Supplementary Material for Chust et al. "Cross-basin and cross-taxa patterns of marine community tropicalization and deborealization in warming European seas"

Supplementary Information 1. Information on biodiversity time series datasets

Biodiversity time series datasets. Information on sampling procedures and time series.

1 Demersal fish in the North-East Atlantic (DATRAS)

Freely available long-term monitoring data on marine fish communities from six bottom-trawl surveys were downloaded from DATRAS-ICES (the Database of Trawl Surveys[1]). The bottom-trawl surveys included the North Sea (NS-IBTS), Baltic Sea (BITS) and the Scottish (SWC-IBTS) International Bottom Trawl Surveys, as well as the French Surveys (EVHOE) in the NE Bay of Biscay[2]. All surveys use standardized sampling protocols, where bottom trawls are towed for an average of 30 min and the species composition and abundances of all captured fishes are identified and recorded to the finest taxonomic level possible. The spatial coverage and resolution differed across surveys, and we therefore aggregated trawl surveys to 1x1° spatial grid cells. The length of time series also differed between surveys, and we therefore examined the period 1980–2015, which maximized temporal overlap between surveys. The arithmetic mean of each single species abundance was calculated for each year on each ecoregion. Within each region, only grid cells with > 20 years observations were selected for further analysis.

2 Demersal and benthic fish, cephalopods, and crustaceans in the Western Mediterranean (MEDITS)

Data on demersal and benthic fish, cephalopods, and crustaceans was collected by the MEDITS program (Spedicato et al. 2020) which started in 1994 in the Mediterranean with the cooperation among research institutes from four countries: France, Greece, Italy and Spain[3]. MEDITS consist of series of bottom trawl surveys that routinely provide abundance indices of target species for tuning stock assessment models of intermediate complexity (Spedicato et al. 2019). The data to calculate the CTI in this study include annual means of species abundance (km m^{-2}) of demersal fish and benthic crustaceans and cephalopods sampled from May to July during the 1994-2019 period in the western Mediterranean Sea, specifically within Geographical Sub Area 6 (GS6) as established by General Fisheries Commission for the Mediterranean. The analysis was carried out in three subregions of the GS6 area: (i) North at > 41° latitude north (North of Ebro Delta),

[1] https://datras.ices.dk/Data_products/Download/Download_Data_public.aspx
[2] https://datras.ices.dk/home/descriptions.aspx#FRA
[3] https://www.sibm.it/SITO%20MEDITS/principaleprogramme.htm.

(ii) Centre within 41-39.2° latitude north and (iii) South at < 39.2° latitude north. The division of these three areas show different ocean warming velocities.

3 Pelagic, demersal and benthic fish, cephalopods, and crustaceans in the Western Mediterranean (PUR/TRA)

Data on abundance and composition of fish, crustaceans and cephalopods during the 2000-2020 period were obtained using purse-seine and bottom trawl daily catch data from different ports and fishing gear across the northern Catalan coast. The data was divided into three regions: (i) north including ports within 41.6° latitude north, (ii) central at 41.2° latitude north and (iii) south including data around 40.6° latitude north.

Daily data on landings span the 2000-2020 period and come from 23 different fishing ports scattered along the Catalan Sea. Raw data were grouped by species, gear, port and year. Here, we exclusively considered main fishing gears in the area: purse-seiners and bottom trawlers (hereafter trawlers). Purse-seiners operate through the water column and target pelagic fish species (mostly anchovy *Engraulis encrasicolus* and sardine *Sardina pilchardus*). Therefore, their catches can mainly inform about the pelagic fish community. Bottom trawlers operate near the bottom and integrate the benthic and demersal community. Whereas purse-seiners mainly target pelagic fish and few cephalopod species, landings from trawlers are taxonomically diverse, including many species of fish and invertebrates. Here, we considered main groups of species for trawlers: fish, crustaceans, and cephalopods. Trends in CTI were evaluated by aggregating daily landing data into annual values. Fishing ports were grouped within three main subregions: North, Central and South.

