56	-11.05	-28.56	-11.05	-28.56
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Full set	n	10		10		10							
all available EM-ESM	2.6	-4.83	3.51	-5.05	3.48	-3.39	5.25						
combinations	4.5	-8.58	6.07	-8.58	6.42	-6.63	8.30						
	6.0	-10.35	7.13	-10.60	7.40	-8.58	9.45						
	8.5	-17.24	10.73	-16.80	12.38	-16.34	13.23						
Reduced set 1	n	8		8		8							
balancing ESMs	2.6	-5.09	3.99	-5.23	4.60	-3.40	24.48						
(without APECOSM	4.5	-9.48	7.33	-9.27	8.18	-7.00	28.21						
and DPBM)	6.0	-11.42	8.53	-11.20	9.78	-8.75	27.92						
	8.5	-18.70	13.37	-17.21	14.15	-16.59	23.00						
Reduced set 2	n	6		6		6							
balancing ESMs & RCPs	2.6	-5.47	4.32	-5.65	5.13	-3.21	29.14						
(without APECOSM,	4.5	-9.48	7.33	-9.27	8.18	-7.00	28.21						
DPBM and DBEM)	6.0	-11.42	8.53	-11.20	9.78	-8.75	27.92						
	8.5	-18.48	14.70	-16.49	15.62	-15.66	27.00						
Reduced set 3	n	6		6		6		6		6		6	
balancing no-fishing	2.6	-4.32	3.87	-4.51	3.88	-2.06	6.11	-18.36	25.47	-17.97	25.89	-33.99	34.15
and fishing runs	8.5	-16.64	11.59	-14.65	13.98	-13.82	15.05	-27.50	24.46	-23.98	28.27	-41.55	30.55
Reduced set 4	n	4		4		4		4		4		4	
set 3 with balanced size	2.6	-4.50	4.46	-4.78	4.45	-1.10	7.32	-24.32	30.52	-23.73	31.24	-47.75	34.31
groups (without DBEM)	8.5	-15.27	12.70	-12.29	15.76	-11.04	17.07	-31.34	29.78	-26.07	35.54	-52.43	32.11
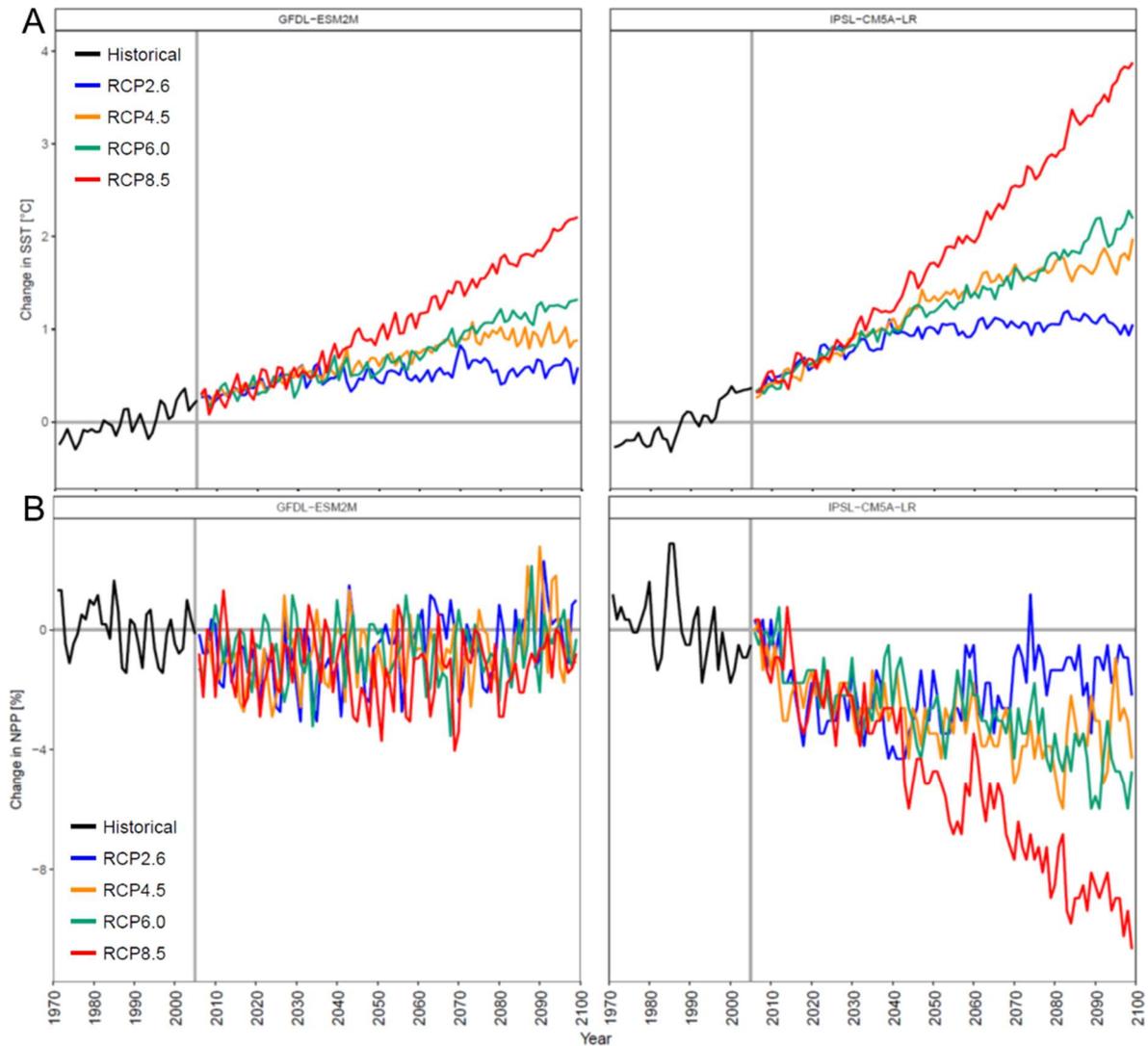
Fig. S1. Annual global change in (*A*) sea surface temperature (SST, ºC) and (*B*) net primary production (NPP, %) relative to the 1990-1999s as projected with GFDL-ESM2M (left) and IPSL-CM5A-LR (right).
