Supplementary Information

Fredston et al.

2022

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1 Supplementary methods

All code used to conduct this analysis is publicly available at https://github.com/afredston/marine_heatwaves_trawl. Raw datasets are publicly available at [DOI LINK].

1.1 Trawl data preparation

To compare biomass across surveys with different methods, it must be converted into an index of catch per unit effort (CPUE; here, kg / km^2). To estimate the fish biomass from each sample, the minimum required information is: taxa specific weight or abundance at length data, swept area or information to estimate it from sampling duration, sampled distance and gear opening. When species weight needed to be estimated from abundance at length data for ICES surveys, length-weight relationships were retrieved from locally relevant areas from FishBase. Missing swept area information was estimated when relevant based on survey variables such as sampling ship, sampling depth, and haul duration. Reported taxonomy in the surveys was cleaned and homogenized with the World Register of Marine Species for a semi-automated method, and information from taxonomic inconsistencies reported by surveys providers and experts was used to correct taxonomic names. We omitted survey-years with very few samples, a change in the area sampled, or other methodological inconsistencies, and only analyzed surveys that were conducted annually or biennially for at least ten consecutive survey-years (methods detailed below). A total of 18 surveys were incorporated, with a total of 202,819 hauls covering 2088 taxa before spatio-temporal standardization of each survey region. 80% of those taxa were identified to species, 12% to genus, and the remaining 8% to higher taxonomic levels. We used all of the taxa for biomass analyses but only the species-level records for community analyses.

Data cleaning scripts from the FISHGLOB project are summarized below and contained in [CODE LINK]:

The marine heatwave analysis began with the harmonized FISHGLOB v1.1 public dataset, and additional data trimming measures are summarized below and contained in prep_trawl_data.R:

- Omit surveys in FISHGLOBv1.1 that show very inconsistent sampling patterns in the summary PDFs [PDF LINK]

- Calculate CPUE for the one region for which it is not calculated in FISHGLOB already: the Northeast US. This region does not report swept area, but staff at the survey agency (NOAA) use a fixed value for the swept area for all hauls, regardless of haul duration (the fixed value is standardized to a 30-minute haul). To make this a more reasonable assumption, we omit hauls more than 5 minutes shorter or longer than the target haul duration, and then calculate CPUE
- Manually trim out years for which, based on the summary PDFs, our expert opinion is that survey methods were not consistent (e.g., far fewer hauls than usual). This step most frequently omits the early years of a survey, when methods and sampling intensity were not yet standardized; these years may also be too early to match to temperature data, and thus would have been omitted later in the analysis anyway
- Remove surveys that have fewer than 10 years of data, as our focus is temporal dynamics. This step removes three small surveys in Canada
- Trim each survey to one season, i.e., the most consistently or frequently sampled three-month interval
- Standardize spatial footprints over time for each survey by creating hexagonal cells covering the Earth's surface, pairing each haul with a cell, and retaining only hauls in the cells that were sampled every year. Cells were created using the dggridR package[1]. We used a cell resolution of 8, corresponding to a cell area of 7,774 km^2, for all regions except the Norway survey. Norway conducts an extremely large-scale scientific trawl survey that has operated in the Norwegian and Barents Seas for decades. Because this survey is larger-scale than all of the others, we used a cell resolution of 7 (cell area of 23,323 km^2) to standardize the footprint of this survey
- Impute zeros for true absences in every instance where a species ever observed in a survey was *not* encountered in a given haul
- Calculate species-specific mean CPUE as the mean of every CPUE for that species in a given survey and year (i.e., average over hauls)
- Calculate species-specific mean depth as the mean of depths where hauls occurred in a given survey and year, weighted by the species' CPUE in each haul

1.2 Power analysis

We simulated data to assess whether our study had sufficient power to detect MHW-driven biomass changes (see power_analysis.R). We fitted an autoregressive linear model of log biomass over time (Gompertz model) to each region's biomass data, including MHW presence/absence as a predictor. We extracted the coefficient ρ, intercept α, and conditional standard deviation σ of this model, and used them to simulate data from the same Gompertz model

$$log(B_t) = \alpha + \rho \times log(B_{t-1}) + \gamma \times MHW_t + \sigma'$$

where B represents biomass, MHW is a binary variable for MHW presence/absence, and γ represents the "true" MHW effect that we vary to explore power. This simulation also includes an error term σ' calculated as a random draw from a normal distribution with mean 0 and standard deviation σ. We (1) varied the number of years the simulation was run (assuming that each region was sampled for the same number of years) from 10 to 100 in 10-year intervals with a fixed value of $\gamma = ln(0.94)$, corresponding to the 6% loss of biomass predicted by,[2] and (2) varied γ to represent biomass losses of 5% to 50% (in 5% intervals, although we also included a $\gamma = ln(0.94)$ trial to correspond to[2]) given the actual number of years of data we have for each region ($n = 460$). For both of these tests, simulations were run for each region individually, converted into log ratio units (used in the main text), and pooled across regions. Each set of simulations was run 1000 times for each condition (region and either number of years or γ).

With these two simulated datasets—annual, regional biomass with a true MHW effect on biomass of -6% and variable numbers of years, and annual, regional biomass with a fixed number of years from the real dataset and a variable effect of MHW on biomass from -5% to -50%—we conducted the same statistical tests as we did in the main text to look for an effect. For every simulation iteration, we split the biomass log ratio data into MHW and non-MHW years and compared the two with a t-test. We then calculated what proportion of those tests were significant ($p <= 0.05$).

1.3 Additional predictors

In addition to the geographical shifts that may lead to changes in biomass and community composition in a fixed area, marine fishes may shift deeper in response to warming@chaikin2022.[3] We tested for this by calculating depth log ratios that describe whether assemblages have gotten deeper or shallower from one survey to the next. Depth log ratio was quantified by: 1. Taking an average of depths at which a species was found in each survey and year, using the depth records for each haul, and weighted by biomass in the haul. 2. Taking a weighted mean of all these species-level depth values for the entire survey, again weighted by species biomass. 3. Calculating the log ratio of these survey-level, biomass-weighted depth values from one year to the next. We find no relationship between MHW duration and depth log ratio (Fig. 4) and no difference between depth changes that do and do not follow a MHW (Fig. 5).

Marine communities across latitudes have responded differently to climate change, with some declines in species richness recorded in the tropics and at equatorward range edges@chaudhary2021[4] and some increases in species richness recorded in colder oceans and at poleward range edges@hastings2020.[5] We also tested for latitudinal trends in biomass log ratios, finding that the direction or magnitude of biomass change was not related to the latitude of the region 6.

Species frequently exhibit individualistic responses to global change@fredston2021. We explored whether species taxonomy, species traits, and regional identity help to predict species-level biomass change at all and in the context of marine heatwaves. All fish species traits were obtained from the database in@beukhof2019. Of the 1753 taxa used in the analysis, 1595 had trophic level data (used in Fig. 9), 1567 had feeding mode data (used in Fig. 10), and 1588 had feeding mode data (used in Fig. 11). The pattern of no relationship between MHW duration and biomass log ratio persists when data are grouped by trophic level (Fig. 9), feeding mode (Fig. 10), or habitat (Fig. 11).

Table 1: Models of biomass change. All models were fitted to scaled and centered biomass log ratio values using MHW duration in days (scaled and centered). Model names correspond to: linear model, linear mixed-effects model with survey identity as a random effect, generalized additive model (GAM), and GAM with survey as a random effect.

	LM	LME	GAM	GAM + RE
(Intercept)	0.000	0.000	0.000	0.000
	(0.049)	(0.049)	(0.049)	(0.049)
anom_days_scale	−0.010			
	(0.049)			
SD (Intercept)		0.000		
SD (anom_days_scale)		0.000		
SD (Observations)		1.000		
Num.Obs.	422	422	422	422
R2	0.000		−0.002	−0.002
R2 Marg.		0.000		
R2 Cond.				
AIC	1202.5	1210.8	1202.6	1203.4
RMSE	1.00		1.01	1.03

Table 2: Models of biomass change. All models were fitted to scaled and centered biomass log ratio values using MHW duration in days (scaled and centered). Model names correspond to: GAM with a matrix of predictors including MHW data from 2-5 years prior to the survey in addition to the year prior to the survey.

	GAM Lag 1	GAM Lag 2	GAM Lag 3	GAM Lag 4
(Intercept)	−0.052	−0.009	−0.036	0.025
	(0.100)	(0.117)	(0.139)	(0.164)
Num.Obs.	404	386	368	350
R2	−0.002	−0.003	−0.003	−0.003
AIC	1140.1	1084.3	1041.4	1000.2
RMSE	1.00	0.99	1.00	1.02

