SUPPLEMENTARY INFORMATION
DOI: 10.1038/s41559-017-0258-8

nature ecology & evolution

In the format provided by the authors and unedited.

Linked sustainability challenges and trade-offs among fisheries, aquaculture and agriculture

Julia L. Blanchard[1,2*], Reg A. Watson[1,2], Elizabeth A. Fulton[2,3], Richard S. Cottrell[1,2], Kirsty L. Nash[1,2], Andrea Bryndum-Buchholz[4], Matthias Büchner[5], David A. Carozza[6], William W. L. Cheung[7], Joshua Elliott[8], Lindsay N. K. Davidson[9], Nicholas K. Dulvy[9], John P. Dunne[10], Tyler D. Eddy[4,7], Eric Galbraith[11,12], Heike K. Lotze[4], Olivier Maury[13], Christoph Müller[5], Derek P. Tittensor[14] and Simon Jennings[15,16,17]

[1]Institute for Marine & Antarctic Studies (IMAS), University of Tasmania, GPO Box 252-49, Hobart, TAS 7001, Australia. [2]Centre for Marine Socioecology, University of Tasmania, GPO Box 252-49, Hobart, TAS 7001, Australia. [3]CSIRO Oceans & Atmosphere, GPO Box 1538, Hobart, TAS 7001, Australia. [4]Department of Biology, Dalhousie University, PO Box 15000, Halifax, NS B3H 4R2, Canada. [5]Potsdam Institute for Climate Impact Research, Telegraphenberg A31, 14473 Potsdam, Germany. [6]Department of Mathematics, Université du Québec à Montréal, Montréal, Canada. [7]Changing Ocean Research Unit, Institute for the Oceans and Fisheries, The University of British Columbia, AERL, 2202 Main Mall, Vancouver, BC V6T 1Z4, Canada. [8]University of Chicago Computation Institute, Chicago, IL 60637, USA. [9]Earth to Ocean Research Group, Biological Sciences, Simon Fraser University, 8888 University Drive, Burnaby, BC V5A 1S6, Canada. [10]National Oceanic and Atmospheric Administration/Geophysical Fluid Dynamics Laboratory, Princeton, NJ 08540, USA. [11]Institut de Ciència i Tecnologia Ambientals (ICTA) and Department of Mathematics, Universitat Autonoma de Barcelona, Bellaterra 08193, Spain. [12]ICREA, Pg. Lluís Companys 23, 08010 Barcelona, Spain. [13]IRD, UMR 248 MARBEC, Av Jean Monnet CS 30171, 34203 SETE cedex, France. [14]United Nations Environment Programme World Conservation Monitoring Centre, 219 Huntingdon Road, Cambridge CB3 0DL, UK. [15]Centre for
Environment, Fisheries and Aquaculture Science, Lowestoft Laboratory, Lowestoft NR33 0HT, UK. [16]School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich NR4 7TJ, UK. [17]International Council for the Exploration of the Sea, H.C. Andersens Blvd 44-46, 1553 København V, Denmark. *e-mail: julia.blanchard@utas.edu.au

Supplementary Notes

"Linked sustainability challenges and trade-offs among fisheries, aquaculture and agriculture"

Blanchard J.L., Watson R.A., Fulton E.A., Cottrell R.S., Buchholz A., Carozza D., Cheung W.W.L., Elliot J., Davidson L.N.K., Dulvy N.K, Dunne J.P., Eddy T.D., Galbraith E., Lotze H., Maury O., Müller C., Nash K.L., Tittensor, D.P. & Jennings S.

Data Compilation and Synthesis

We compiled information on fisheries, aquaculture, agriculture, human population and wellbeing, climate change projections, biodiversity and biodiversity threat from a variety of published model outputs and publicly available databases. Further details of the data sources and the methods used to synthesise these data and generate land-sea indicators are provided below.

Global fish supply

To assess fish supply marine and freshwater capture fisheries landings (catch), freshwater and marine aquaculture production and trade data (imports, exports, re-exports) for each country were obtained from the Food and Agriculture Organization (FAO). Total fish supply was limited to fish, crustaceans and molluscs and was calculated as the balance of domestic production of combined marine and freshwater fisheries and aquaculture production plus imports minus exports (including re-exports).

Marine capture fisheries

For marine capture fisheries a compilation of global landings was mapped by intersecting the FAO Major Fishing areas with fisheries access patterns and marine species distributions. Only fish, molluscs and crustaceans were included.

The catch data, normally referred to as landings data, reflects catch that was taken to markets, usually by legal means. While it represents seafood production well, it underestimates actual take by 5-10%, as some catch is discarded at sea or, for various reasons, not reported[1]. Small-scale fisheries can contribute significantly to total landings for some countries, however, accurate statistics are still problematic to obtain and it is often not clear when they have already been included in FAO statistics[2].