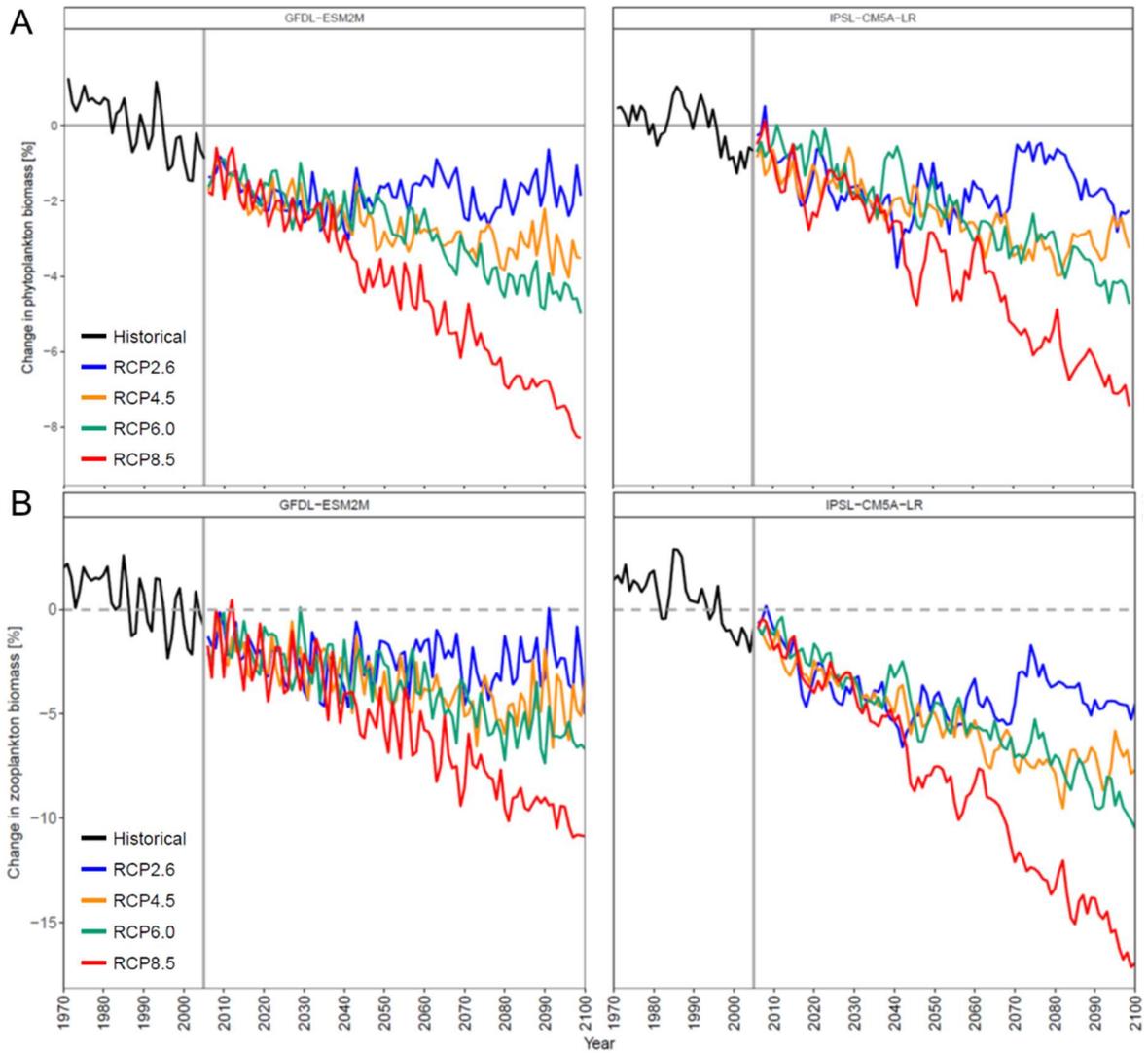
Fig. S2. Annual global change in (*A*) phytoplankton biomass (%) and (*B*) zooplankton biomass (%) relative to the 1990-1999s as projected with GFDL-ESM2M (left) and IPSL-CM5A-LR (right).