2 Supplementary tables

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## Random effect variances not available. Returned R2 does not account for random effects.
```

Table 3: Linear mixed-effect models of overall biomass as predicted by single-species biomass, with survey identity included as a random intercept. All models were fitted to scaled and centered biomass values. Model names correspond to the number of species used as predictors. Species were ranked by from highest overall biomass in the survey to lowest.

	LME-1	LME-2	LME-3	LME-4	LME-5
(Intercept)	−0.543	−0.569	−0.474	−0.242	0.028
	(0.060)	(0.054)	(0.051)	(0.039)	(0.040)
spp1	0.557	0.501	0.499	0.502	0.505
	(0.026)	(0.022)	(0.019)	(0.016)	(0.014)
SD (Intercept)	0.173	0.168	0.167	0.105	0.045
SD (Observations)	0.688	0.570	0.490	0.400	0.370
spp2		0.466	0.443	0.445	0.430
		(0.033)	(0.029)	(0.023)	(0.021)
spp3			0.507	0.537	0.523
			(0.041)	(0.034)	(0.031)
spp4				0.530	0.436
				(0.035)	(0.034)
spp5					0.513
					(0.053)
Num.Obs.	435	435	435	435	435
R2 Marg.	0.513	0.654	0.737	0.826	0.857
R2 Cond.	0.542	0.682	0.764	0.837	0.859
AIC	941.3	787.4	665.6	491.2	417.4
RMSE	0.68	0.56	0.48	0.39	0.37

Table 4: Models of CTI change. All models were fitted to scaled and centered CTI log ratio values using MHW duration in days (scaled and centered). Model names correspond to: linear model, linear mixed-effects model with survey identity as a random effect, generalized additive model (GAM), GAM with survey as a random effect, and GAM with a matrix of predictors including MHW data from 1-4 years prior to the survey in addition to the year prior to the survey.

	LM	LME
(Intercept)	0.000	0.000
	(0.049)	(0.049)
anom_days_scale	−0.002	
	(0.049)	
SD (Intercept)		0.000
SD (anom_days_scale)		0.000
SD (Observations)		1.000
Num.Obs.	422	422
R2	0.000	
R2 Adj.	−0.002	
AIC	1202.6	
BIC	1214.7	
RMSE	1.00	1.00

Table 5: Model of depth change. Depth log ratio and MHW duration variables were scaled and centered.