When catches had to be allocated to Exclusive Economic Zones and/or individual nations, landings of marine and freshwater fishes, both wild caught and aquaculture production was mapped to 30-min spatial cells. Marine capture fisheries data was sourced from http://dx.doi.org/10.4226/77/58293083b0515 and this represents a harmonized and mapped compilation of global catch from 1950 to 2014 sourced in turn from the FAO Capture Production 1950-2014 dataset (Release date: March 2016 www.fao.org), International Committee for the Exploration of the Sea (ICES) 1950-2014 (www.ices.dk), Northwest Atlantic Fisheries Organisation (NAFO) Catch and Effort 1960-2014 (www.nafo.int), Southeast Atlantic (SEAFO) Capture Production 1975-2014 (Release date: June 2016) (www.seafo.org), General Fisheries Commission for the Mediterranean (GFCM) Capture production 1970-2014 (Release date: April 2016) (www.gfcm.org), Fishery Committee for the Eastern Central Atlantic (ECAF) Capture production 1970-2014 (Release date: May 2016) (www.fao.org/fishery/rfb/ecaf), Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) Statistical Bulletin 2016 Vol. 28 1970-2014 (www.ccamlr.org) and Sea Around Us project (SAUP) – records for FAO area 18 (Arctic) v1 1950 TO 2010 (extrapolated to 2014) (www.seaaroundus.org). See description in [1,3] (and references therein) for full details of data acquisition and processing.

Freshwater fisheries

Landings of freshwater species were obtained from FAO Capture Production 1950-2014 dataset (Release date: March 2016 www.fao.org). Only fish, molluscs and crustaceans were included.

Marine and freshwater aquaculture production

Aquaculture data were obtained from FAO (Aquaculture Production (Quantities and values) 1950-2014 (Release date: March 2016 www.fao.org). Only fish, mollusc and crustaceans were included.

Trade data

Seafood trade statistics were obtained from FAO[4] and covered the period 1976-2009. Traded seafood could have originated as wild capture or aquaculture production[5]. Freshwater species, plants, shells and corals were excluded.

Human Population Estimates

To assess per capita changes in fish supply we divided the fish supply estimates calculated from the harmonised dataset by the human population in each country for two time periods: 1980-1984 and 2010-2014. We then compared the percentage change in human population to percentage change in per capita fish supply (Figure 1b, main text).

Country–level projected human populations were obtained from the Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (2015) (http://esa.un.org/unpd/wpp/index.htm). The World Population Prospects 2015 Revision is the twenty-fourth round of the official United Nations population estimates and projections. The demographic models used to generate the projections are based on life tables that utilize census and survey data from 94 countries and estimates of the three components of population change: fertility, mortality and migration.

Fisheries stock assessments

Information on the proportion of stocks sustainably fished and overfished was obtained from the FAO (2016)[6] reports for the FAO statistical regions (Table 1), with the highest levels of overfishing estimated in the Mediterranean. Other estimates for the Mediterranean are even higher, because they address the status of more small inshore stocks[7]. In contrast, in the eastern-central and northeast Pacific regions, the FAO estimates ≤14% of stocks are overfished, compared with a global mean estimate of 32.4%[6].

A quantitative analysis of stock assessment data collated in the RAM Legacy database has generally implied higher levels of overfishing than the FAO approach in those regions where comparisons were possible[8]. In the northeast Pacific, the biomass of 26% of stocks was <80% of biomass expected to produce maximum sustainable yield (B_{MSY}), but in the northwest Pacific, southeast Pacific, northeast and northwest Atlantic ≥50% of stocks were <80% B_{MSY}. The discrepancy between the FAO analyses and the assessments collated in the RAM database arises because FAO analyses focus on larger stocks, while there are relatively smaller stocks in the RAM Legacy database[8]. Large stocks, which account for a large proportion of global fisheries landings and are often targeted by larger vessels and relatively fewer fishers per unit catch, are, in general, the focus of more rigorous management and likely to have better status than smaller stocks[9,10].

Among smaller stocks, those with assessments are expected to have better overall status than those without assessments; because the existence of an assessment is typically linked to the existence of management, better governance and more resources to influence or support fishers[10].

Table 1: Proportion of overfished stocks assessed and reported by FAO (2016)[6]

FAO Major Fishing Area code	FAO Major Fishing Area Region	Proportion of stocks overexploited (FAO)
21	Atlantic, Northwest	0.31
27	Atlantic, Northeast	0.21
31	Atlantic, Western Central	0.44
34	Atlantic, Eastern Central	0.465
37	Mediterranean and Black Sea	0.59
41	Atlantic, Southwest	0.5
51	Indian Ocean, Western	0.32
57	Indian Ocean, Eastern	0.15
61	Pacific, Northwest	0.24
67	Pacific, Northeast	0.14
71	Pacific, Western Central	0.23
77	Pacific, Eastern Central	0.09
87	Pacific, Southeast	0.41

Biodiversity: threatened sharks and rays by EEZ

The status of Chondricthyans (hereafter:sharks and rays) provides a good broad-scale-indicator of the effects of fishing on the marine environment because (a) sharks and rays are caught in directed fisheries and as bycatch, (b) a large proportion of species are sensitive to additional mortality owing to their large body size and low intrinsic rates of population growth, (c) they are the most comprehensively assessed Class of marine organisms, (d) they are predominately threatened by fishing, and (s) they have the highest percentage of threatened species (25%) recorded in any marine Class[11].