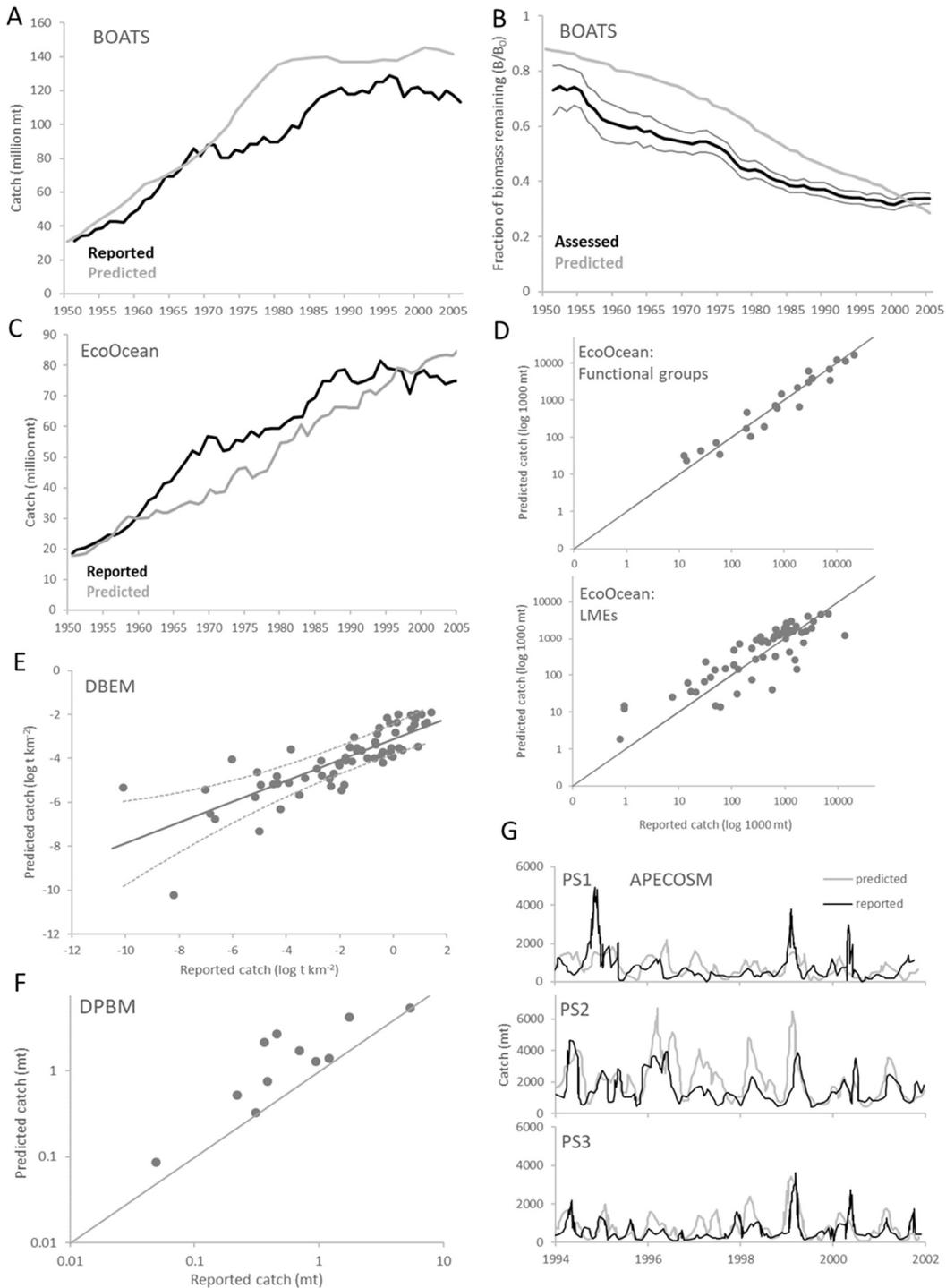
Fig. S3. Comparison of previously published model-predicted and observed data for individual MEMs. BOATS predicted and reported global catch (including unreported catch) from SAUP (*A*) and biomass trends (B/B$_0$) from RAM database (*B*) (2, 3). EcoOcean predicted and reported global catch from SAUP (*C*) and catch by functional groups and LMEs (*D*) (7). DBEM predicted and reported catch by LME from SAUP (*E*) (13). DPBM time-averaged predicted catch and reported landings of 11 regions based on 78 EEZs from FAO (*F*) (5). APECOSM predicted and reported catch of 3 skipjack tuna schools (PS1-3) in the Indian Ocean (*G*) (18). For more detail see *SI Methods*.
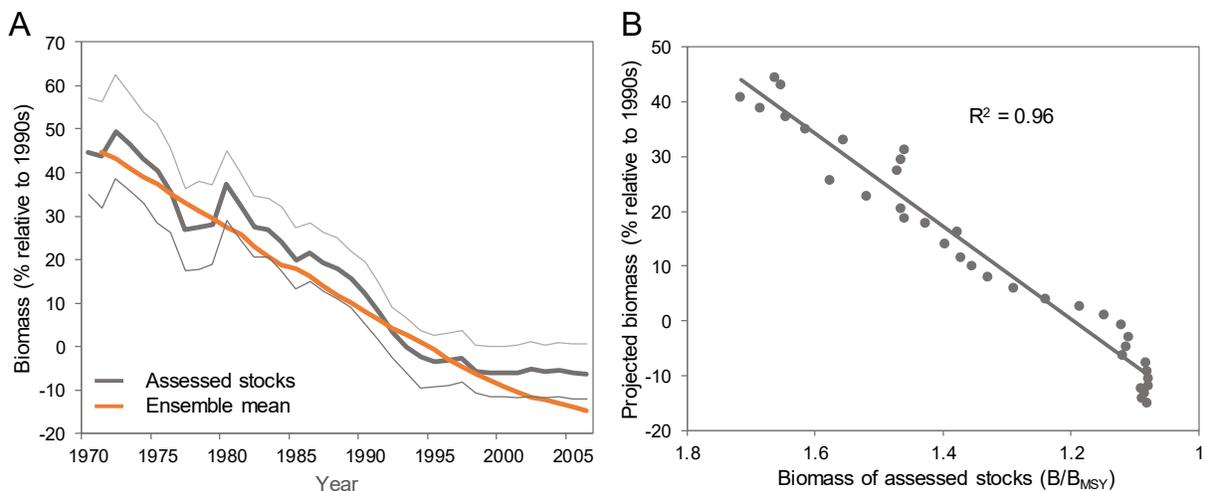
Fig. S4. Empirical validation in a fished ocean. Shown are the historical mean global biomass trends for our multi-model ensemble (orange line, n = 6) with fishing compared with assessed exploited fish stocks (grey lines, ±95% CI) (*A*) and the linear regression fit between the two time series (*B*). The ensemble mean is based on biomass for animals >10 cm and assessed stocks represent the mean exploited biomass (relative to the biomass at maximum sustainable yield, B/B_{MSY}) across 331 stocks (27). The stabilization of biomass since 1995 in assessed stocks is likely representing some successful management efforts for those stocks, which is not included in our global ensemble simulations.