	Model 1
(Intercept)	0.000
	(0.051)
anom_days_scale	0.062
	(0.050)
Num.Obs.	389
R2	0.004
R2 Adj.	0.001
AIC	1107.4
BIC	1119.3
RMSE	1.00

Table 6: Models of biomass change as a function of MHW duration and median survey latitude. All variables were scaled and centered.

	Model 1
(Intercept)	0.000
	(0.049)
anom_days_scale	−0.011
	(0.049)
med_lat_scale	−0.027
	(0.049)
Num.Obs.	422
R2	0.001
R2 Adj.	−0.004
AIC	1204.2
BIC	1220.4
RMSE	1.00

3 Supplementary figures

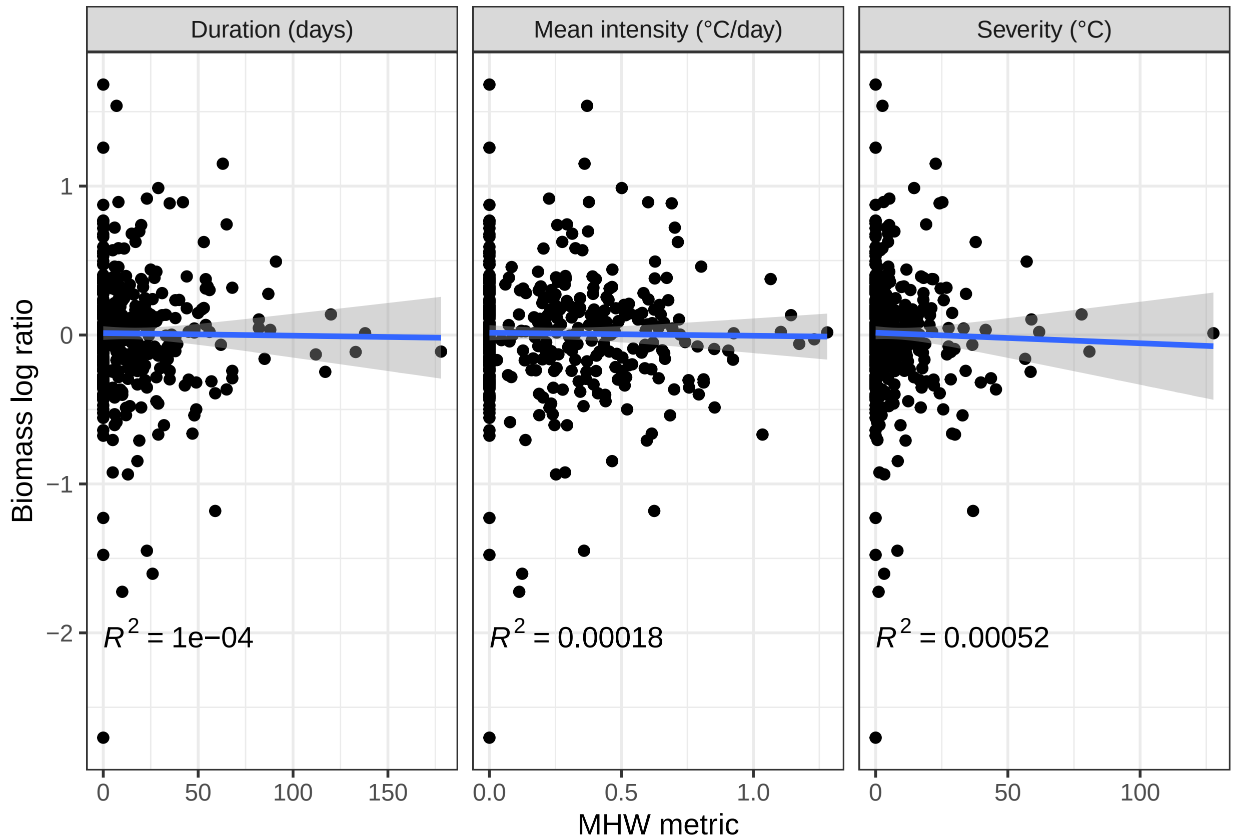

Figure 1: Biomass change (log ratio) and three metrics of measuring MHW impacts: severity (total anomaly in °C), duration (number of days), and mean intensity (severity divided by duration, i.e., the average anomaly over the course of the MHW).

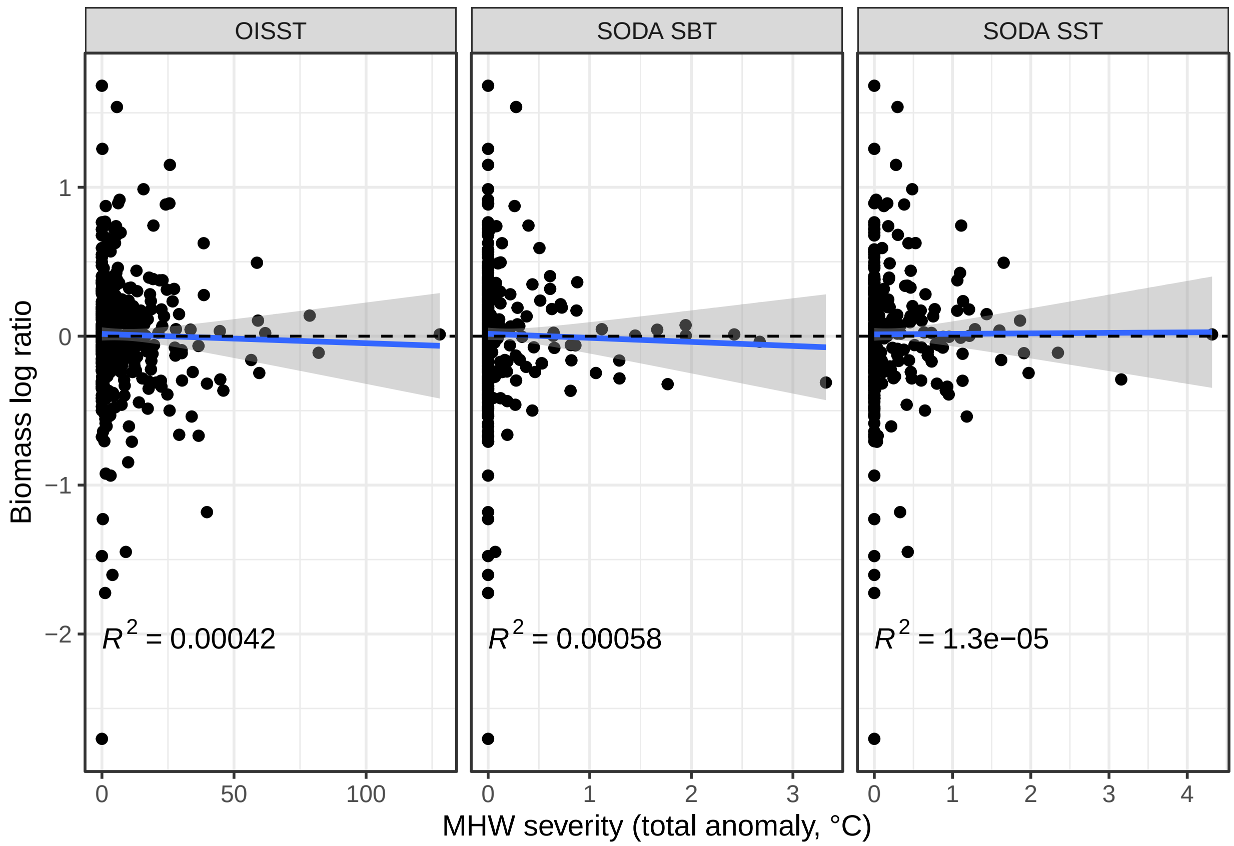

Figure 2: Biomass change (log ratio) and MHW severity from three data products. Here, we consider all anomaly-days in OISST to be MHWs, regardless of