To determine the number of sharks and rays threatened with elevated extinction risk within each country's Exclusive Economic Zone (EEZ; the EEZ boundaries were taken from high resolution shapefiles obtained from marineregions.org) we collated data from the International Union of the Conservation of Nature's (IUCN) Red List (IUCN, 2016)[12]. The distribution and status of sharks and rays was mapped, and species allocated to each EEZ where they were recorded. We (a) summed the number of threatened species within each country's EEZ (N_T), (b) estimated the ratio of threatened species to total shark and ray species richness per each EEZ (P_T), and (c) calculated weighted threat (W_T): the summed fraction of each threatened species' geographic range within each EEZ[13].

Whilst N_T and P_T provide an account of the broad-scale and country-level EEZ patterns of biodiversity status, they do not account for the extents to which species are distributed within the boundaries of country EEZs. W_T accounts for the extent of species' distributions within each EEZ and can be interpreted as one measure of the relative responsibility of each country towards the conservation of globally threatened species[13].

We define threatened species as those classified as Critically Endangered, Endangered, and Vulnerable. However, we also included as threatened the 68 species that are predicted to be threatened based on biological and ecologically characteristics, even though they are currently categorized as Data Deficient (DD; not enough information available to place them in one the other categories). There was a close correlation between the absolute numbers of shark and ray species by EEZ for which available data indicated they were threatened and the total number of sharks and ray species classified as threatened using data as well as predicted threatened DD species[11](Spearman's *rho*=0.99). For this reason we report the total number of sharks and ray species classified as threatened along with the predicted threatened DD species in the main text. For seven countries, the inclusion of predicted threatened Data Deficient species modelled estimates increases the proportion of threatened species by >10% (Georgia, Ukraine, Bulgaria, Romania, Turkey, Sudan and Eritrea). These are all nations with very low-medium levels of resources for monitoring and analysing the marine environment. Therefore, we report the proportion of shark and ray species classified as threatened to include the predicted threatened DD species. We believe this metric gives a more realistic estimate of the number of threatened species in countries with relatively low levels of marine environmental monitoring.

Biodiversity: threatened terrestrial birds by country

Estimates of the number of threatened bird species (N_T) in each country were estimated as the sum of the number of species reported in IUCN (2001)[14] Red List categories 'Critically Endangered', 'Endangered' or 'Vulnerable'). To calculate P_T these were divided by the sum of the number of recorded species of land birds, migratory birds, breeding endemics and waterbirds in each country, obtained from Birdlife International[15]. We focused on birds as a group for which the status of 100% of known species have been assessed (IUCN, 2016)[12], because every species has been assessed on a regular basis since 1998, and because birds are regarded as the most comprehensively documented class of organisms on the Red List[16]. Land-use change is one of the main drivers of changes in bird populations and so their status is a suitable broad-scale indicator of pressures on the terrestrial and freshwater environment[17] although responses of a given species in given habitats or regions to a given change in practices is clearly more nuanced[18,19].

Human well-being indicators

Fisheries dependency index by country

To determine the relative ‘fisheries dependency’ of each nation we used three component indices to generate a metric of the relative importance of marine wild capture fisheries in all countries for which data were available[20]. The component indices measure fisheries’ contribution to society by creating employment, to the economy by adding economic value and to food security by providing animal protein and micronutrients. Employment was measured as the number of people working in marine fisheries[21] as a proportion of the total economically active population. Economic value was measured as the value of marine fish landings as a proportion of GDP. Contribution to food security was measured as (fish protein intake / total animal protein intake) / (total animal protein intake / required animal protein intake). Each component index was normalised and the values summed and divided by three to provide the final fisheries dependency index. Although the food security component will account for freshwater fish, the employment and economic components were only available for marine fisheries and hence this index will underestimate the importance and dependence of some countries on freshwater fisheries.

Agricultural dependency index by county

To determine the relative ‘agricultural dependency’ of each nation we used three component indices to generate a metric of the relative importance of agriculture in all countries for which data were available. To support comparison with the fisheries dependency index the agricultural dependency index accounted for the contribution of agriculture to employment, the economy and food security. The component index for employment was the number of people working in agriculture as a proportion of the economically active population. The component index for economic value was the value of agricultural production as a proportion of GDP. The component index for food security was Average Dietary Energy Supply Adequacy (ADESA). This indicator expresses the Dietary Energy Supply as a percentage of the Average Dietary Energy Requirement. The most recent available data in the period 2010 to 2014 were obtained from FAO and the World Bank. Each component index was normalised and the values summed and divided by three to provide the index.