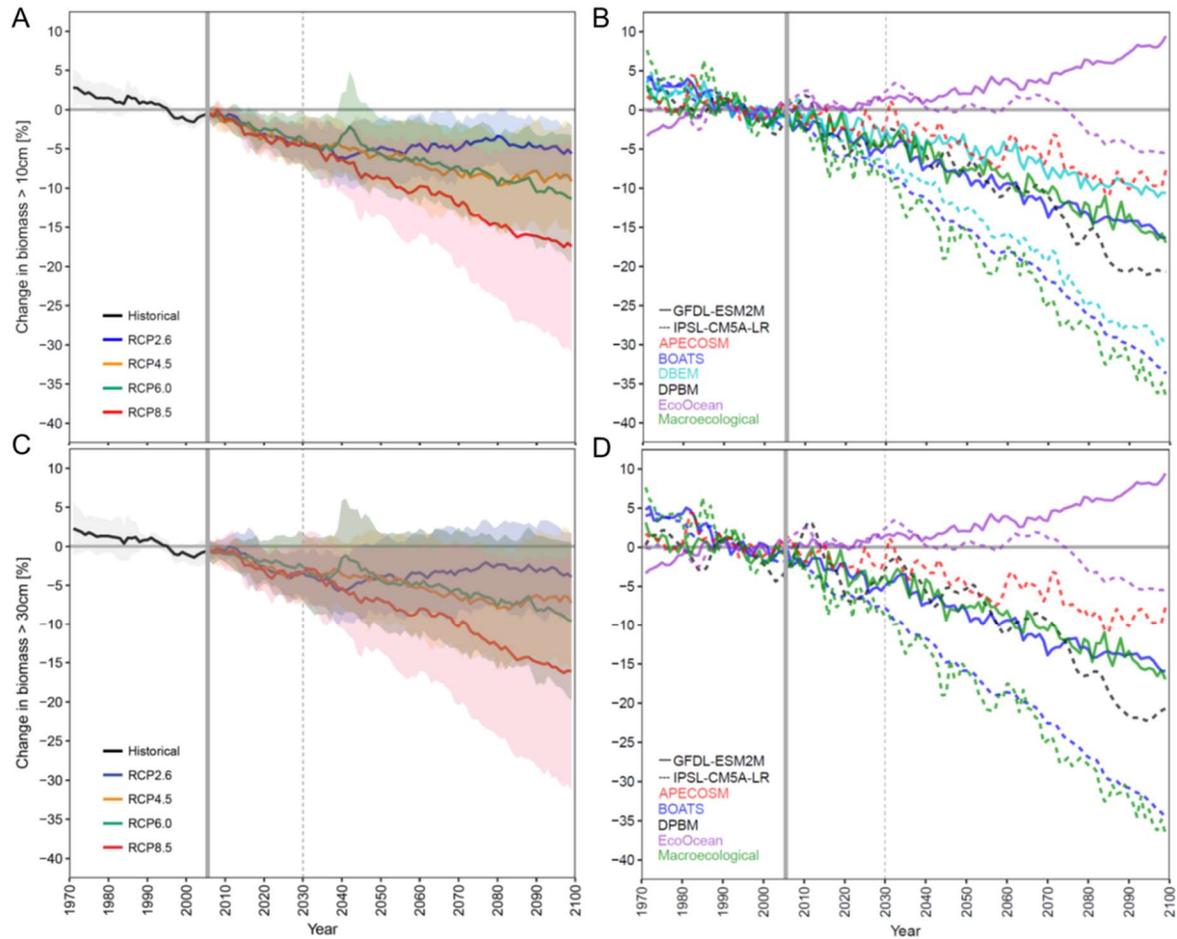
Fig. S5. Ensemble projections of global animal biomass with climate change from 1970-2100 for (*A*) animals >10 cm and (*B*) animals >30 cm. Left panels: Multi-model mean change in biomass for the historical period and four future emission scenarios (RCPs) with one inter-model standard deviation (shading). Right panels: Individual model projections for one emission scenario (RCP8.5) showing the spread across different ecosystem (color code) and ESMs (dashed/solid) combinations. All trends are relative to 1990-1999. The vertical grey line indicates the separation of historical and future projections, the vertical orange line indicates the SDG target year 2030.
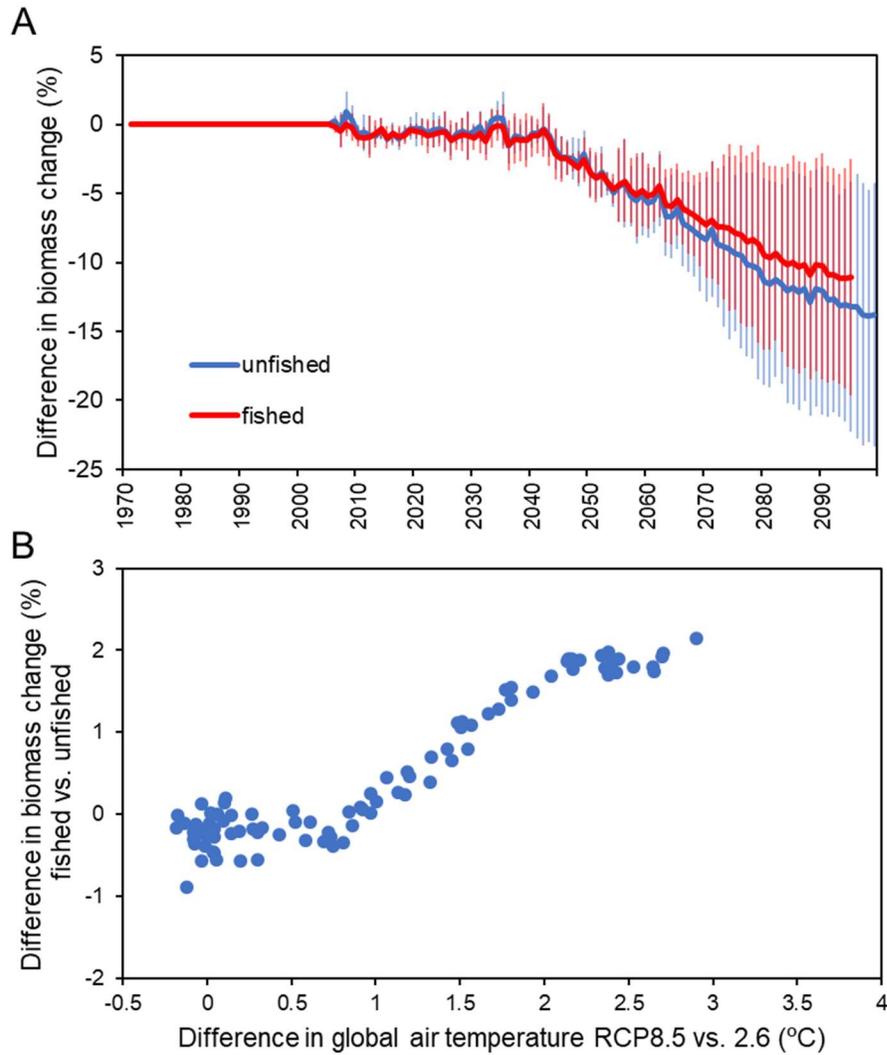
Fig. S6. Comparing projected climate-change effects in a fished and an unfished ocean. (*A*) Mean difference and standard variation in biomass change (%) between RCP8.5 and RCP2.6 in a fished and an unfished ocean over time based on three ecosystem models (BOATS, EcoOcean, DBEM) combined with two ESMs (n = 6). (*B*) Mean difference in biomass change (RCP8.5 vs. 2.6) in fished vs unfished oceans in relation to the differences in global air temperature between RCP8.5 vs. 2.6.