MHW duration (i.e., no 5-day cutoff). Severity is calculated as the total anomaly (°C) over the 12-month interval to which each biomass log ratio is paired. Note that the greater magnitude of severity values in OISST (see x-axis) are due to its higher (daily) temporal resolution revealing greater temperature anomalies than those that appear in the monthly SODA datasets.

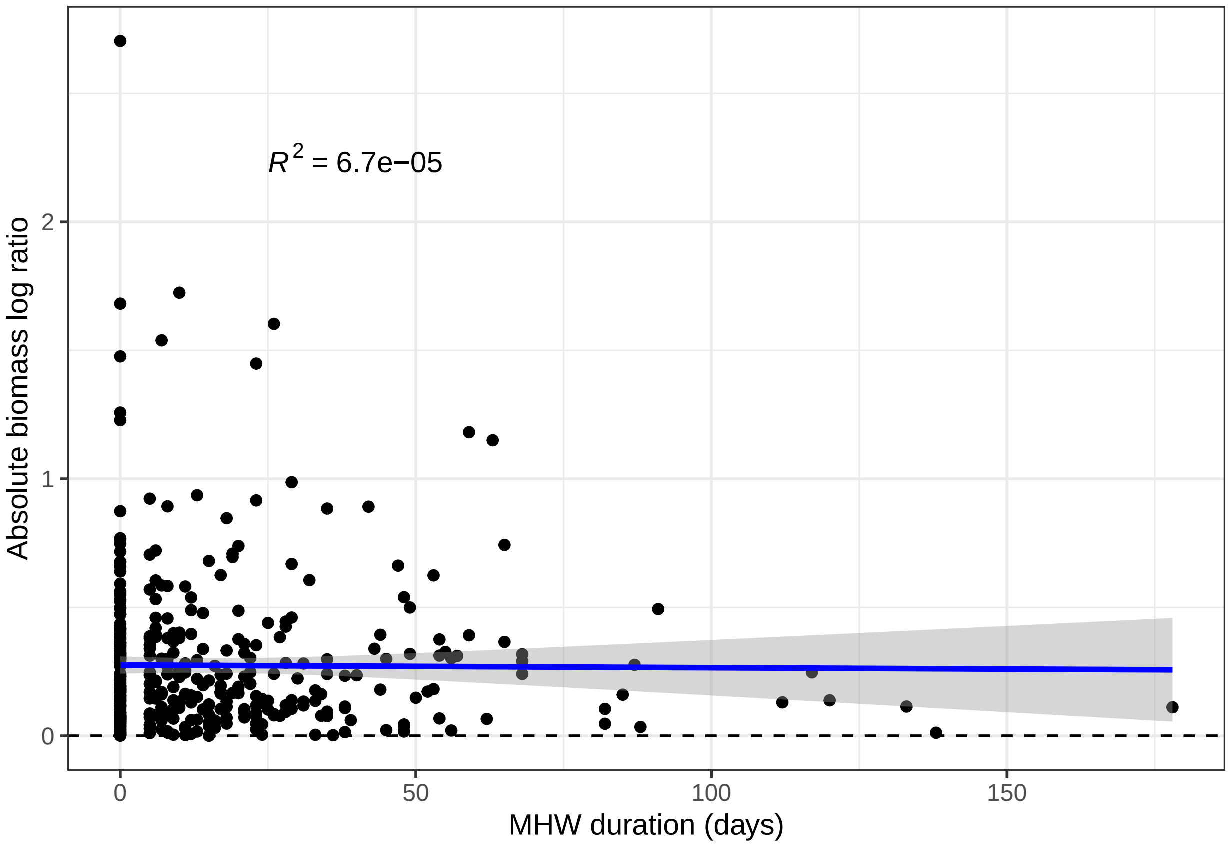

Figure 3: MHW duration and absolute value of biomass log ratio.

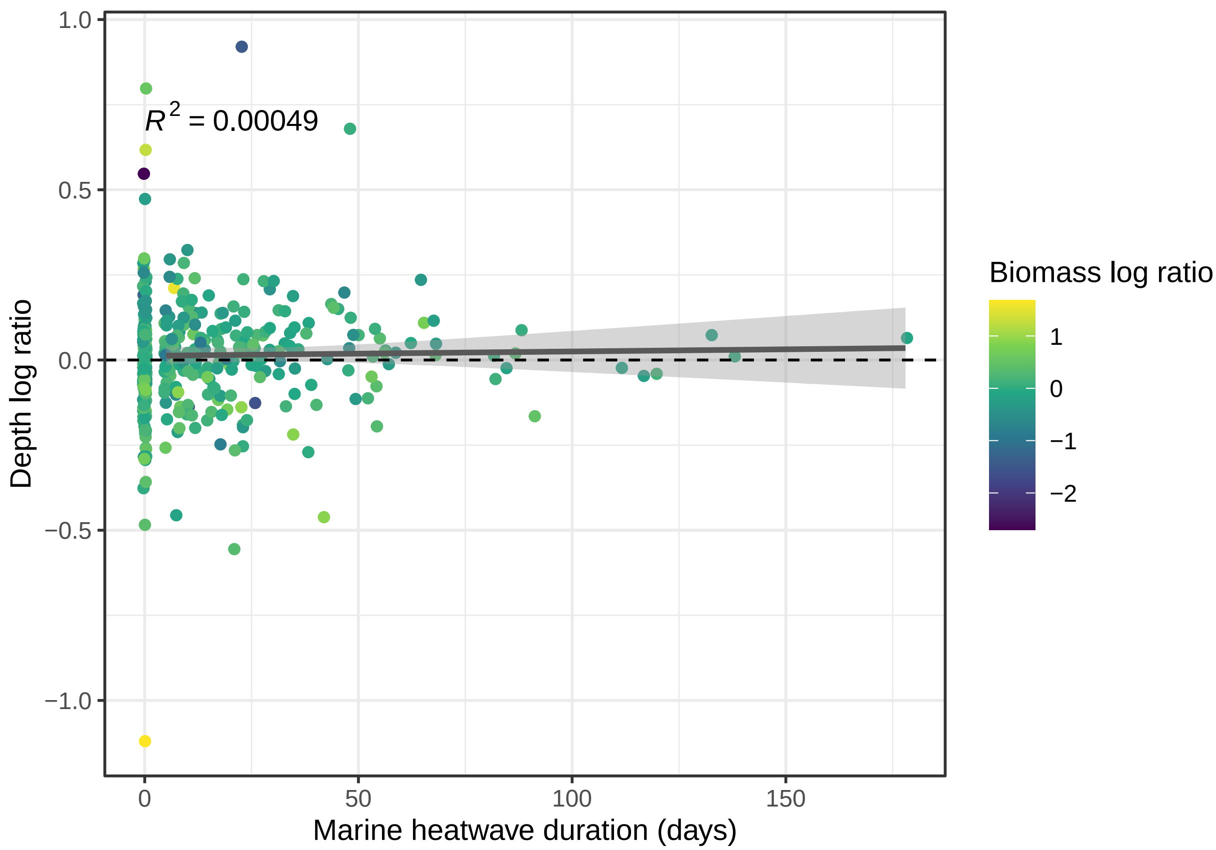

Figure 4: Fish assemblage depth change (log ratio) and MHW duration.

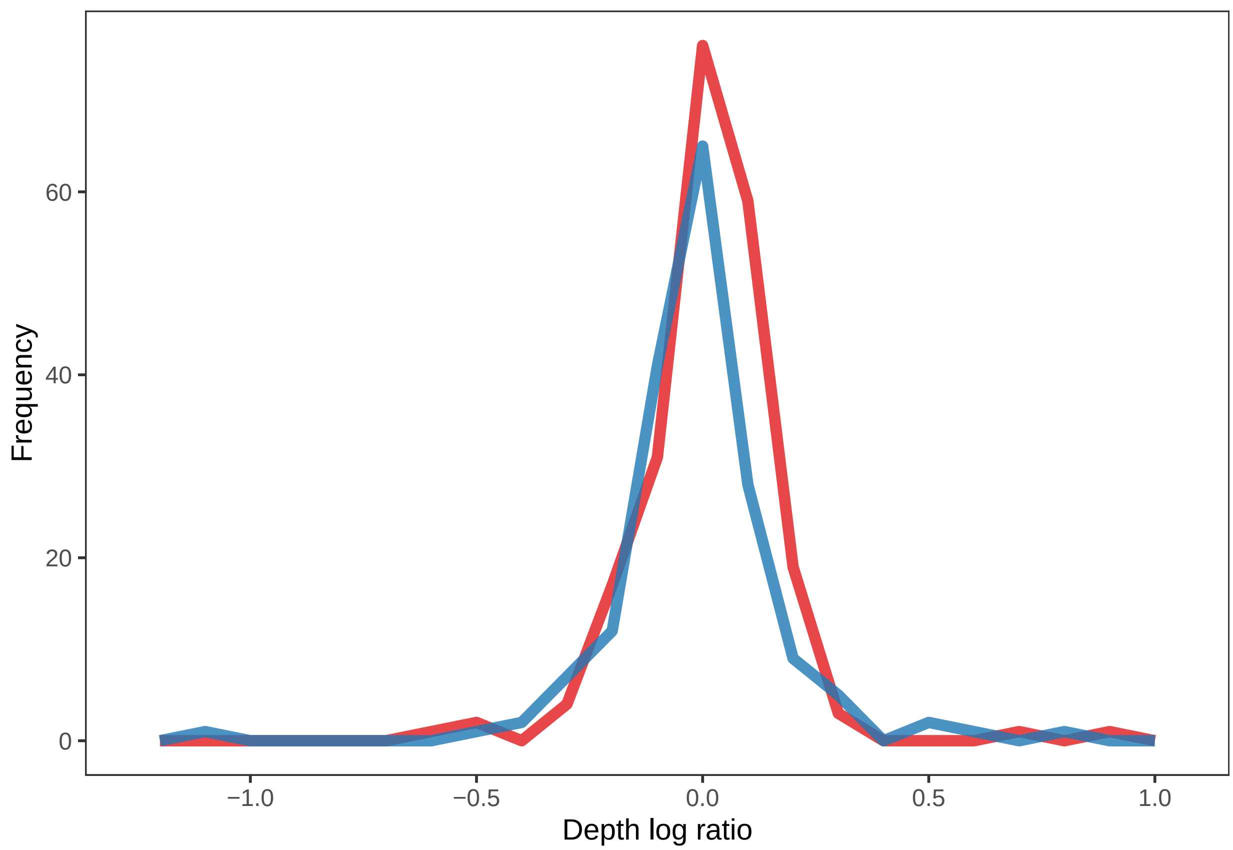

Figure 5: Fish assemblage depth change (log ratio) and MHW occurrence.

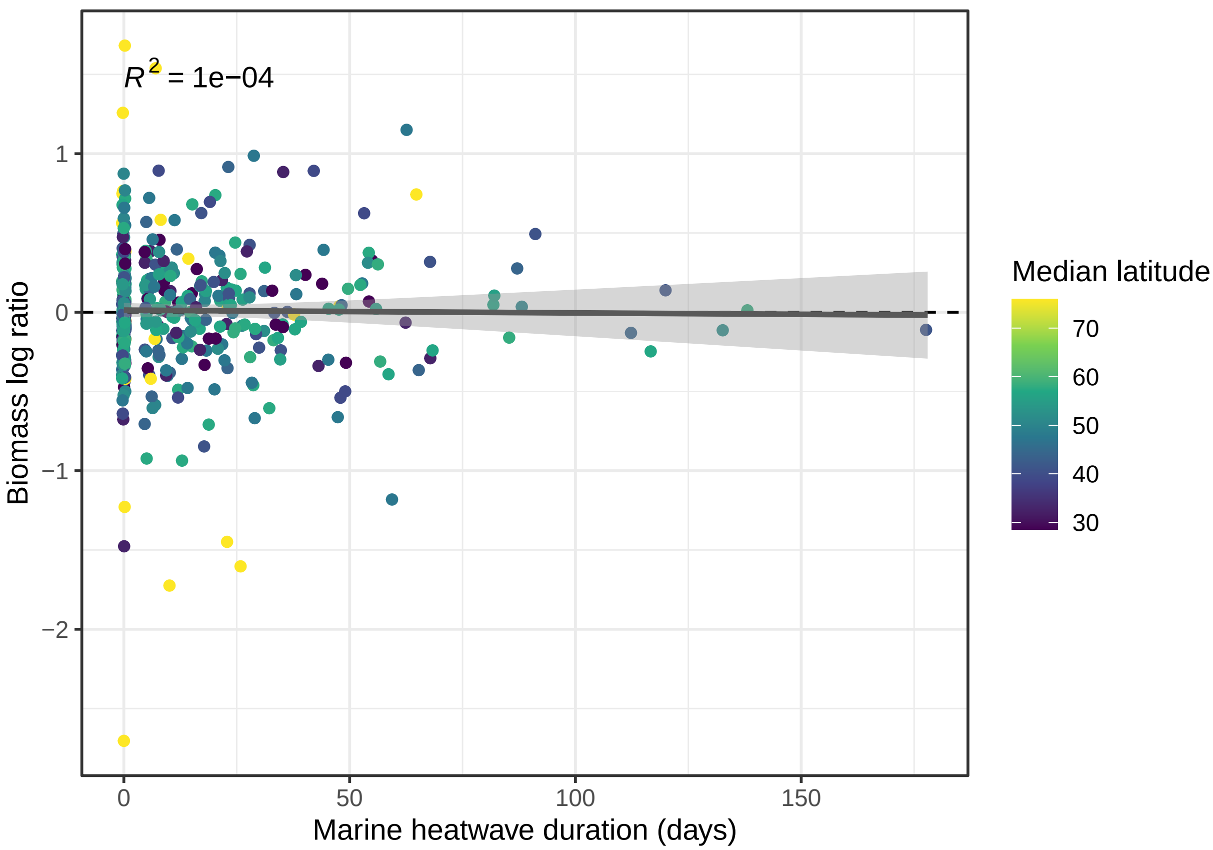

Figure 6: Biomass change (log ratio) and MHW duration, color-coded by median latitude of each survey region.

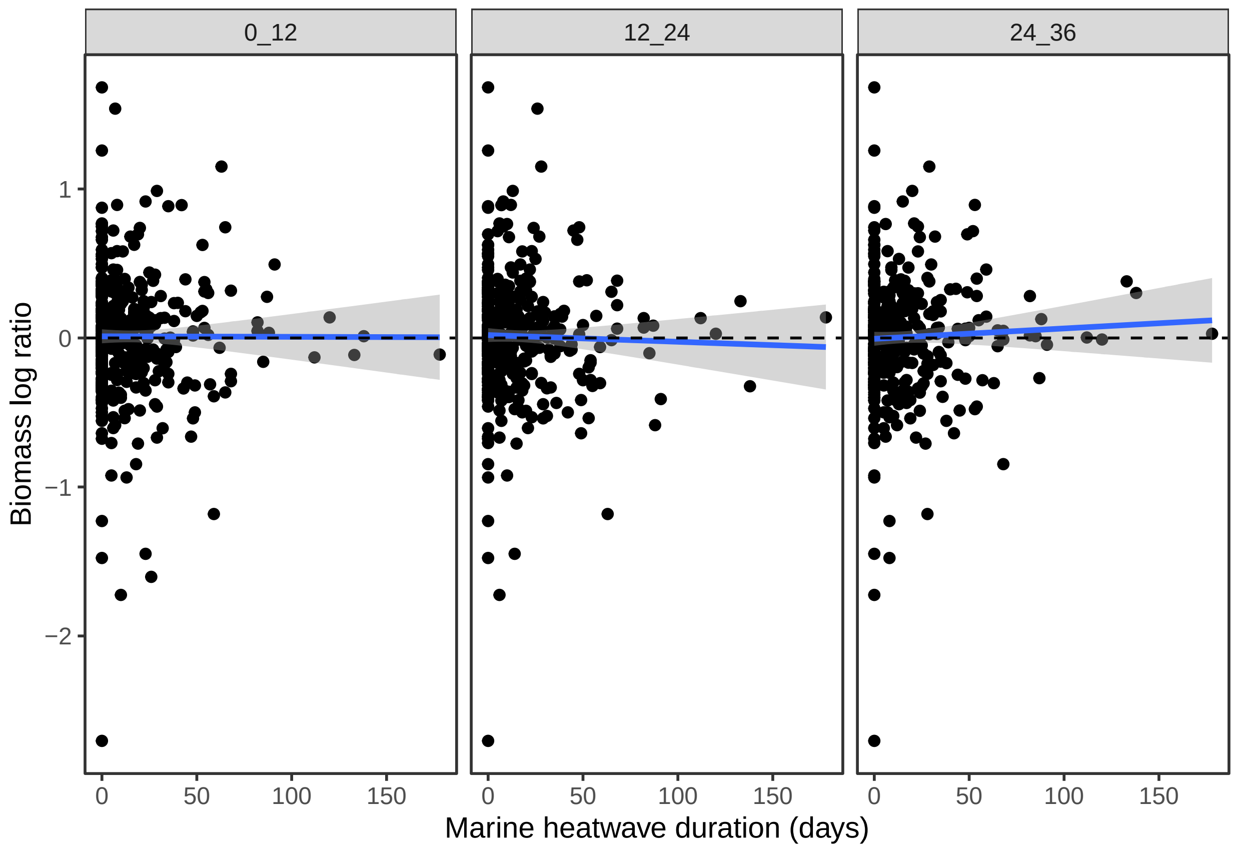