Adaptive capacity

The Human Development Index (HDI) is a summary measure of average achievement in dimensions of human development relating to health and length of life, knowledge and standard of living. Values of the HDI, by country, for 2015, were obtained from data held by the United Nations Development Programme and previously published in their 2015 Human Development Report[22].

An alternative index of Adaptive Capacity was used by Allison et al.[23], which is a composite of four component human development indices: healthy life expectancy (years from birth), education (literacy, school enrolment), governance (governance indicator) and size of economy (GDP). These component indices were selected because Allison et al.[23] expected countries with high levels of economic and human development to have the resources and institutions necessary to undertake planned adaptation to climate change.

Data to calculate the Adaptive Capacity index were not available for several countries. However, HDI and the Adaptive Capacity Index were proportional when they could both be calculated. Given the HDI has been generated for more countries in 2015 than the number for which the Adaptive Capacity Index can be generated we took HDI as our proxy of adaptive capacity.

Climate change impact models for fisheries and agriculture

Marine fisheries sector

Global projections of changes in potential marine fisheries production were obtained from the preliminary model results collated by the Fisheries and Marine Ecosystem Modeling Inter-comparison Project (FISH-MIP) component of ISI-MIP. The full suite of FISH-MIP models are described in Tittensor et al.[24] and at the time of writing the simulation outputs were available for 5 global fisheries and marine ecosystem models: APECOSM[25,26], BOATS[27,28], DBEM[29,30], DPBM[31] and MACROECOLOGICAL[32]. Simulation protocols are detailed here: https://www.isimip.org/gettingstarted/marine-ecosystems-fisheries/. These models were coupled to inputs of two general circulation models (GFDL-ESM2M, IPSL-CM5A-LR). These and other global and regional marine ecosystem models are currently being developed as part of a multi-model ensemble to advance representation of the fisheries sector when projecting the inter-sectoral impacts of climate change. Simulations were carried out under all four Representative Concentration Pathways (RCPs). DBEM output was only available for two RCPs (2.6 and 8.5) and the ensemble projections with and without DBEM are shown in Supplementary Figure 2. We used simulations that were conducted without fishing and ocean acidification impacts. We used multi-model mean changes in total consumer biomass as a proxy for changes in potential production. Changes are time-averaged projections over 2050-2059 relative to time-averaged historical scenario model outputs for each model over the 1980-2005 historical scenario period. Previously published[31] downscaled regional climate model outputs (under SRESA1b) were compared with GCM-forced (IPSL-CM5A-LR, RCP60) for the same marine ecosystem model (DPBM[31]) and showed differences in climate projections at the aggregate EEZ scale (Supplementary Figure 3).

Agriculture sector

Future projections of yields for wheat, rice, maize and soy were taken from the Inter-Sectoral Impact Model Intercomparison Project fast-track archive (https://www.isimip.org/outputdata/), as coordinated by the Agricultural Modeling Intercomparison and Improvement Project (AgMIP). These projections have previously been summarised[33,34]. Following the guidance provided in Rosenzweig et al.[33] we considered relative yield changes as they provide a more consistent set of results for comparison. For each country, the mean change in total productivity across the 4 major crop types, averaged between rain-fed and irrigated productivity and based on present-day distributions of farm management, was calculated for 2050-2059 from the output of 7 global gridded crop models that include nutrient, temperature and water stresses (EPIC, GEPIC, pDSSAT, LPJmL, LPJ-GUESS, IMAGE_LEITAP and PEGASUS). Five general circulation models (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM and NorESM1-M) were selected. These models were driven by all four Representative Concentration Pathways (RCPs) (Supplementary Figure 1). Simulations were conducted both with and without CO_2 fertilization effects, without full irrigation. Changes are relative to mean historical scenario model outputs for each model over the 1980-2009 baseline period. The final relative change per country was calculated as an area weighted average of the mean change in total production (summing across the crop types). Note that the PEGASUS model did not provide results for rice.