4 Demersal and benthic fish, cephalopods, and crustaceans in the Eastern Mediterranean

A large bottom trawling fishery-independent time series data provided by the Israel fishery Department was used in the analysis. The targeted groups included demersal fish, crustaceans, and cephalopods in the 31-50 m. Surveys took place onboard bottom trawlers with fishing the Israeli continental shelf, between latitudes 31º20' N and 33º05' N. Depths ranged between 15 and 300 m. The catch sampling protocol (Edelist et al. 2011) from 1990 to 1994 was repeated in all subsequent periods. The data used in this analysis covers a period from the early 1990s to recent years with some gaps mostly in the first two decades. The units used in the CTI analysis are individuals per sampling box or haul.

5 Fish in Wadden Sea (FYKE)

The Royal Netherlands Institute for Sea Research (NIOZ) collects data on the Wadden Sea fish community using traditional fixed gear at a specific location (Lat 52.997ºN, Long 4.775ºE) since 1960. The fixed gear is known as a 'kom-fyke' (van Leeuwen et al. 2023)[4]. It is a passive fish trap consisting of a 200-m net running from the beach towards deeper waters. Fish captured each day are identified to species level. To carry out the CTI

[4] https://dataverse.nioz.nl/dataset.xhtml?persistentId=doi:10.25850/nioz/7b.b.ud

analysis, the average yearly catch per species was corrected for effort (number of fishing days) and the data were filtered for the period 1980-2021.

6 Fish in Gironde estuary

The Gironde estuary, located SW France is one of the largest European estuaries (Lobry et al. 2003). Its surface area is approximately 625 km^2 at high tide. The dataset comes from the Blayais Power Plant monitoring program. In the frame of this program, fish sampling surveys are conducted monthly since the late 1970s. Data from 1985 was selected since the sampling protocol is considered stable and standardized from this date. Three sampling sites are located along four transects. On each site, simultaneously, one fishing sample is taken near the surface and one near the bottom. Surface samples are taken using two 4.0 x 1.0 m rectangular frame nets fitted both sides of the boat. Details in the sampling protocol can be found in Lobry et al. (2006) and in Chevillot et al. (2017). The monitored fauna consists mainly of small fish species and juveniles of larger species. In total, 47 species are considered in the analysis. They can be divided into 4 ecological guilds (Marine M, Freshwater FW, Diadromous DIA and Estuarine Resident ER) following (Franco et al. 2008) and (Courrat et al. 2011) (Dethier et al. 1993). In this case study, the CTI was calculated by averaging fish abundance (i.e., the number of individuals per 1,000 m^3 of filtered water) across the twelve sites (i.e., 3 sites and 4 transects) for each year.

7 Fish in the Pertuis Charentais nursery ground

The Pertuis Charentais (SW France) are a complex ensemble that includes the estuary of the Seudre and Charente rivers, as well as their discharges in two semi-enclosed bays (Pertuis Breton and Pertuis d'Antioche) sheltered by two islands (Ile de Ré and Ile d'Oléron). This 540 km^2 macrotidal embayment serves as a major nursery ground for juvenile marine fish in the Bay of Biscay. Here, we analysed a 9-year time-series of fish abundance data collected by Ifremer (see for instance: (Le Pape et al. 2003, Trimoreau et al. 2013)) during late summer-early autumn, between 1997 and 2019, using a 2.9 m wide and 0.5 m high scientific beam trawl with a 20 mm stretched mesh size in the cod end. Trawls were conducted during the day for 15 minutes at a mean speed of 2.5 knots.