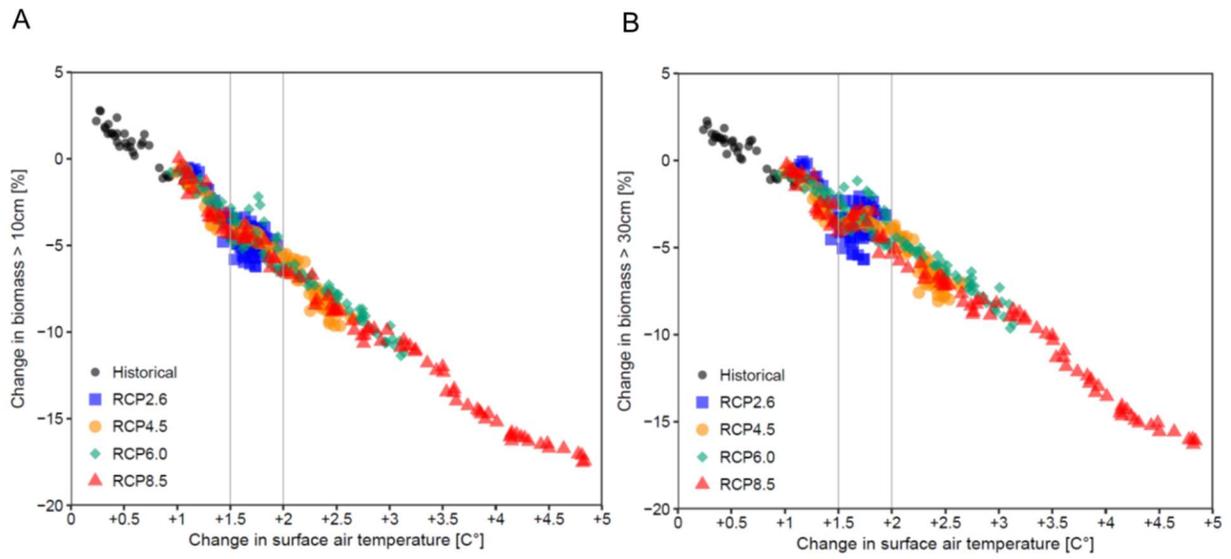
Fig. S7. Relationship between the projected change in (*A*) biomass of animals >10 cm and (*B*) animals >30 cm in the absence of fishing and increases in global air temperature since pre-industrial times (1860s). Changes in biomass are relative to the 1990s. The vertical lines frame the difference between 1.5 °C and 2 °C warming.
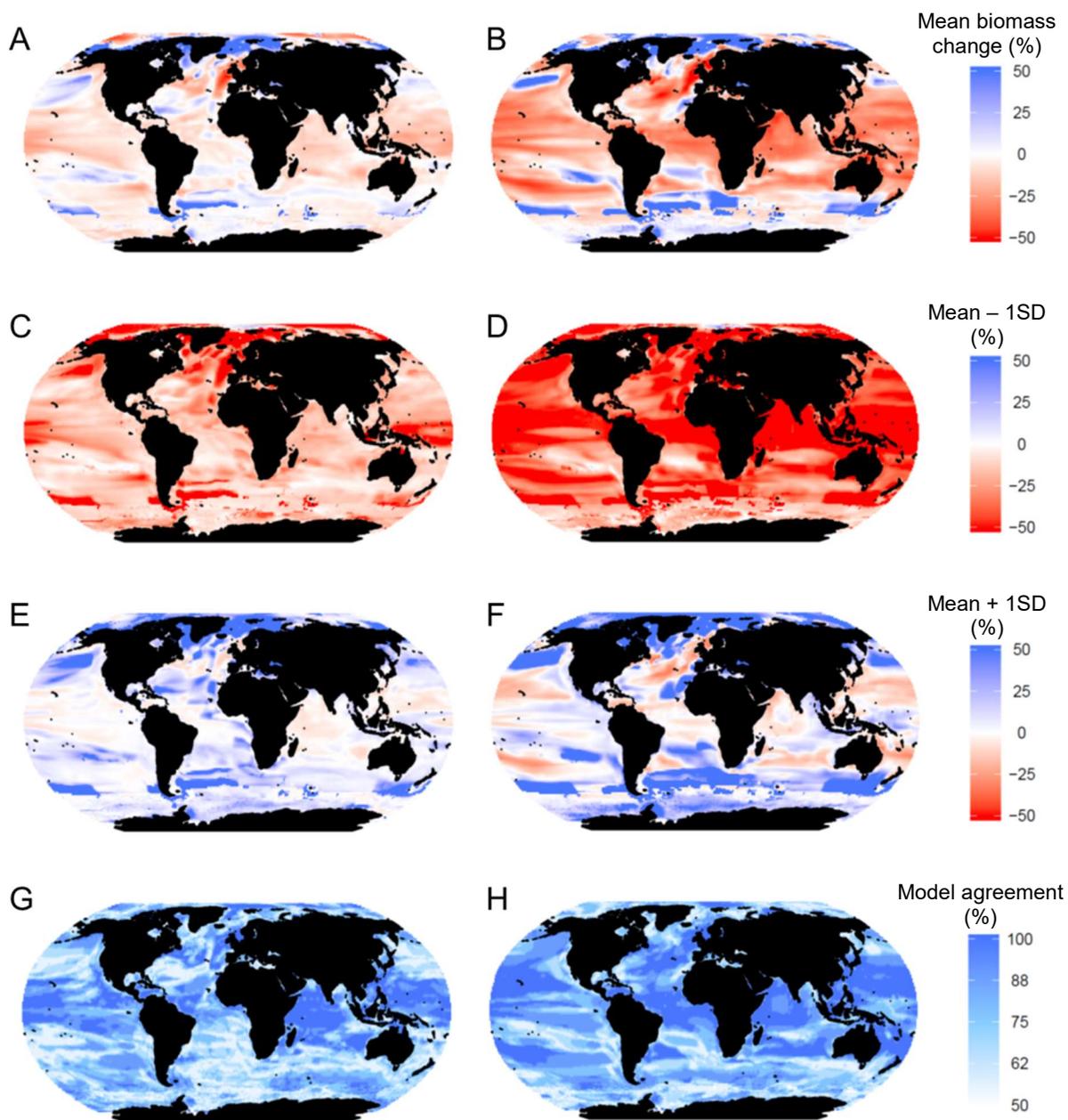
Fig. S8. Global spatial patterns of ensemble projection results for RCP 2.6 (left) and RCP 8.5 (right). (*A, B*) Multi-model mean change (%, n = 10) in total marine animal biomass in 2090-99 relative to 1990-99 without fishing (as in Fig. 1*A, B*), and the multi-model mean (*C, D*) minus 1 standard deviation (%) and (*E, F*) plus 1 standard deviation (%); and (*G, H*) model agreement (%) on the direction of change.
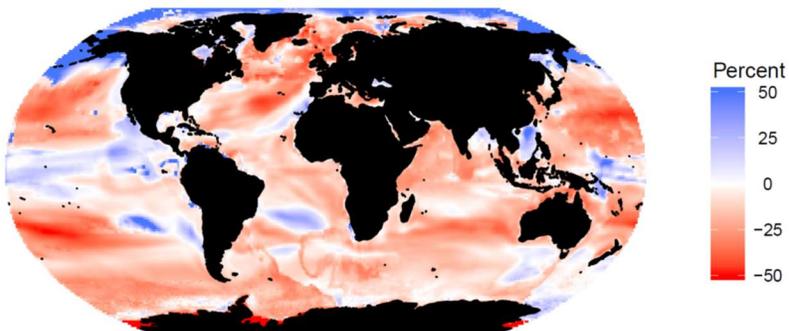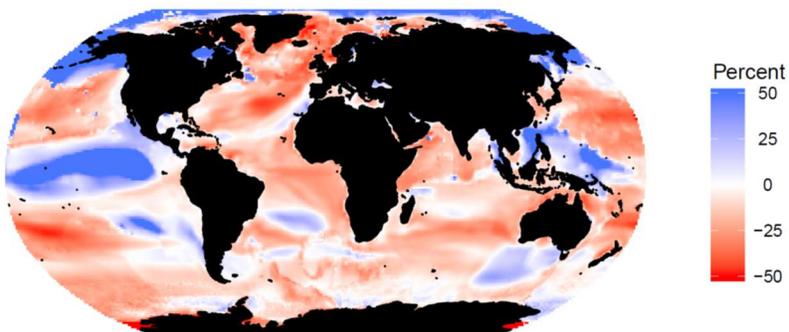