Figure 7: Biomass change (log ratio) and MHW duration calculated the preceding year as in the main text (0-12 months), a one-year lag (12-24 months), and a two-year lag (24-36 months).

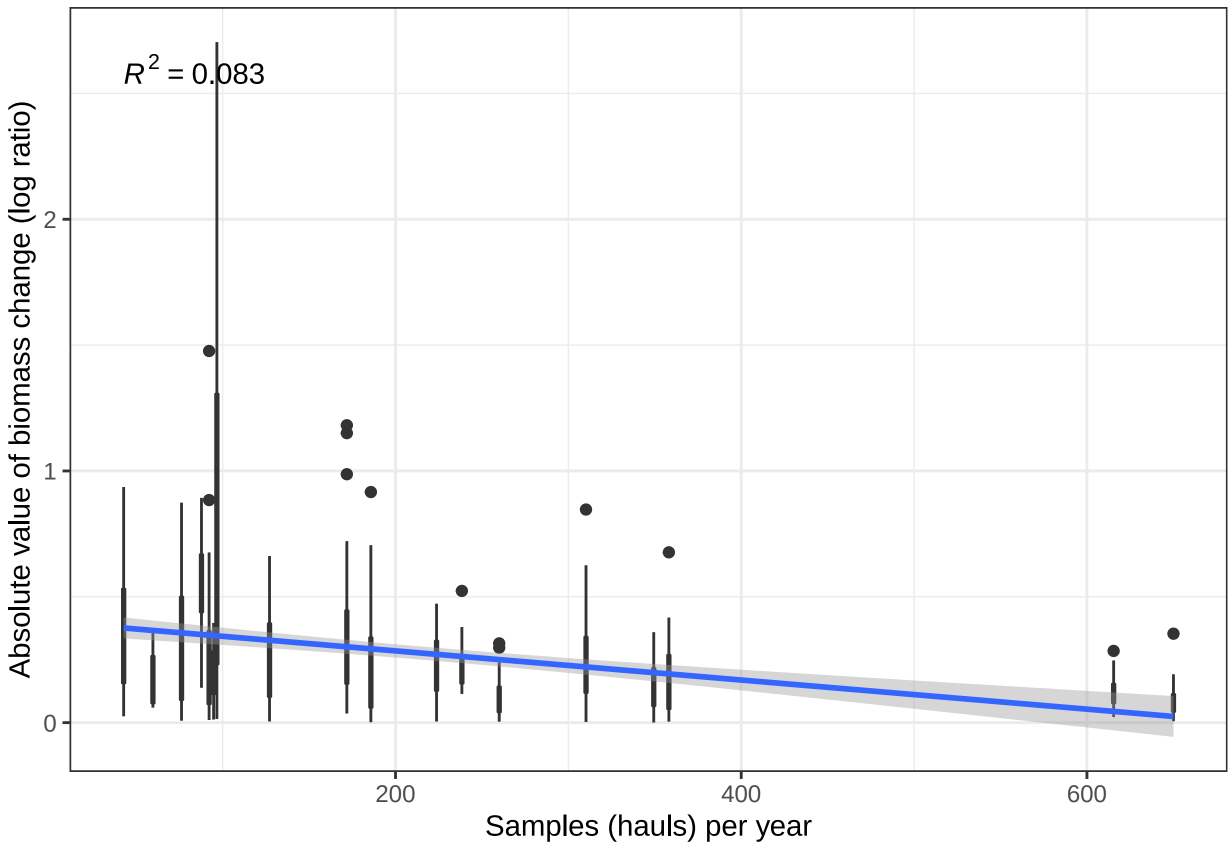

Figure 8: Absolute value of biomass log ratios vs. sampling intensity, defined as the average number of samples (hauls) per year in each region. The relationship between biomass log ratio magnitude and sampling is highly significant ($p < 0.001$).

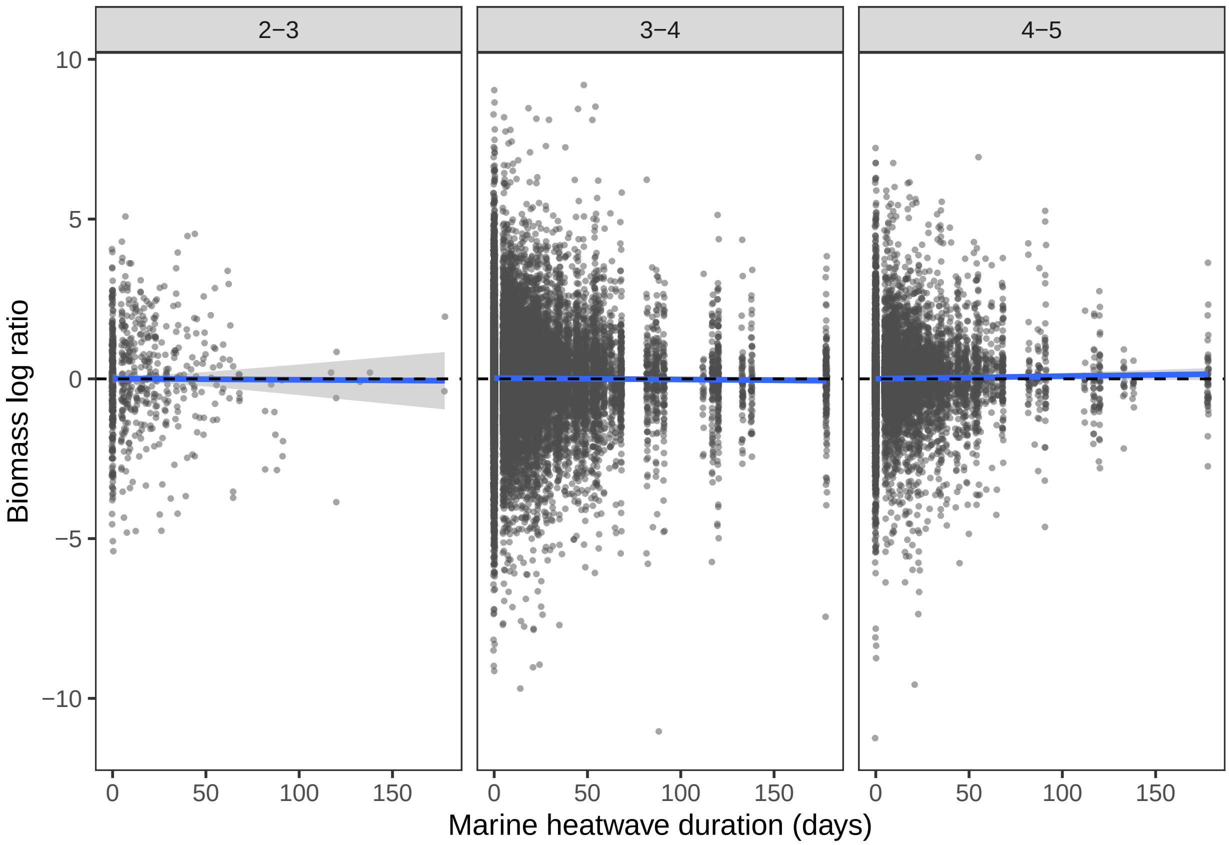

Figure 9: Biomass log ratio and MHW duration grouped by trophic level of each taxon.

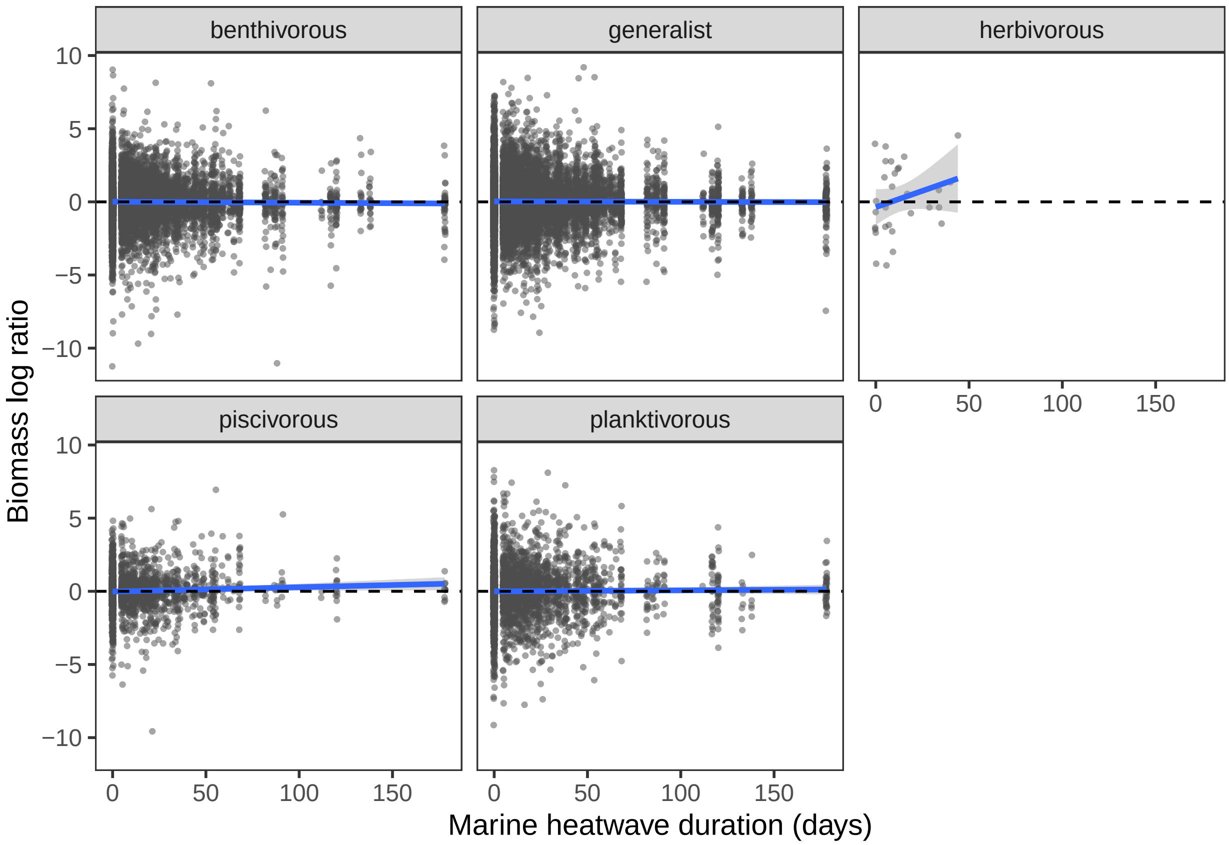

Figure 10: Biomass log ratio and MHW duration grouped by feeding mode of each taxon.

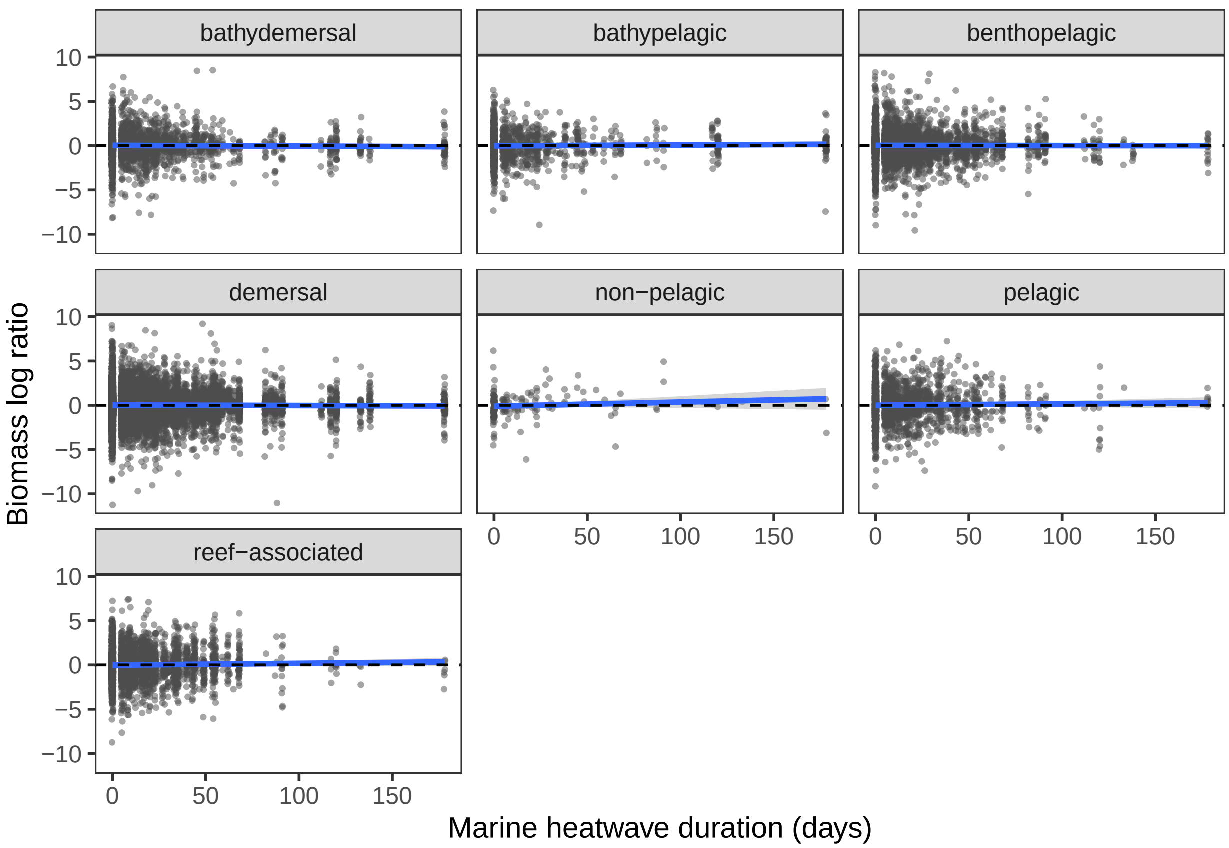

Figure 11: Biomass log ratio and MHW duration grouped by habitat preference of each taxon.

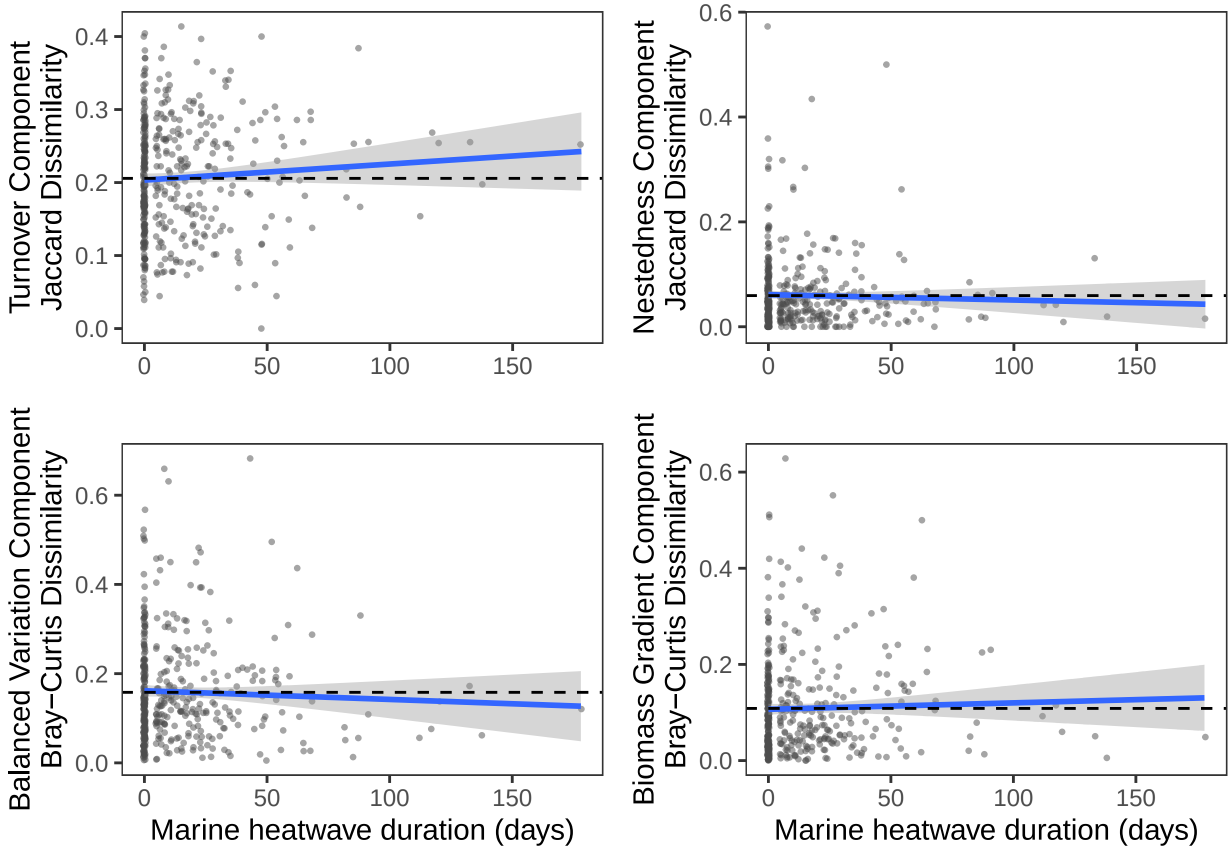