8 Fish in Basque estuaries

A network of monitoring trawl lines along the 12 main Basque estuaries, from the inner, middle, and outer reaches (three to five trawl lines, per estuary), was established by the Basque Government, from which we selected 4 estuaries with extensive intertidal flats and lowest historical anthropogenic pollution (Barbadun, Lea, Urola, Butroe) (Borja et al. 2016). The demersal assemblage sampling was carried out every September – October, at high tide, between 2002 and 2022, once every 3 years at each of the estuaries. According to Hemingway and Elliott (2002), at each of these trawl lines, three hauls (replicates) were collected, using a 1.5 m wide beam trawl with a tickler chain; the first part of the net has 10 mm mesh size and 8 mm mesh size cod end; and towed for 10 min at 1.5 knots (sometimes the trawl period might differ, when rocks or other obstacles made the trawling difficult). Site locations were initially determined by the suitability of the seabed for trawling sampling as well as by the requirement to incorporate the whole of the salinity range within each of the estuaries. Finally, fish density was calculated considering fishing effort (beam width, time of trawling and boat speed). Samples were

identified and counted on-board immediately. Species which could not be identified were fixed in a solution of 4% ethanol, then examined in the laboratory (Uriarte and Borja 2009). The mean of each single species abundance was calculated for each year.

9 Hard bottom benthic intertidal communities in UK coastline

MarClim survey intertidal invertebrates and macroalgae species. Surveys are in areas of extensive, exposed intertidal rocky reef or artificial, hard, coastal structures/defences away from areas of coastline that are heavily developed or utilized for social or economic purposes, and avoiding riverine and estuarine outputs. Rocky intertidal surveys for MarClim are in SACFOR scale and represent species cover in quadrats (Burrows et al. 2020). The four ecoregions analysed here were UK Southwest, North Wales, South Wales and UK South) consist of time series data including sites >15 years along the UK and Ireland coasts during 2002-2020.

10 Hard-bottom coralligenous communities in the Western Mediterranean

Coralligenous assemblages represent a mosaic of different habitats home to calcareous algae and invertebrates such as corals, sponges, bryozoans or tunicates. Long-term ecological data on coralligenous assemblages was obtained from two monitoring stations (replicates, i.e., Petit Conglue and Grotte Pères) established in Calanques Natural Park (Marseille, France) in 2008 at a depth of 18-22 m. Photographs of the two sites were first analysed separately at three different years (i.e., 2018; 2012 and 2020), and then pooled together into single annual values representative for the Calanques location. Overall, 48 photographic quadrats (sub-replicates) of 25 x 25 cm (24 quadrats per site) were analysed. The sampling unit (625 cm^2 per quadrat) was selected following previous studies in the same communities (e.g., Gómez-Gras et al. (2021)). The percent cover of the different subtidal macro-benthic sessile species was calculated in each quadrat by over-imposing 100 stratified random points and identifying the underlying species to the lowest possible taxonomic level, using Photoquad software (Trygonis and Sini 2012).

11 Hard-bottom benthos in the Ligurian Sea

Data on rocky benthos was collected along the coast of the Island of Capraia (43.048 N, 9.828 E), about 40 miles off the west coast of Italy, in the Ligurian Sea (northwest Mediterranean). Low intertidal assemblages (0 and −0.3 m above mean low water level) are dominated by belts of the canopy-forming fucoid *Ericaria amentacea* (previous name *Cystoseira amentacea* Bory var. *stricta* Montagne) which alternate with patches occupied by algal turfs, encrusting coralline algae or bare rock (Bulleri et al. 2002, Tamburello et al. 2013), varying in size between tens to hundreds of cm^2.

Assemblages were sampled annually in summer, from 2007 to 2016, in 64 contiguous quadrats, 50 x 50 cm in size. The abundance of sessile macroalgae and invertebrates was assessed visually in 20 x 20 cm quadrats that were placed in the center of each 50 x 50

cm quadrat along each transect. The final percentage covers were calculated by summing over the 25 sub-quadrats (Dethier et al. 1993). Data were classified at the species level.

12 Soft and hard-bottom macrobenthic communities in the Bay of Biscay

Hard-bottom macrobenthic community: Intertidal rocky benthic communities including hard bottom macroinvertebrates, lichens and macroalgae were analysed during 2002-2020 within "Littoral Water Quality Monitoring and Control Network", from the Basque Water Agency (URA) (Borja et al. 2016). Samples were collected every 3 years in 26 intertidal transects along the Basque coast, perpendicular to the shoreline. A semi-quantitative sampling of surface coverage similar to Braun-Blanquet[3] was carried out across the transects, scaled from 1 (low coverage) to 7 (high coverage). The arithmetic mean of each single species abundance was calculated for each year.