Fig. S9. Global spatial patterns of the climate effect defined as the multi-model mean biomass change in RCP8.5 vs. RCP2.6 in a fished (top) compared to an unfished (bottom) ocean based on three ecosystem models (BOATS, EcoOcean, DBEM) and two ESMs.
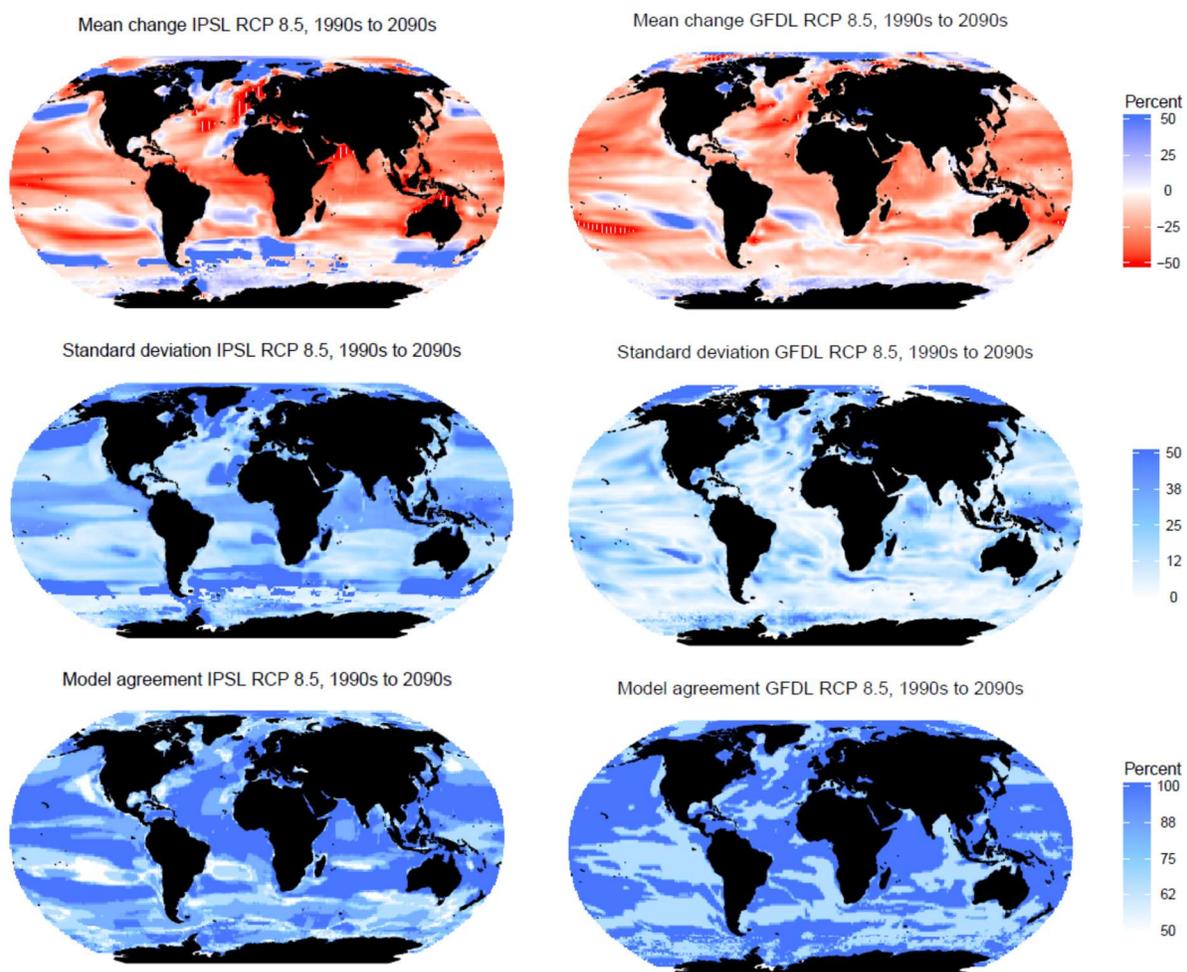
Fig. S10. Global spatial patterns of ensemble mean change (%) in total animal biomass in 2090-99 relative to 1990-99 for RCP8.5, the standard deviation, and robustness (% model agreement) among different ecosystem models for the two Earth-system models IPSL-CM5A-LR (left) and GFDL-ESM2M (right).

BOATS IPSL RCP2.6 no fishing (relative change)
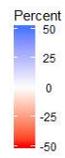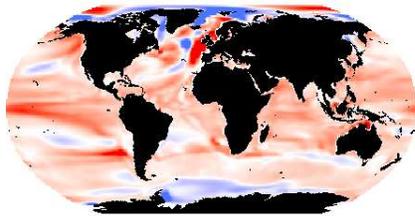
BOATS GFDL RCP2.6 no fishing (relative change)
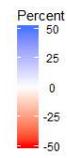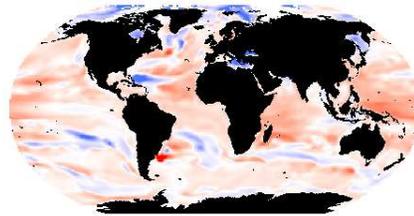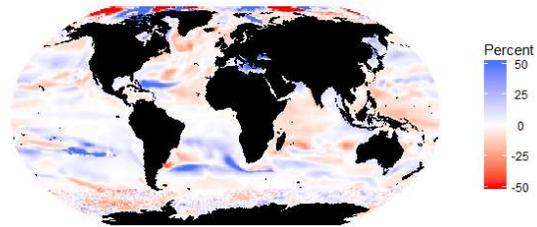
BOATS IPSL RCP8.5 no fishing (relative change)