References

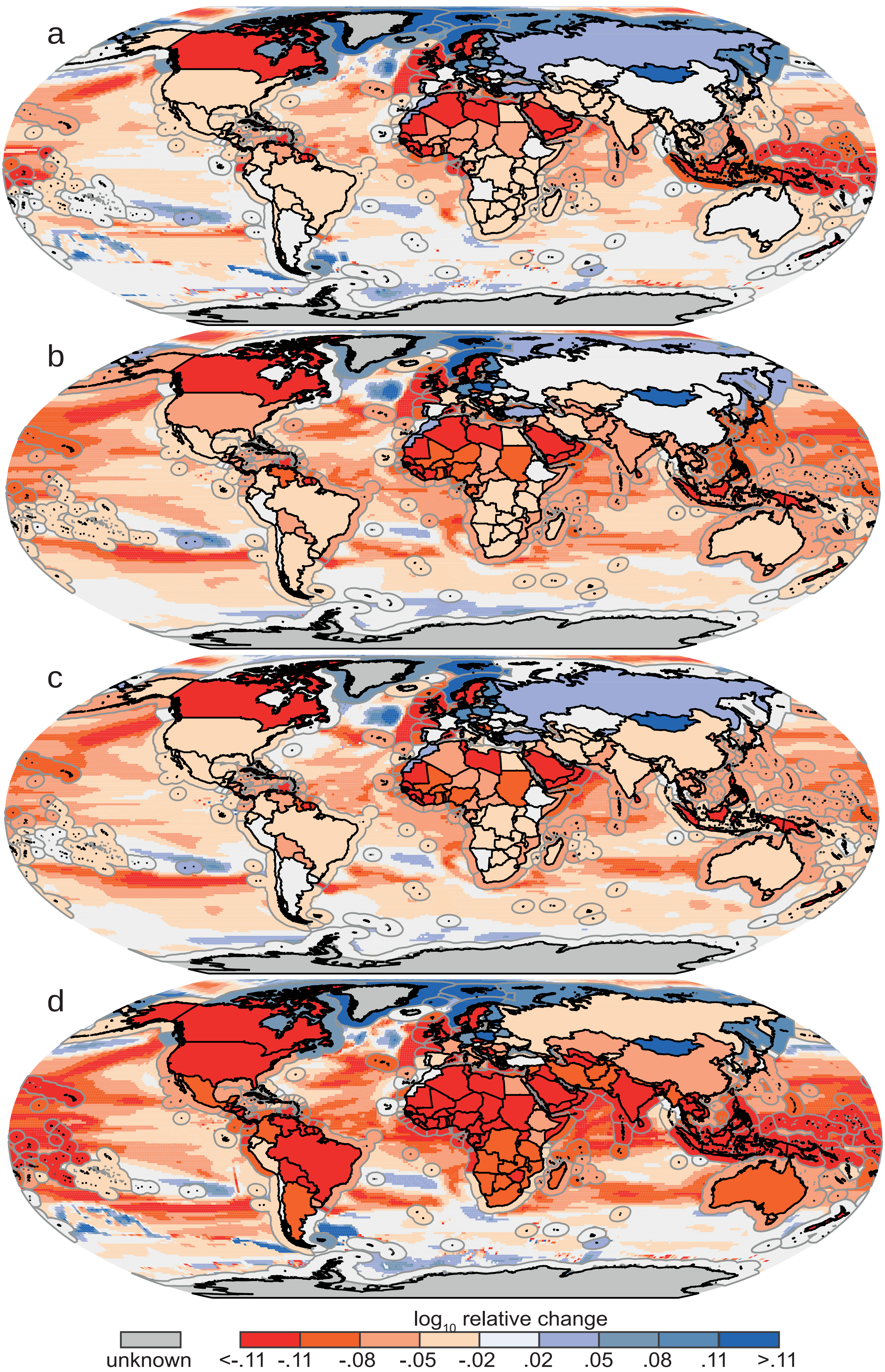
1. Watson, R. A database of global marine commercial, small-scale, illegal and unreported fisheries catch 1950-2014. *Nat. Sci. Data* **4,** (2017).
2. Chuenpagdee, R., Liguori, L., Palomares, M. L. D. & Pauly, D. Bottom-Up, Global Estimates of Small-Scale Marine Fisheries Catches. *Fish. Cent. Res. Reports* **14,** 105 (2006).
3. Watson, R., Kitchingman, A., Gelchu, A. & Pauly, D. Mapping global fisheries: Sharpening our focus. *Fish Fish.* **5,** 168–177 (2004).
4. FAO. Fishery commodities and trade. *http://www.fao.org/fishery/statistics/software/fishstatj/en* (2014).
5. FAO. FAO Statistical Databases. *http://faostat.fao.org* (2014).
6. FAO. *The state of world fisheries and aquaculture 2016. Contributing to food security and nutrition for all.* (2016).
7. GFCM. *Report of the seventeenth session of the Scientific Advisory Committee. FAO headquarters, Rome, 24–27 March 2015.* (2015).
8. Hilborn, R. & Ovando, D. Reflections on the success of traditional fisheries management. *ICES J. Mar. Sci.* **71,** 1040–1046 (2014).
9. Costello, C. *et al.* Status and Solutions for the World's Unassessed Fisheries. *Science* **338,** 517–520 (2012).
10. Costello, C. *et al.* Global fishery prospects under contrasting management regimes. *Proc. Natl. Acad. Sci. USA* **113,** 5125–5129 (2016).
11. Dulvy, N. K. *et al.* Extinction risk and conservation of the world' s sharks and rays. *Elife* **3,** 1–35 (2014).
12. IUCN. IUCN Red List of Threatened Species. *Version 2016-1* www.iucnredlist.org (2016). at <www.iucnredlist.org>
13. Rodrigues, A. S. L. *et al.* Spatially explicit trends in the global conservation status of vertebrates. *PLoS One* **9,** 1–17 (2014).
14. IUCN. *IUCN Red List categories and criteria: Version 3.1.* (2001).
15. BirdLife International. Country profiles. *http://www.birdlife.org/datazone* (2016).
16. Butchart, S. H. M. *et al.* Measuring global trends in the status of biodiversity: Red list indices for birds. *PLoS Biol.* **2,** (2004).
17. Green, R. E., Cornell, S. J., Scharlemann, J. P. W. & Balmford, A. Farming and the fate of wild nature. *Science* **307,** 550–5 (2005).
18. Chamberlain, D. E., Fuller, R. J., Bunce, R. G. H., Duckworth, J. C. & Shrubb, M. Changes in the abundance of farmland birds in relation to the timing of agricultural intensification in England and Wales. *J. Appl. Ecol.* **37,** 771–788 (2000).
19. Donald, P., Green, R. & Heath, M. Agricultural intensification and the collapse of Europe's farmland bird populations. *Proc. R. Soc. B-Biological Sci.* **268,** 25–9 (2001).
20. Barange, M. *et al.* Impacts of climate change on marine ecosystem production in societies dependent on fisheries. *Nat. Clim. Chang.* **4,** 211–216 (2014).
21. Teh, L. C. L. & Sumaila, U. R. Contribution of marine fisheries to worldwide