Soft-bottom macrobenthic community: Subtidal soft-bottom macroinvertebrates were sampled with a van Veen grab (0.1 m^2) at ~30 m depth and identified to species level to estimate abundance (individuals/m^2) and community composition at all stations along the Basque coast within "Littoral Water Quality Monitoring and Control Network", from the Basque Water Agency (URA) (Borja et al. 2016). The sampling of most of the stations started in 1995. At each station, an annual sample was taken in winter, consisting of 3 replicates. The data used in the calculation of CTI includes stations with the lowest anthropogenic impact. The arithmetic mean of each single species abundance was calculated for each year.

13 Soft-bottom benthos in the Kattegat

The Danish soft-bottom benthic macrofauna in the Kattegat Sea was divided into Northwest and Southwest areas according to a salinity gradient observed in the region (Sildever et al. 2015). 85% of the stations analyzed were sites with >15 years within the 1980-2012 period. Subtidal soft-bottom macroinvertebrates samples were taken from surface to 60 m depth. Freely available data contains abundance (number of individuals per species) and biomass (wet weight or dry weight per species) information (Josefson and Rytter 2015)[5]. We used number of counts per species across the Southwest and Northwest areas in the CTI analysis.

14 Soft-bottom benthos in Wadden Sea

Intertidal benthic macroinvertebrates were sampled at 15 sampling stations in the Balgzand tidal flat (Western Wadden Sea). Samples were taken yearly in March from 1970 until 2019. Only data from 1980 onwards were used for this study. Twelve of the sampling stations consisted of a 1 km transect in which 50 equally spaced core samples of 0.018 m^2 were taken to a depth of 30 cm. Three more sampling stations consisted in squares of 900 m^2 were nine randomly positioned cores of 0.1 m^2 plus nine cores of 0.01 m^2 were taken. All cores were sieved with a 1 mm mesh and animals caught were identified and counted in the lab. Abundance values in terms of individual per m^2 for each

[5] https://ipt.vliz.be/eurobis/resource?r=danishbenthicmonitoring

year were used in the CTI analysis across the sampling stations. A more detailed description of the methods can be found in (Beukema 1974, Beukema and Cadée 1997).

15 Soft-bottom benthos in western Chanel (L4)

Starting in 2008, the Plymouth Marine Laboratory benthic survey is an ongoing ecological survey within the Western Chanel Observatory. Monthly benthic biological sampling is undertaken at a variety of sites within the Plymouth Sound, focusing primarily on the marine biodiversity reference site, station L4. L4 is an exposed site with a depth of approximately 54 m, with sediments ranging from mud to sand. For this research, we have used subtidal benthic macroinvertebrates data collected using 0.1 m^2 box-cores deployed from the Plymouth Marine Laboratory research vessel Plymouth Quest and separated using a 0.5 mm mesh. For each sampling occasion 4 replicates are taken. Abundance is presented as individuals per m^2. In the CTI analysis, the mean of each single species abundance for each year was used.

16 Zooplankton across European seas

We included time series data of copepods across the North Atlantic and Mediterranean Sea (Urdaibai, Saronikos, Kattegat), previously reported in Villarino et al. (2020), as well as the L4 for zooplankton in the western English Channel. Year means of abundance in terms of individuals per m^3 were used in the CTI analysis across the four time-series.

The Kattegat is a sub-area of the North Sea (56.95° N, 11.30° E), which is a transition zone between the Baltic Sea and the North Sea, with a substantially higher salinity range than the 2 sea areas it connects. The mean depth is ~20 m with a maximum depth > 90 m at the northern boundary, and half the area is shallower than 25 m (Matthews et al. 1999).