Figure 12: Temporal Community Dissimilarity and MHW duration for partitioned occurence based beta diversity metrics (Jaccard turnover and nestedness; top) and partitioned biomass based beta diversity metrics (Bray-Curtis balanced variation and biomass gradient; bottom).

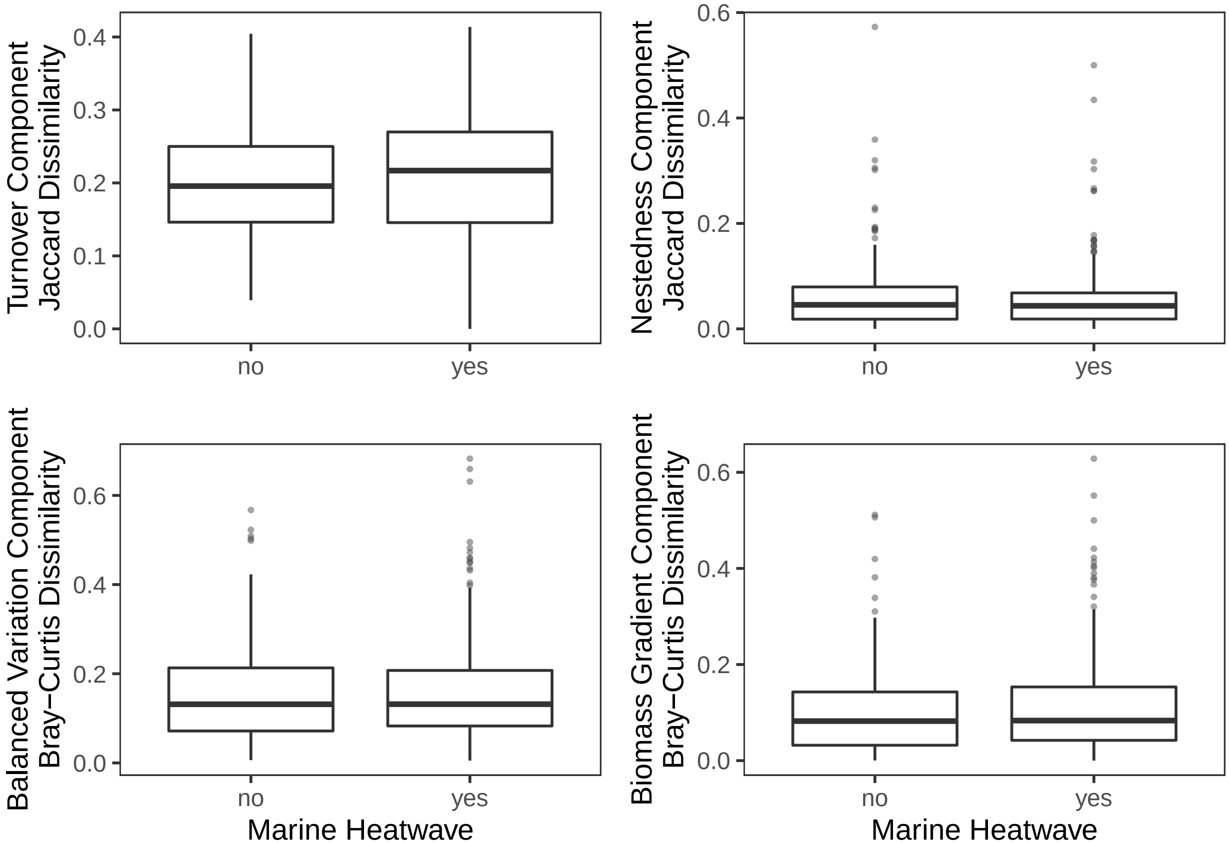

Figure 13: Temporal Community Dissimilarity and MHW event for partitioned occurence based beta diversity metrics (Jaccard turnover and nestedness; top) and partitioned biomass based beta diversity metrics (Bray-Curtis balanced variation and biomass gradient; bottom).

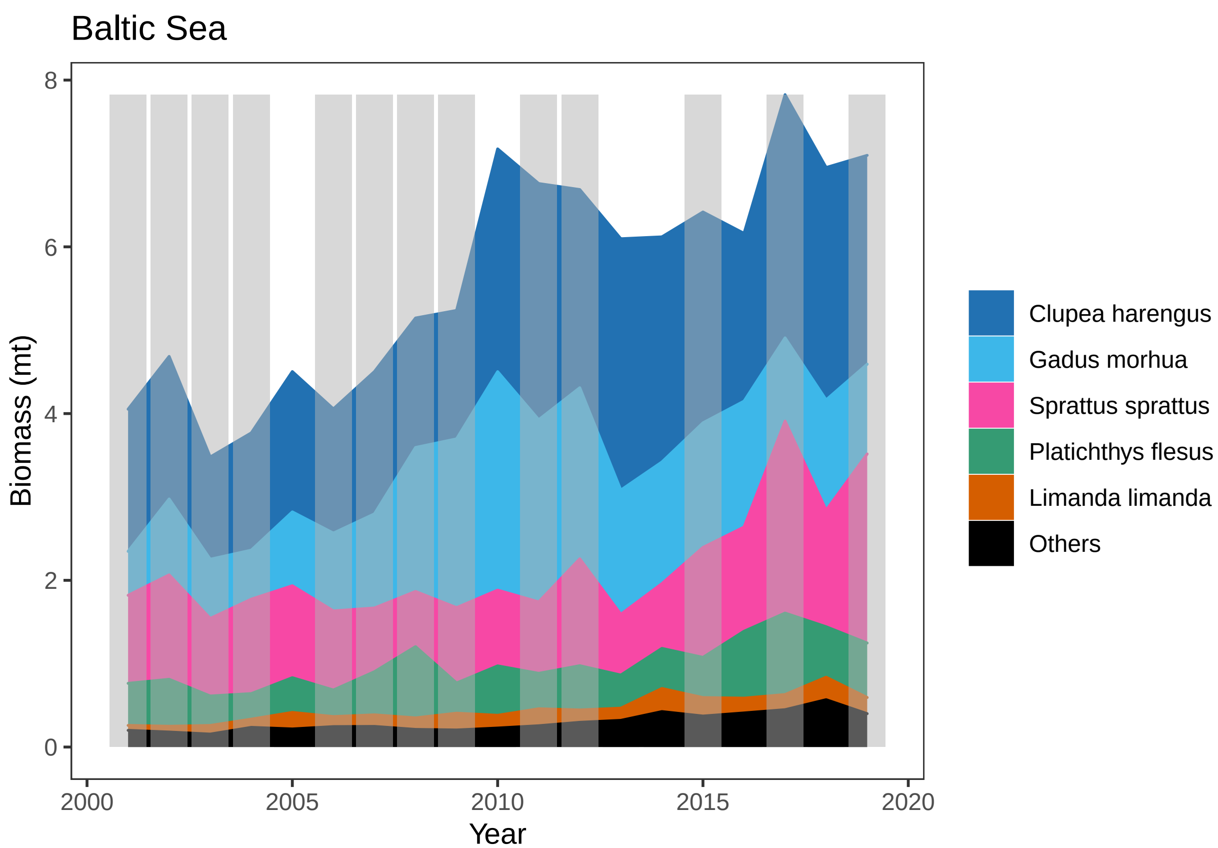

Figure 14: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

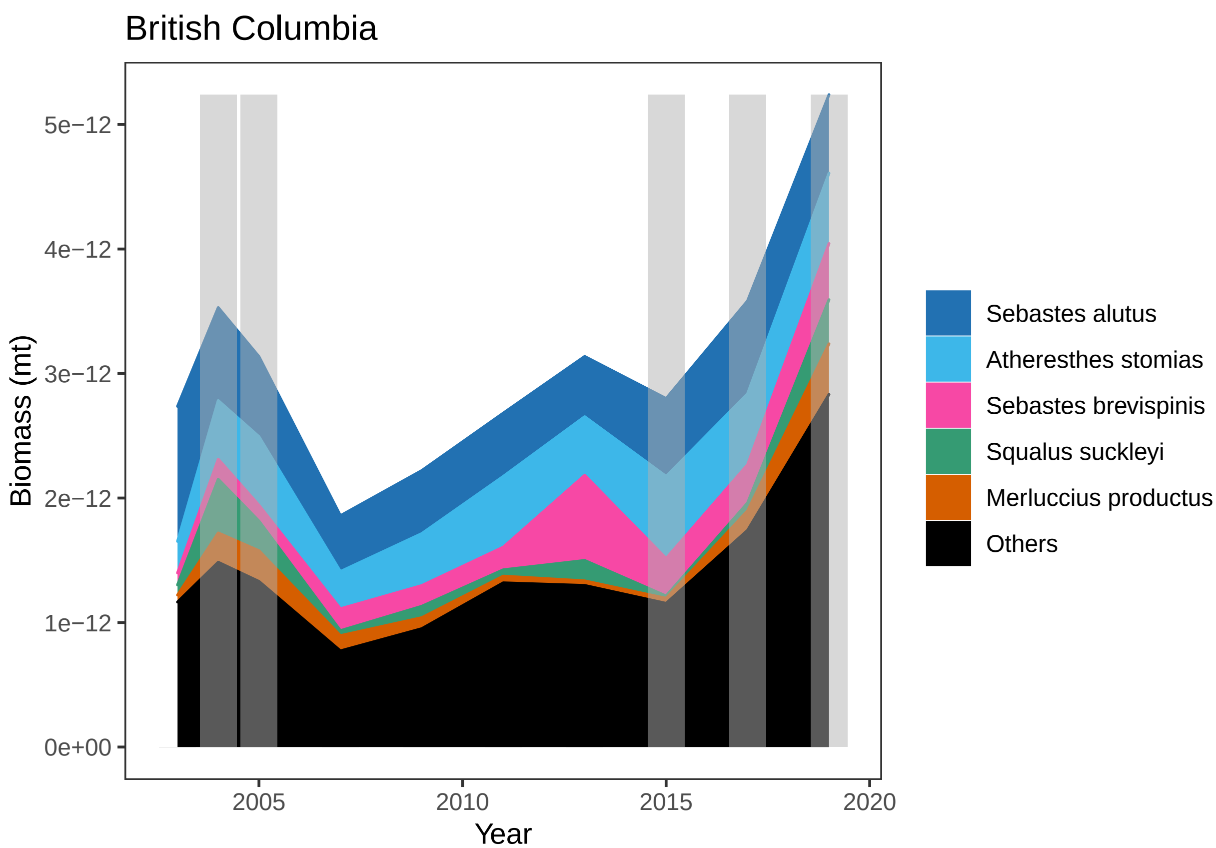

Figure 15: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

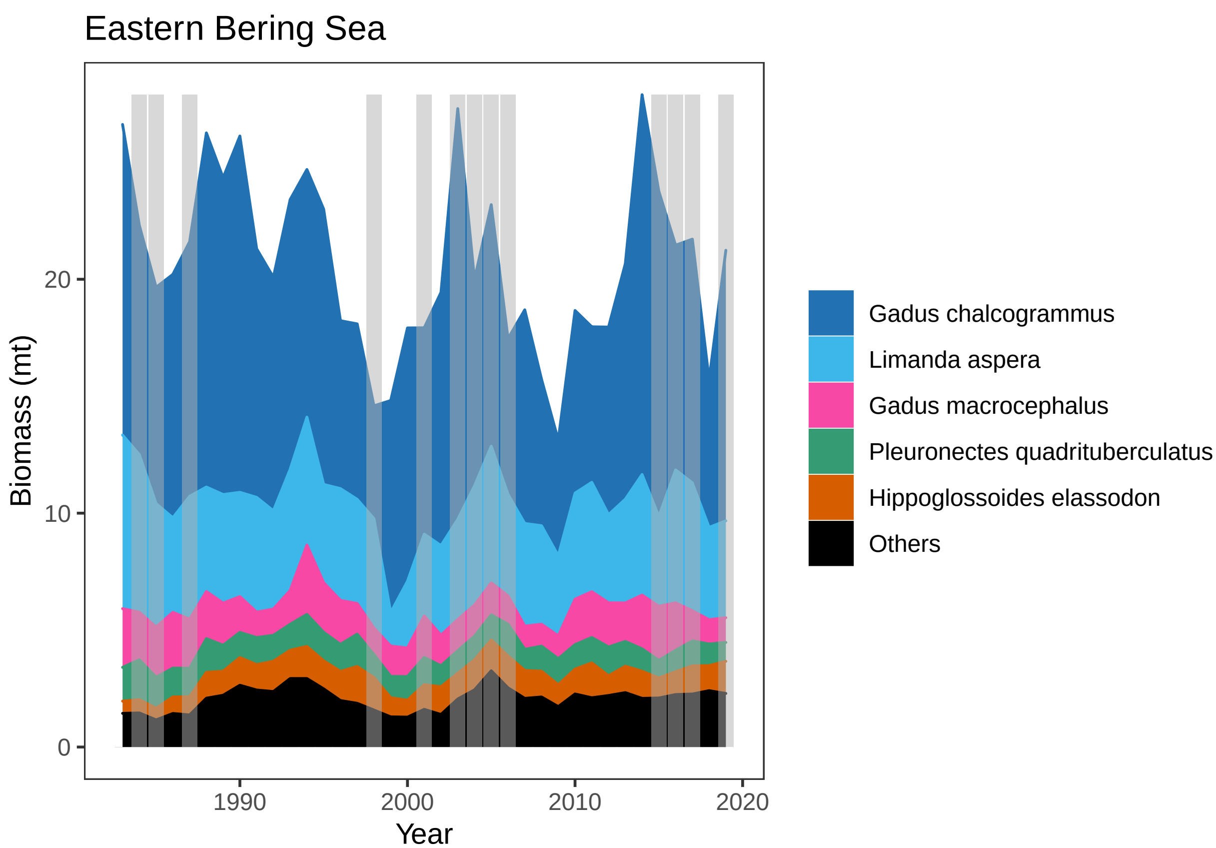

Figure 16: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

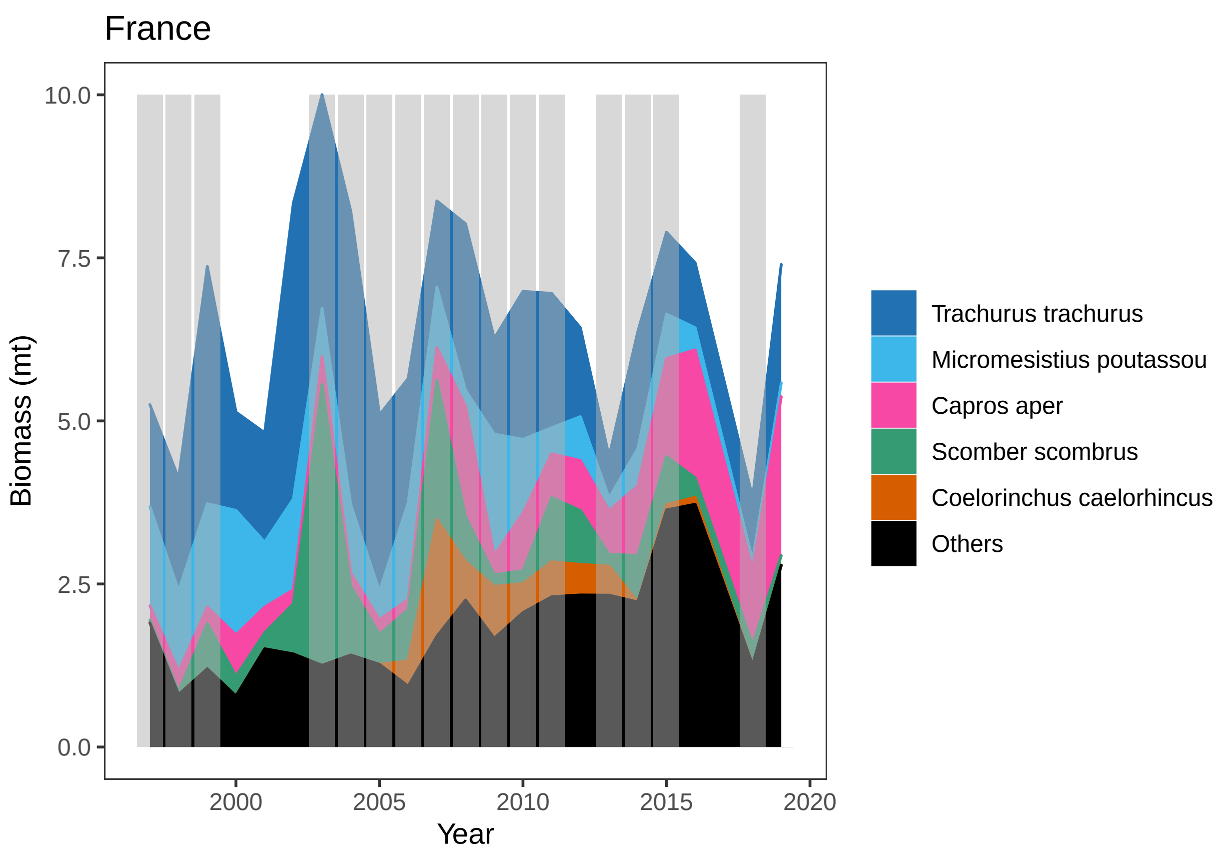

Figure 17: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

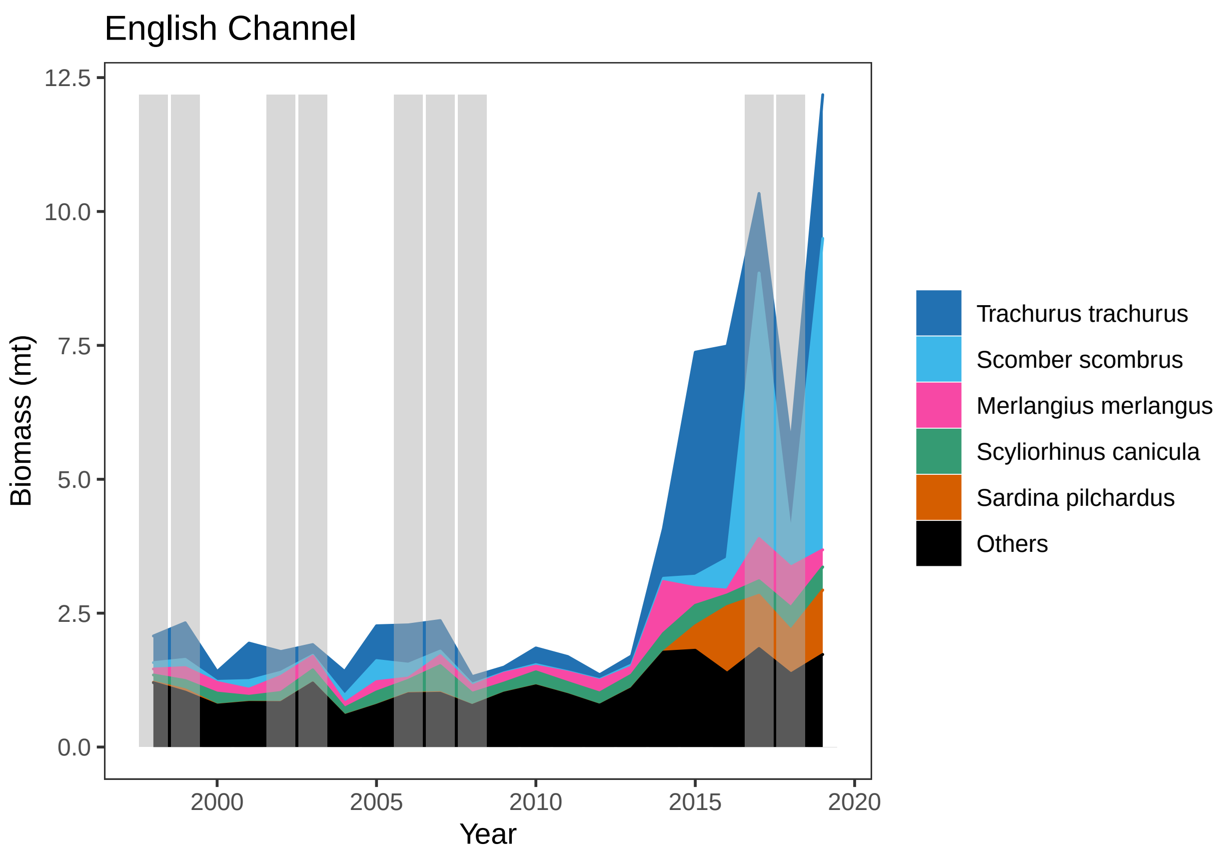

Figure 18: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