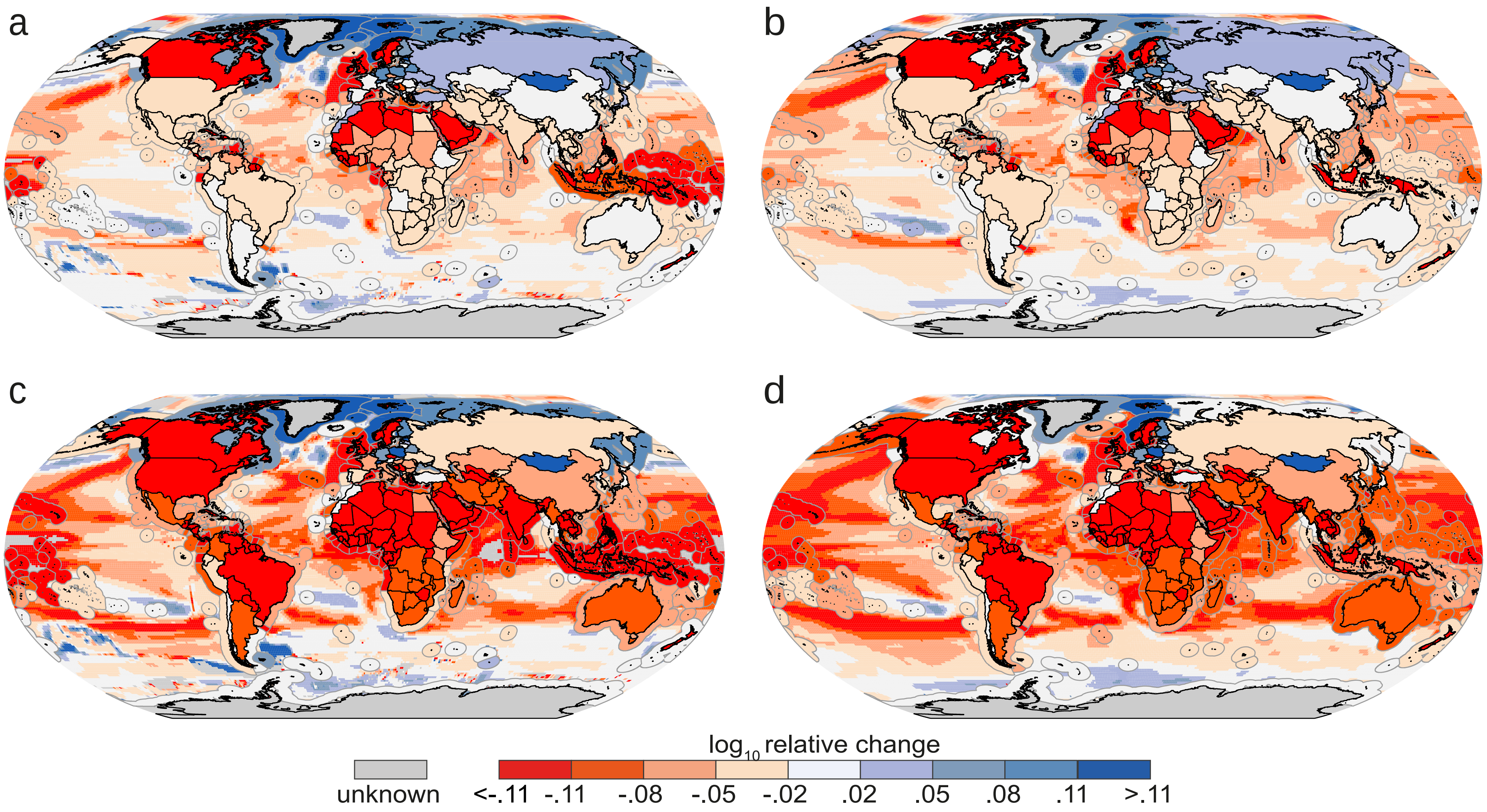
employment. 77–88 (2013). doi:10.1111/j.1467-2979.2011.00450.x
22. UNDP. *Human development report 2015*. *UN Development Programme* (2015). doi:ISBN: 978-92-1-126340-4
23. Allison, E. H. *et al.* Vulnerability of national economies to the impacts of climate change on fisheries. *Fish Fish.* **10,** 173–196 (2009).
24. Tittensor, D. P. et al. Challenges and opportunities in the intercomparison of fisheries and marine ecosystem models. *Geosci. Model Dev.* **in review,** (2017).
25. Maury, O. An overview of APECOSM, a spatialized mass balanced 'Apex Predators ECOSystem Model' to study physiologically structured tuna population dynamics in their ecosystem. *Prog. Oceanogr.* **84,** 113–117 (2010).
26. Lefort, S. *et al.* Spatial and body-size dependent response of marine pelagic communities to projected global climate change. *Glob. Chang. Biol.* **21,** 154–164 (2015).
27. Carozza, D. A., Bianchi, D. & Galbraith, E. D. The ecological module of BOATS-1.0: a bioenergetically-constrained model of marine upper trophic levels suitable for studies of fisheries and ocean biogeochemistry. *Geosci. Model Dev.* **8,** 10145–10197 (2016).
28. Galbraith, E. D., Carozza, D. A. & Bianchi, D. A coupled human-Earth model perspective on long-term trends in the global marine fishery. *Nat. Commun.* **8,** 14884 (2017).
29. Cheung, W. W. L. & Reygondeau, G. Large benefits to marine fisheries of meeting the 1.5°C global warming target. *Science* **354,** 1591–1594 (2016).
30. Lam, V. W. Y., Cheung, W. W. L., Reygondeau, G. & Sumaila, U. R. Projected change in global fisheries revenues under climate change. *Sci. Rep.* **6,** 32607 (2016).
31. Blanchard, J. L. *et al.* Potential consequences of climate change for primary production and fish production in large marine ecosystems. *Philos. Trans. R. Soc. B* **367,** 2979–2989 (2012).
32. Jennings, S. & Collingridge, K. Predicting Consumer Biomass , Size-Structure, Production, Catch Potential , Responses to Fishing and Associated Uncertainties in the World's Marine Ecosystems. **10(7): e01,** 1–28 (2015).
33. Rosenzweig, C. *et al.* Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proc. Natl. Acad. Sci. U. S. A.* **111,** 3268–73 (2014).
34. Elliott, J. *et al.* Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proc. Natl. Acad. Sci. U. S. A.* **111,** 3239–44 (2014).