The estuary of Oka, in Urdaibai (43° 22’ N, 2°43’W) is a temperate estuary located on the Basque coast in the southern Bay of Biscay. It is a relatively short (12.5 km), shallow (mean depth of 3 m), meso-macrotidal and marine-dominated system, with high salinity waters in the outer half and a stronger axial gradient of salinity towards the head (Villate et al. 2008). The zooplankton series used in this study corresponds to the monthly sampling at high tide in the salinity zone of around 35 located at the mouth of the estuary, which is inhabited by neritic zooplankton (Fanjul et al. 2018).

The Gulf of Saronikos is a semi-enclosed embayment on the western coastline of the Aegean Sea, in the eastern Mediterranean Sea. Saronikos Station 11 (Saronikos S11) is in the Saronikos Gulf at 37° 52.36’ N, 23° 38.30’ E with a bottom depth of 78 m. Mesozooplankton sampling was performed by vertical hauls (WP2 net, 200 μm) from ~75 m to the surface.

Station L4 is a well-established European coastal time-series station located in the western English Channel[6] (Eloire et al. 2010). Samples are collected weekly by vertical net hauls (WP2 net, mesh 200 μm) from 50 m to the surface (Atkinson et al. 2015). Sea floor depth is 54 m and most of the water column zooplankton are sampled by these 0-50 m hauls (Parry et al. 2020). Abundance is presented as numbers per m^3. Here, year means

[6] https://www.westernchannelobservatory.org.uk/l4_zooplankton.php

of individual per m^3 over 1988-2017 period were used for the CTI analysis in the L4 case study (Atkinson et al. 2015).

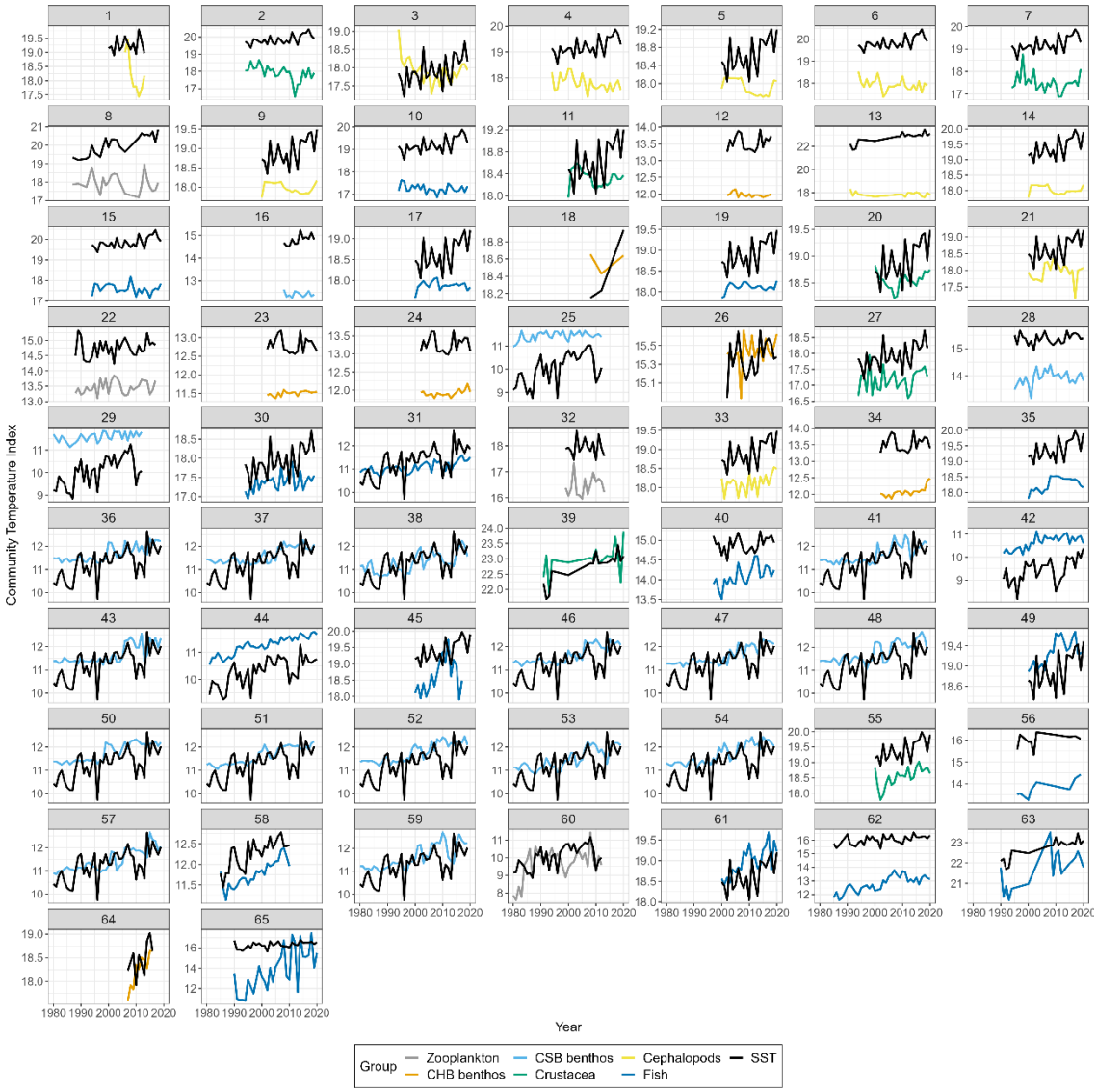
Supplementary Table 1. Linear models of tropicalization and deborealization