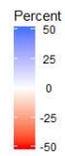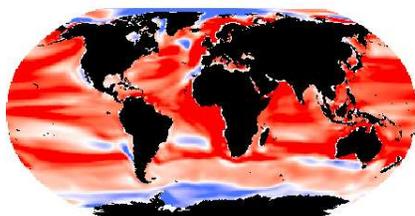
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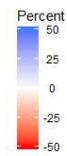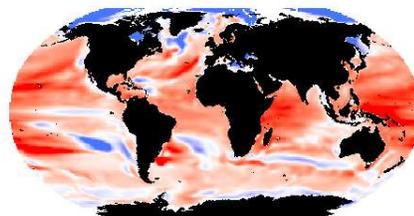
MACROECOLOGICAL IPSL RCP2.6 no fishing (relative change)
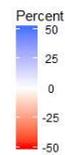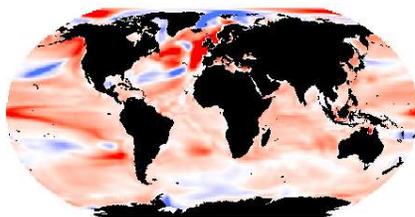
MACROECOLOGICAL GFDL RCP2.6 no fishing (relative change)
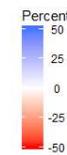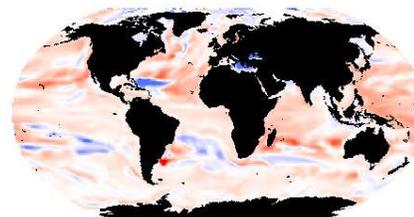
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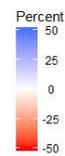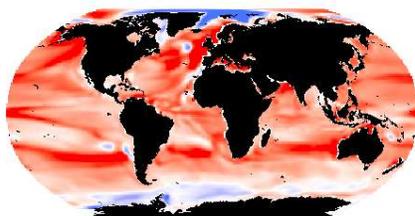
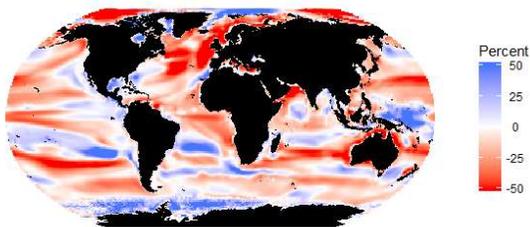MACROECOLOGICAL GFDL RCP8.5 no fishing (relative change)
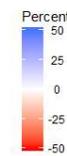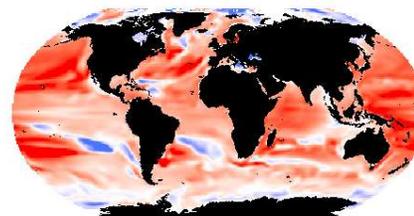
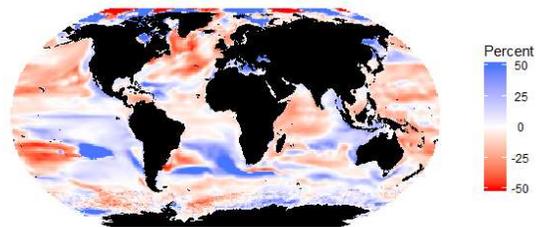ECOOCEAN IPSL RCP2.6 no fishing (relative change)
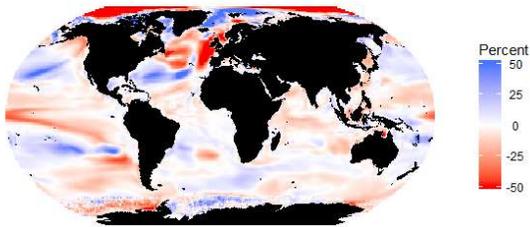