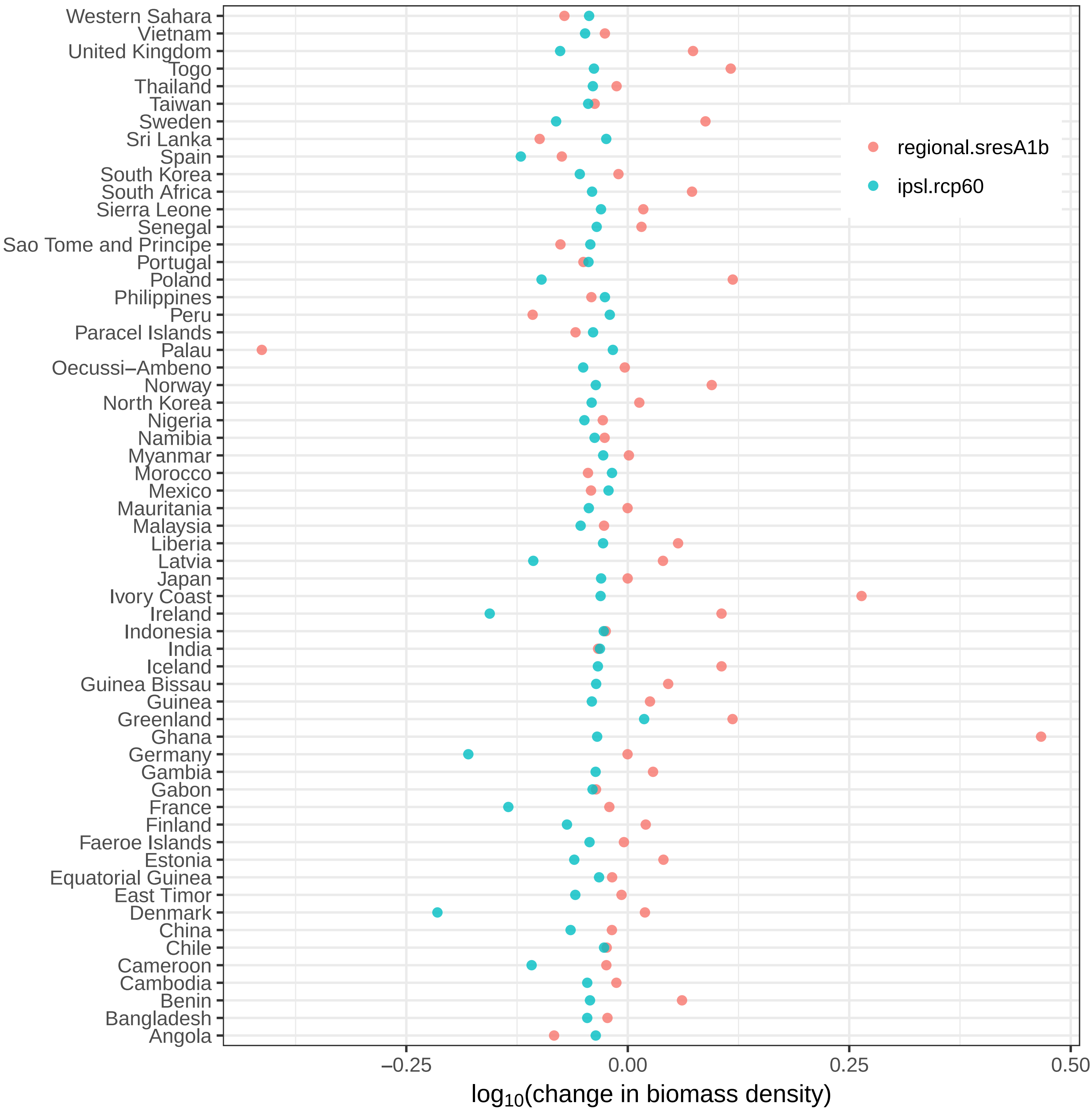
Supplementary Fig. 1 **|** Multi-model ensemble climate change projections for potential production of marine fisheries and agriculture sectors under scenarios RCP2.6 (a), RCP4.5 (b), RCP6.0 (c and RCP8.5 (d). Projected relative changes in potential crop (maize, wheat, rice and soy combined) and fish production from the Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP) and Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble outputs[92,116]. Crops are from the published agriculture model intercomparison project (AgMIP) for model ensemble outputs based on 7 crop models and 7 general circulation models[84]. Predicted mean relative changes for total marine fish consumer biomass from the marine fisheries and ecosystem model intercomparison project (FISH-MIP) model ensemble consists of four global marine ecosystem models[82,85,87,95] forced by two earth system models without fishing impacts.