Tropicalization minus deborealization at per-species level analysed with linear mixed models by factors for positive temporal rate of Community Temperature Index (CTI_r>0). t- and p-values correspond to two-sided Wald test CHB: coastal hard bottom; CSB: coastal soft bottom. SE: Standard Error. AICc: Akaike's Information Criterion corrected. Significant p-values (p<0.05) are in bold.

Factor	Level	n	Tropicalization *minus* Deborealization mean (ºC y^{-1})	Tropicalization *minus* Deborealization SE	n	t-value	p-value	AICc
Biological group	CHB benthos	6	0.0233	0.0194	2809	1.202	0.2342	-3577.94
	CSB benthos	18	0.0239	0.0115	2809	2.082	**0.0416**	
	Zooplankton	3	-0.0158	0.0288	2809	-0.548	0.5853	
	Demersal crustaceans	4	0.0238	0.0207	2809	1.147	0.2559	
	Cephalopods	5	-0.0031	0.0210	2809	-0.148	0.8822	
	Fish	16	-0.0200	0.0114	2809	-1.758	0.0838	
Habitat	Benthic / demersal	40	0.0175	0.0055	2770	3.190	**0.0023**	-3623.56
	Estuarine	3	0.0043	0.0221	2770	0.195	0.8458	
	Pelagic	8	-0.0908	0.0154	2770	-5.908	**<0.0001**	
Region	Baltic Sea	4	0.0043	0.0241	2809	0.179	0.8582	-3596.88
	Mediterranean Sea	19	-0.0133	0.0100	2809	-1.321	0.1912	
	Northeast Atlantic	29	0.0198	0.0090	2809	2.193	**0.0321**	
Basin type	Non-enclosed seas	26	0.0215	0.0094	2809	2.275	**0.0263**	-3604.01
	Semi-enclosed seas	26	-0.0093	0.0088	2809	-1.056	0.2946	