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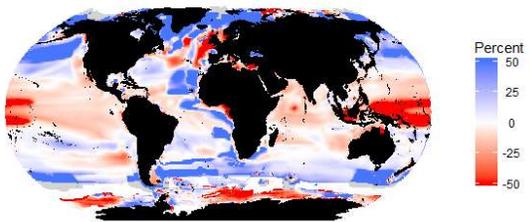

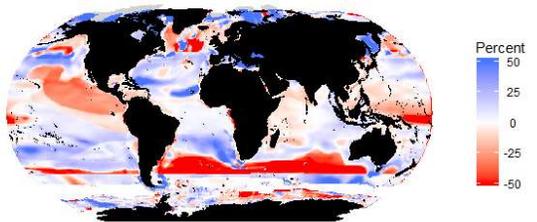ECOOCEAN IPSL RCP8.5 no fishing (relative change)

ECOOCEAN GFDL RCP8.5 no fishing (relative change)
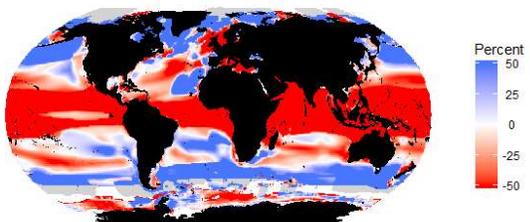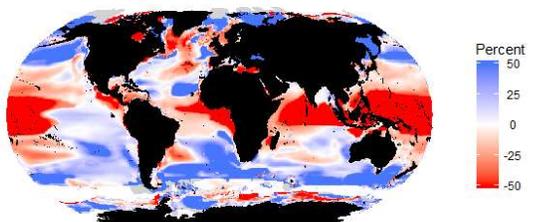

DBEM IPSL RCP2.6 no fishing (relative change)

DBEM GFDL RCP2.6 no fishing (relative change)

DBEM IPSL RCP8.5 no fishing (relative change)

DBEM GFDL RCP8.5 no fishing (relative change)

DPBM IPSL RCP2.6 no fishing (relative change)

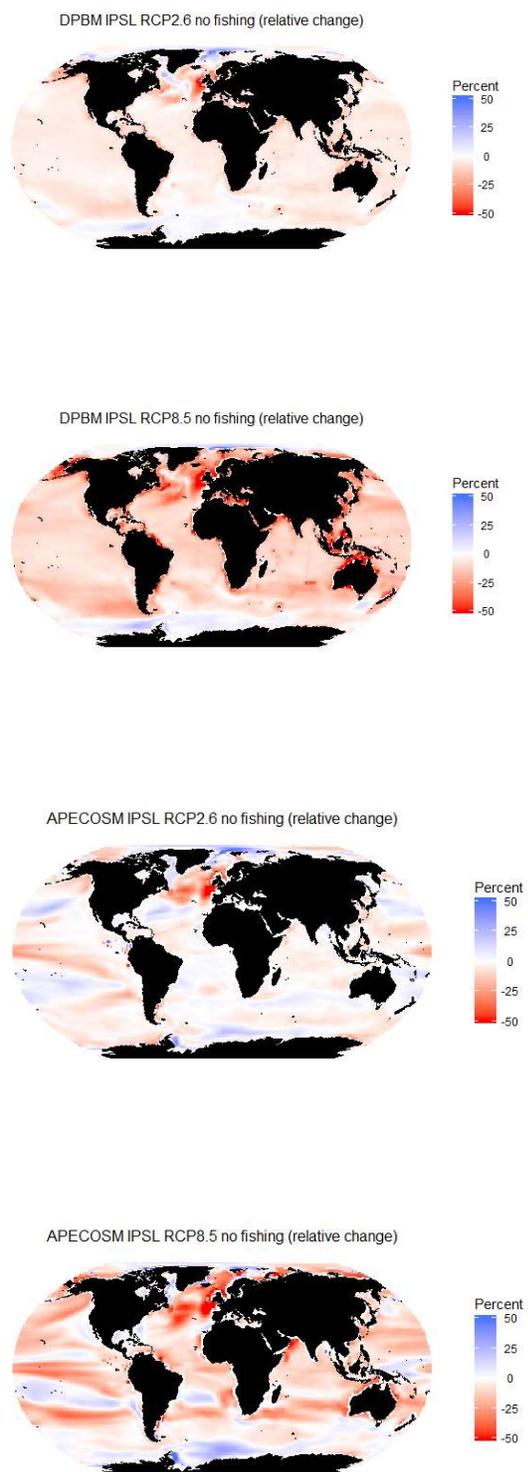DPBM IPSL RCP8.5 no fishing (relative change)

APECOSM IPSL RCP2.6 no fishing (relative change)

APECOSM IPSL RCP8.5 no fishing (relative change)

Fig. S11. Maps for each global ecosystem model highlighting relative changes in total animal biomass without fishing in the 2090s vs 1990s for IPSL-CM5A-LR and GFDL-ESM2M RCP2.6 and RCP8.5.

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