Supplementary Fig. 2 **|** The effect of including an additional single marine fisheries model on the multi-model ensemble climate change projections for potential production of marine fisheries under scenarios RCP2.6 (a,b) and RCP8.5 (b,c). The marine fisheries dynamic bioclimate envelope model (DBEM)[86] was only available for these two scenarios and this figure shows the effect on the global marine ecosystem ensemble of excluding (a,c) and including (b,d) that model. Unlike the other marine fishery models DBEM included fishing exploitation rates consistent with long-term maximum sustainable yields. All other details are the same as Figure 1 and Supplementary Figure 1.

Supplementary Fig. 3 **|** Comparison of country-level projections using the same single marine ecological model (DPBM82) but with different climate forcing to 2050 based on the IPSL-CM5A-LR general circulation model under RCP6.0 forcing scenario (blue) and previously published[82,83] downscaled regional shelf seas model inputs under the SRESA1b climate emissions scenario (red). See Supplementary Information for further details.


a
b
c
d
log10 relative change
unknown
<-.11 -.11 -.08 -.05 -.02 .02 .05 .08 .11 >.11


a
b
c
d
log$_{10}$ relative change
unknown
<-.11
-.11
-.08
-.05
-.02
.02
.05
.08
.11
>.11


Western Sahara
Vietnam
United Kingdom
Togo
Thailand
Taiwan
Sweden
Sri Lanka
Spain
South Korea
South Africa
Sierra Leone
Senegal
Sao Tome and Principe
Portugal
Poland
Philippines
Peru
Paracel Islands
Palau
Oecussi–Ambeno
Norway
North Korea
Nigeria
Namibia
Myanmar
Morocco
Mexico
Mauritania
Malaysia
Liberia
Latvia
Japan
Ivory Coast
Ireland
Indonesia
India
Iceland
Guinea Bissau
Guinea
Greenland
Ghana
Germany
Gambia
Gabon
France
Finland
Faeroe Islands
Estonia
Equatorial Guinea
East Timor
Denmark
China
Chile
Cameroon
Cambodia
Benin
Bangladesh
Angola
regional.sresA1b
ipsl.rcp60
–0.25
0.00
0.25
0.50
log10(change in biomass density)