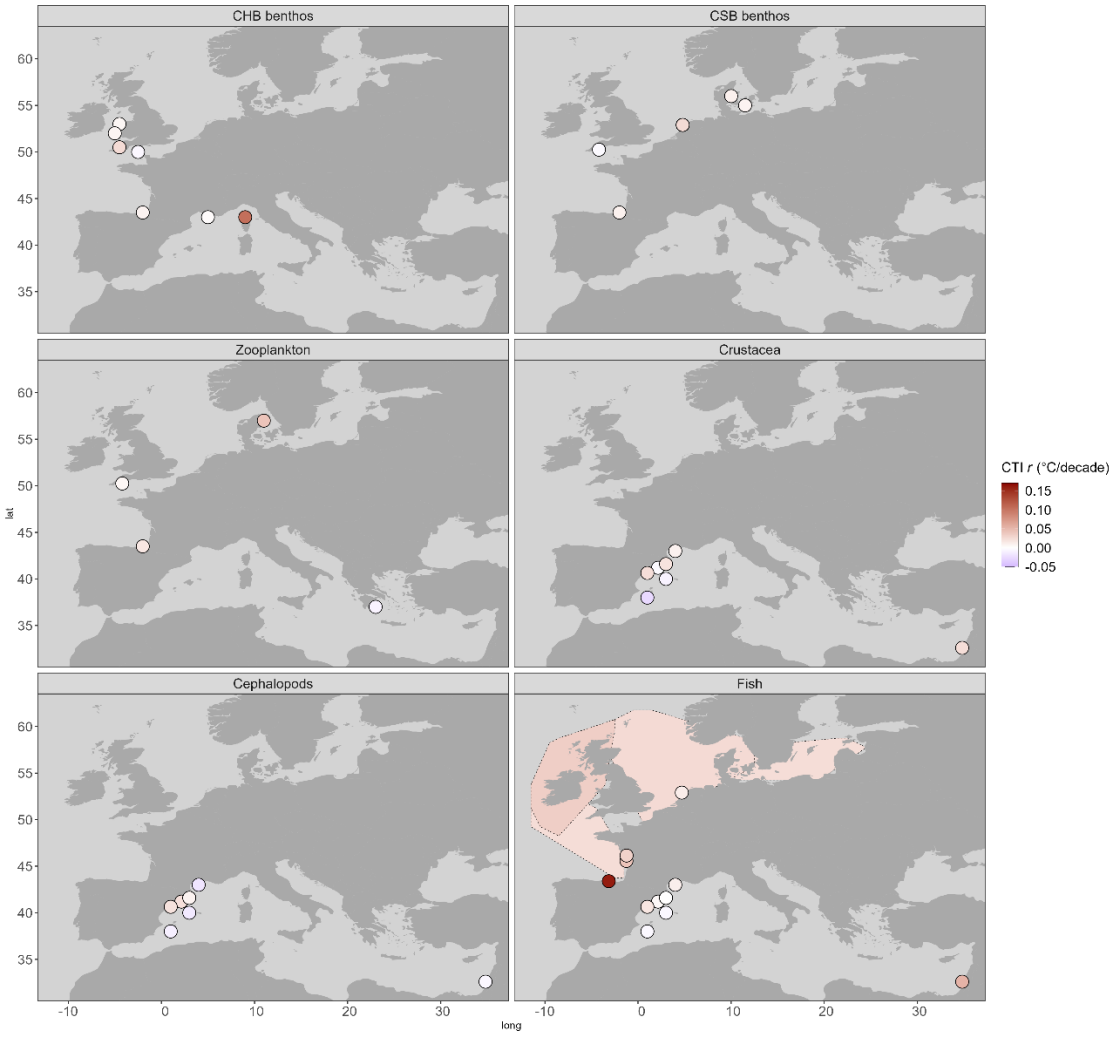
Supplementary Figure 1. CTI and SST trends for each time series

CTI and SST annual means over time for each time series. For time series labelling, see Supplementary Data.



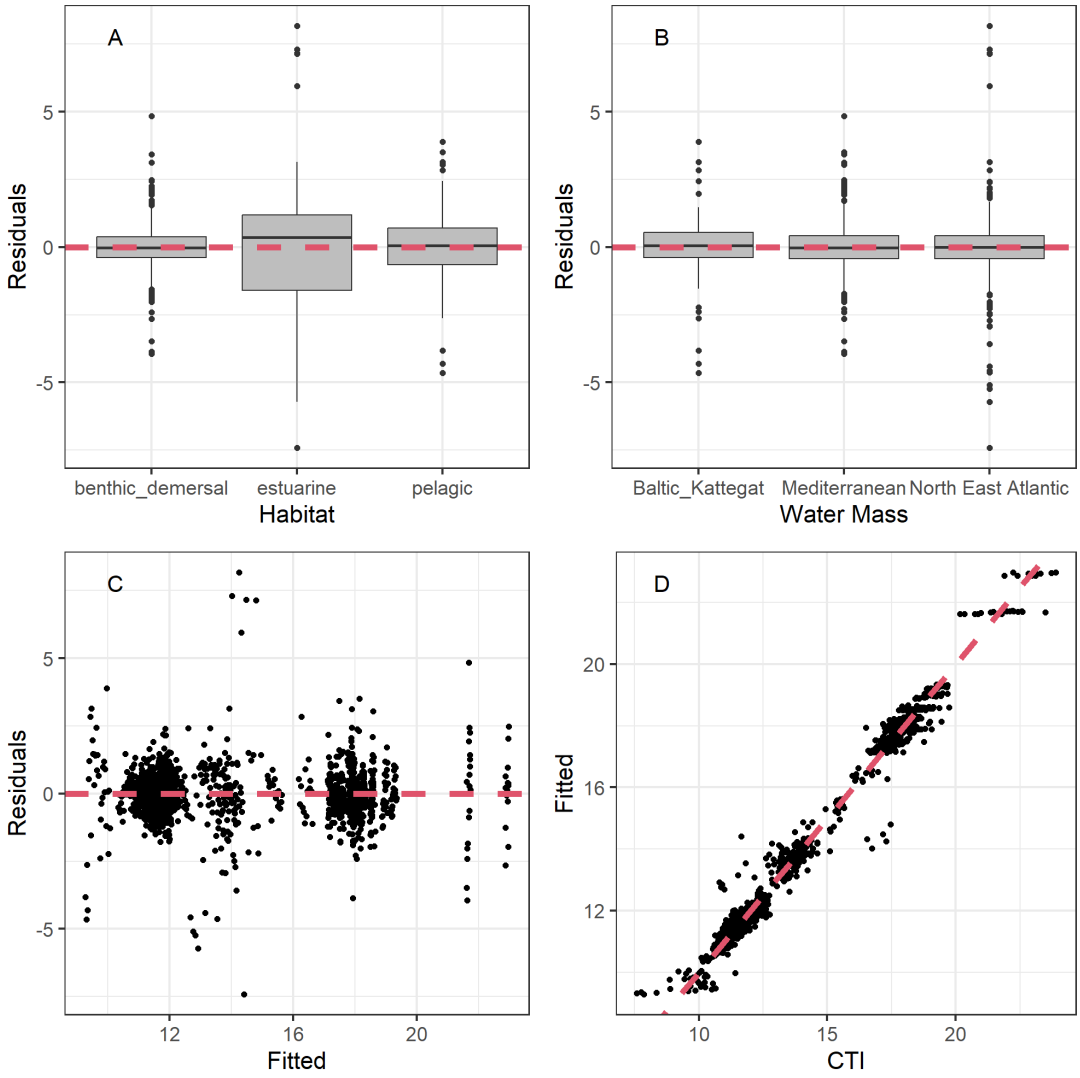
Supplementary Figure 2. Spatial Distribution of rates of change in CTI

Spatial Distribution of rates of change in Community Temperature Index (CTI) over time (ºC decade^{-1}) across biological groups within European seas. CTI_r for same biological group and location has been averaged for map visualization. CHB: coastal hard bottom; CSB: coastal soft bottom. Map source: geom-sf function from ggplot2 R package (Wickham 2016).



Supplementary Figure 3. Diagnostic plots of CTI linear mixed model

Diagnostic plots of residuals for factors selected in the linear mixed model of CTI (A and B), residuals *vs* fitted values (C), and CTI *vs* fitted values (D). The bottom and top of the boxplots (A and B) are the lower (Q1, i.e. 25%) and upper (Q3, i.e. 75%) quartiles, and the band inside the box is the median. n=51(benthic-demersal), 3 (estuarine), 10 (pelagic), 4 (Baltic), 30 (Mediterranean), 31 (NE Atlantic). Source data are provided as a Source Data file.



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