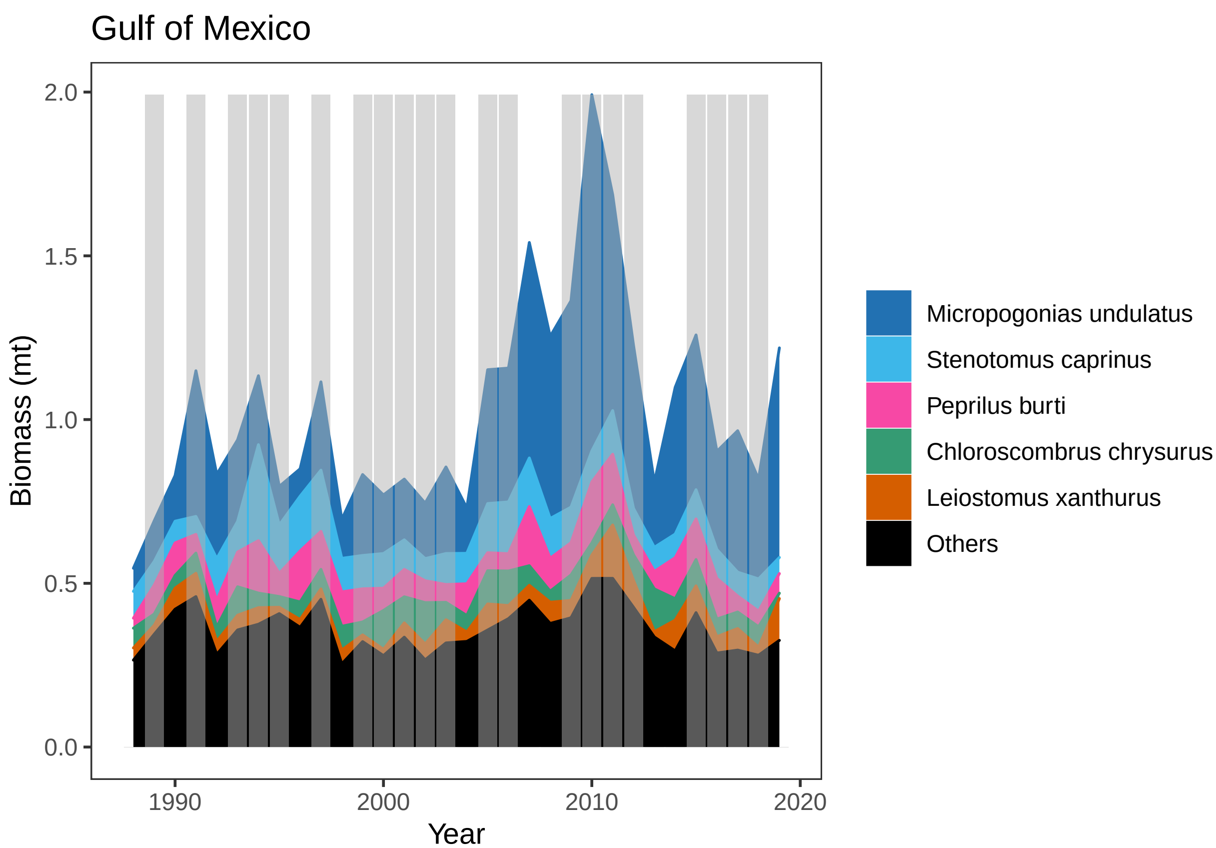

Figure 19: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

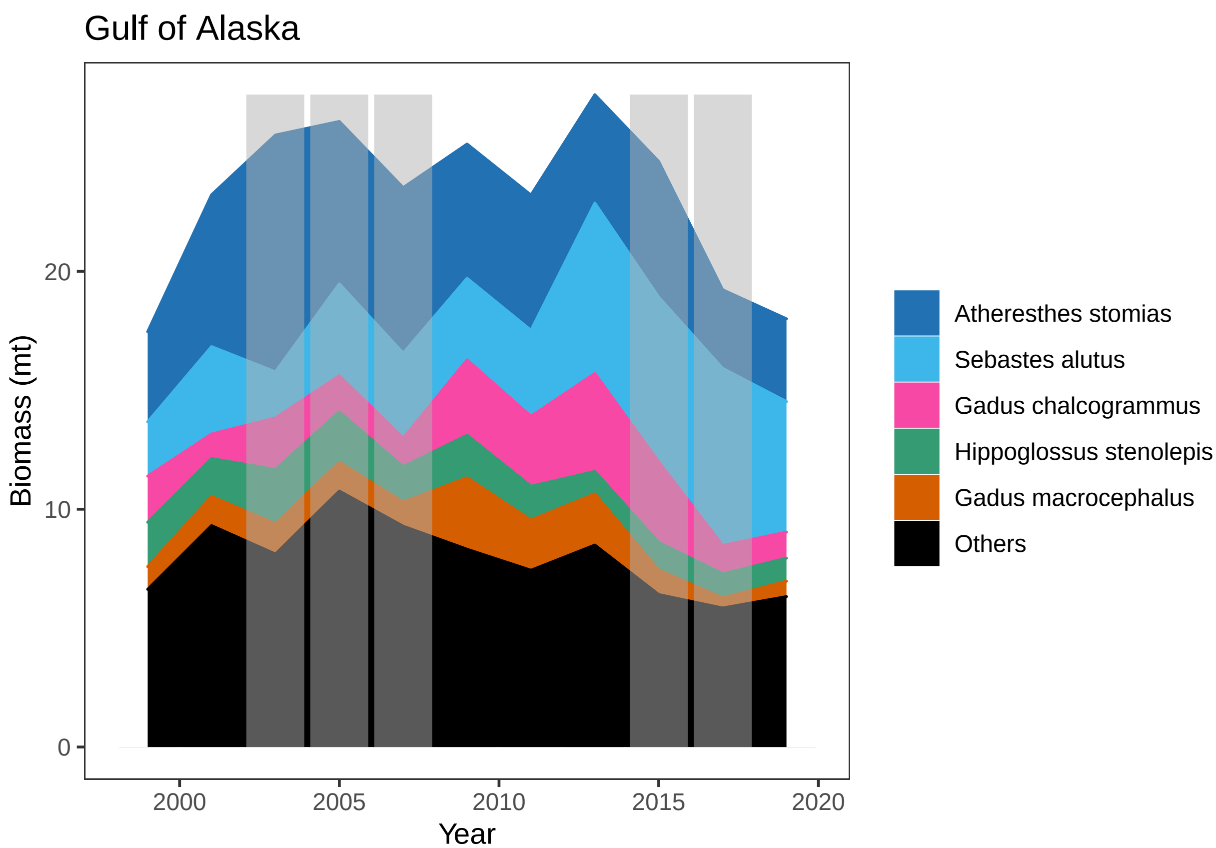

Figure 20: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

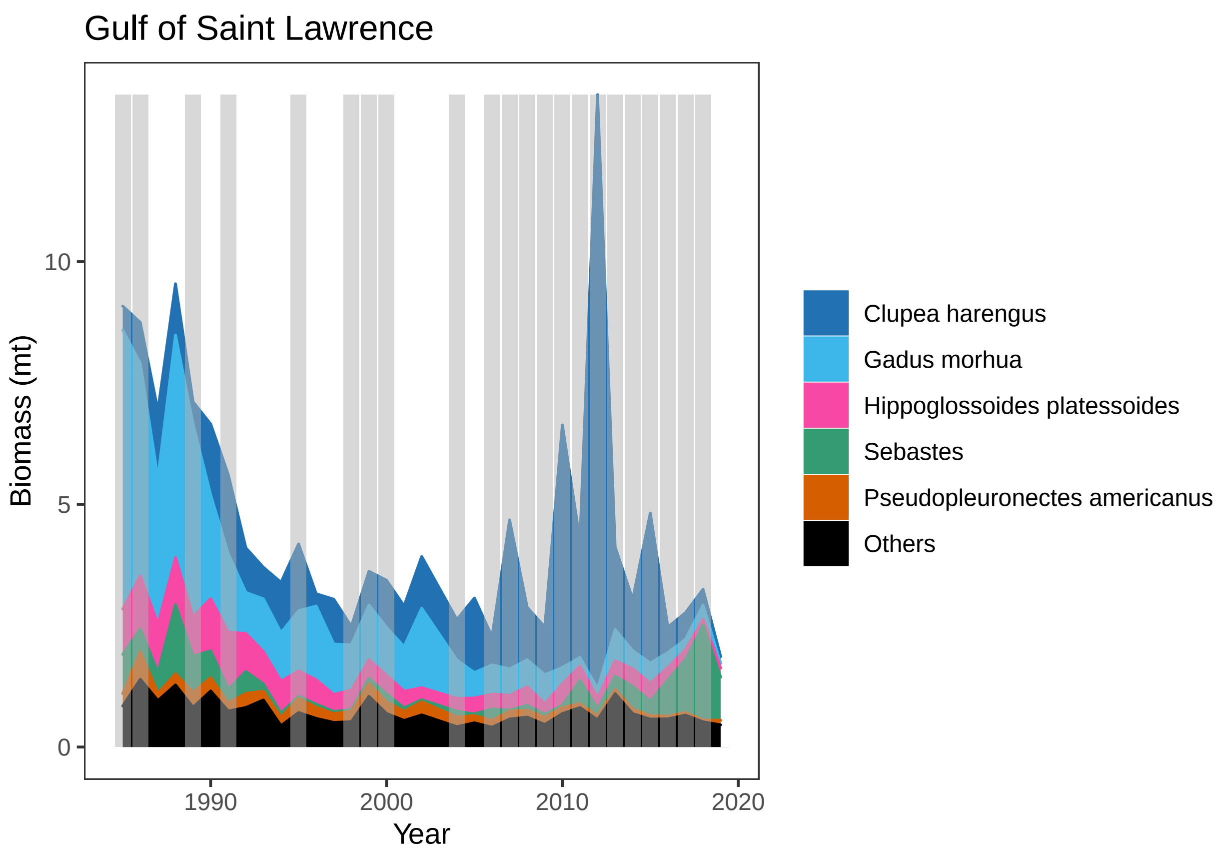

Figure 21: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

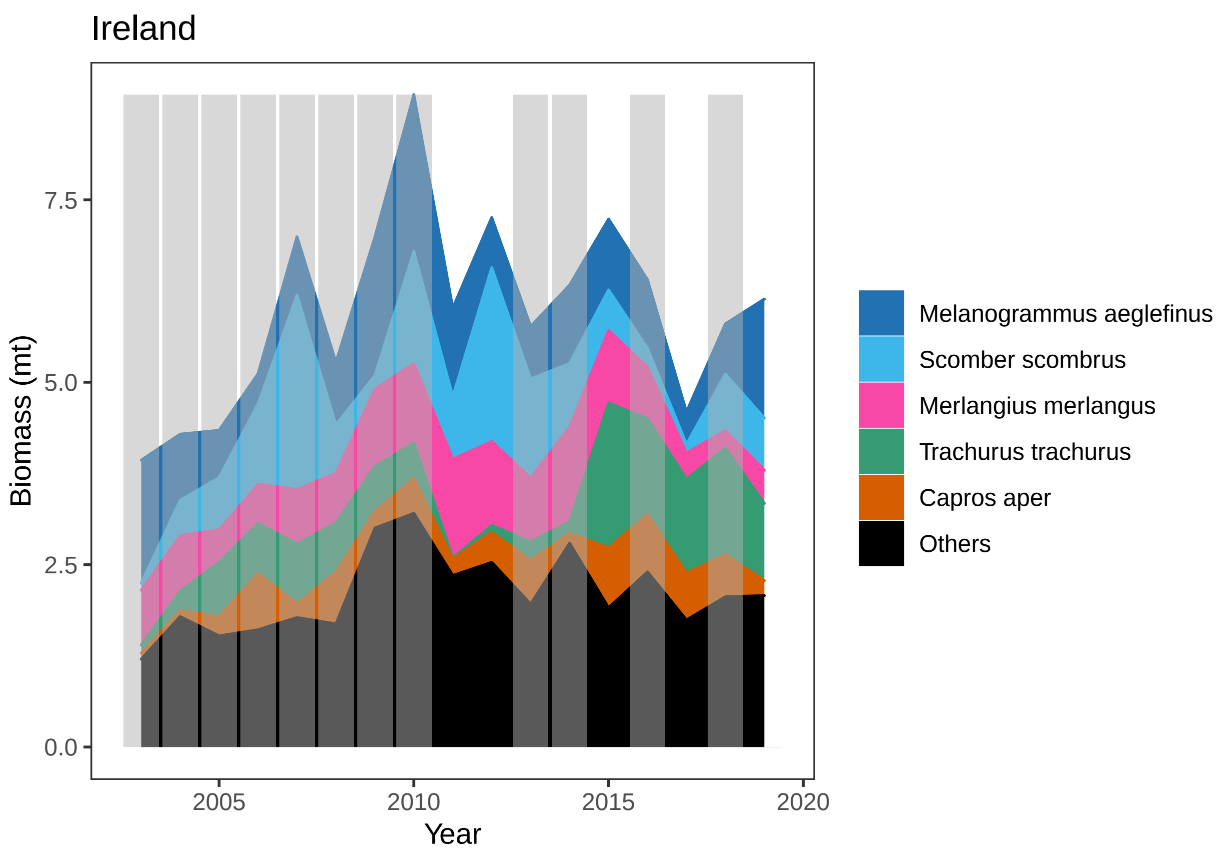

Figure 22: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

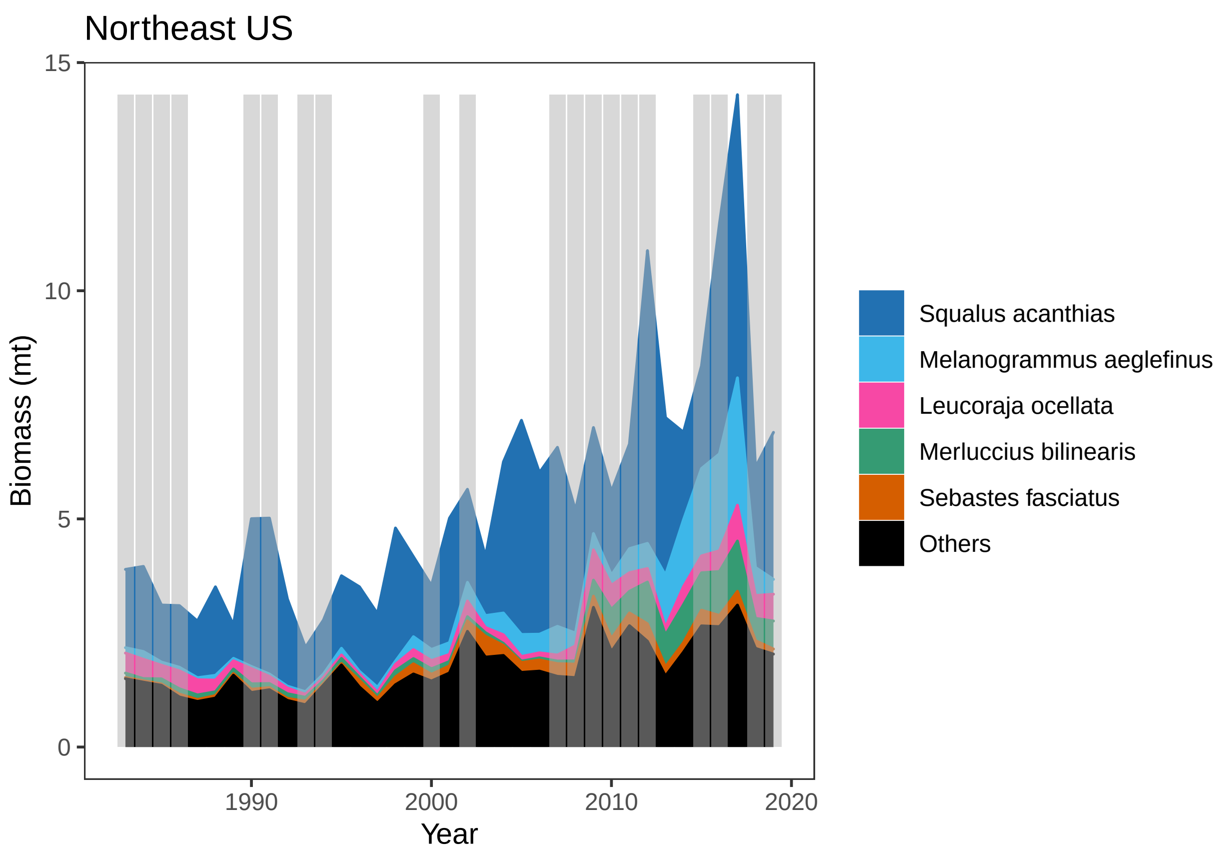

Figure 23: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

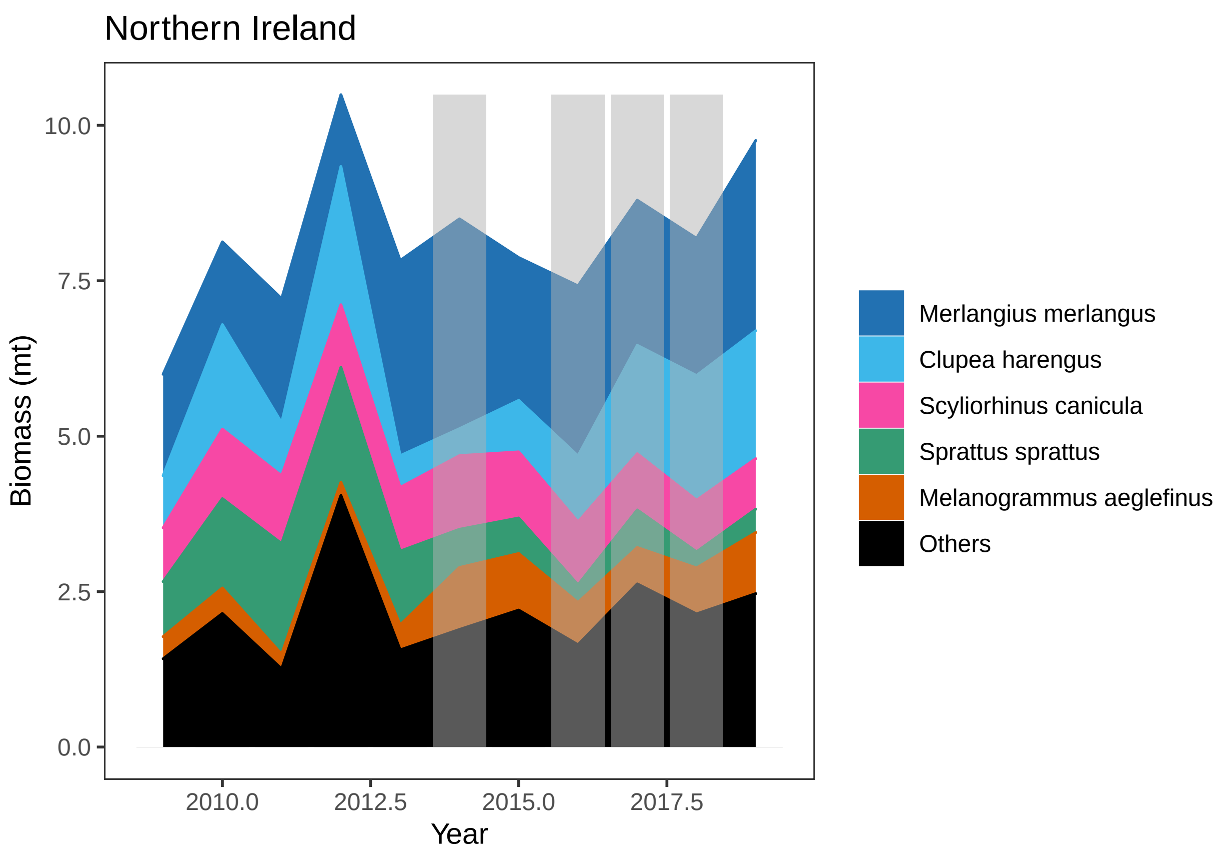

Figure 24: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

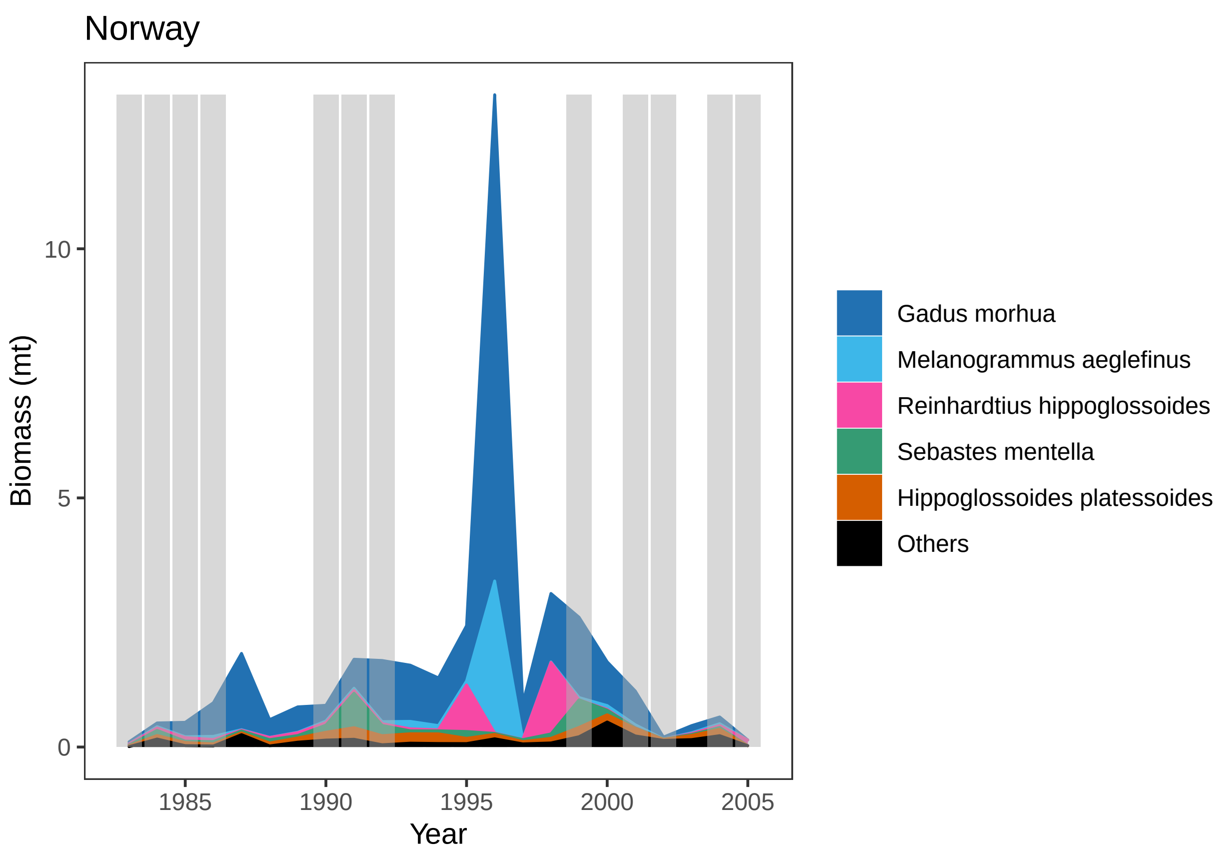

Figure 25: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

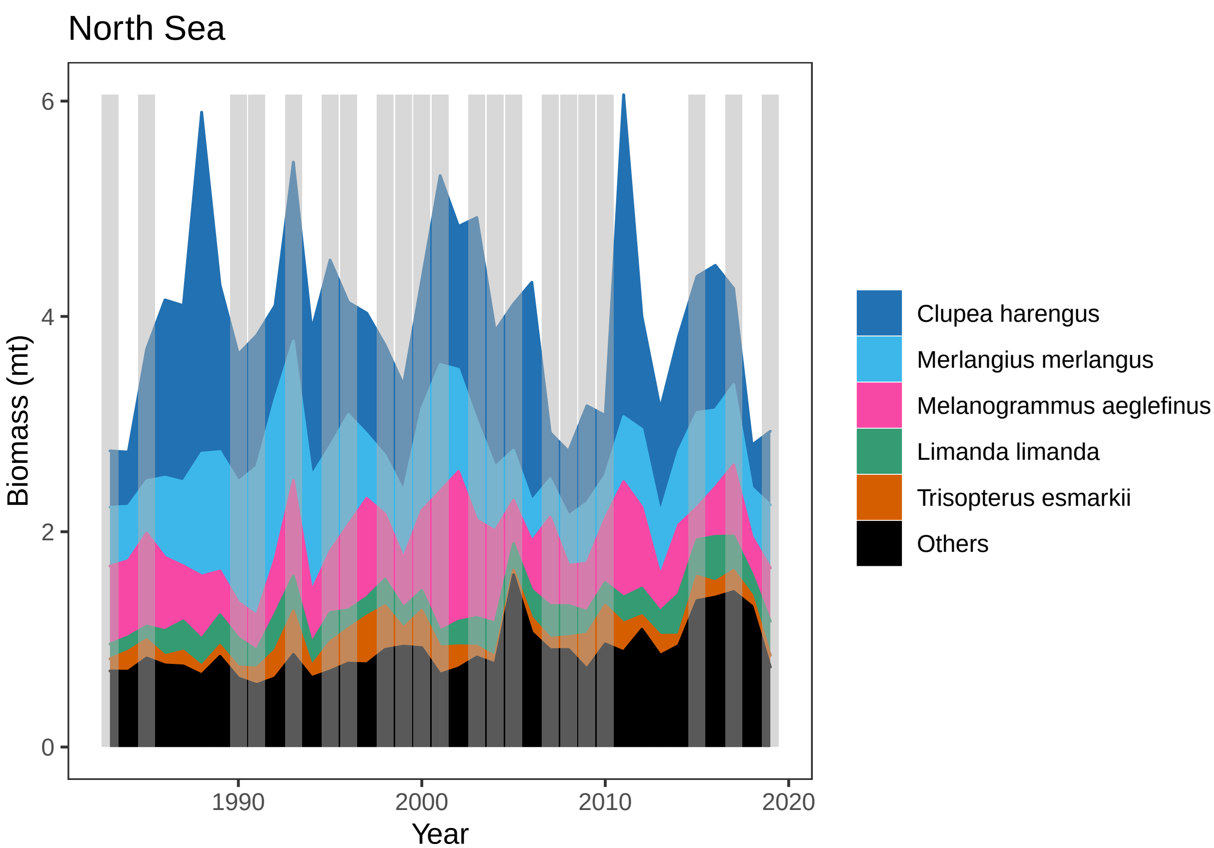

Figure 26: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

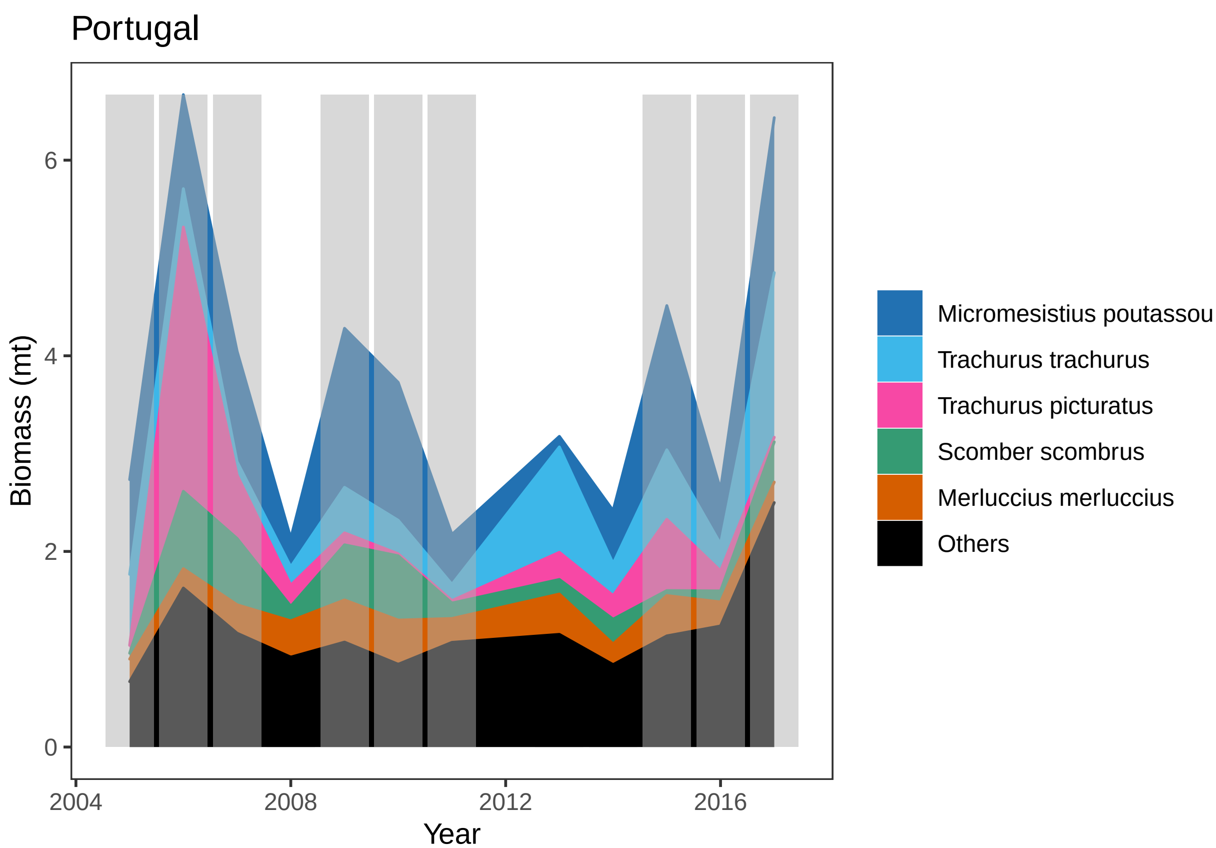

Figure 27: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

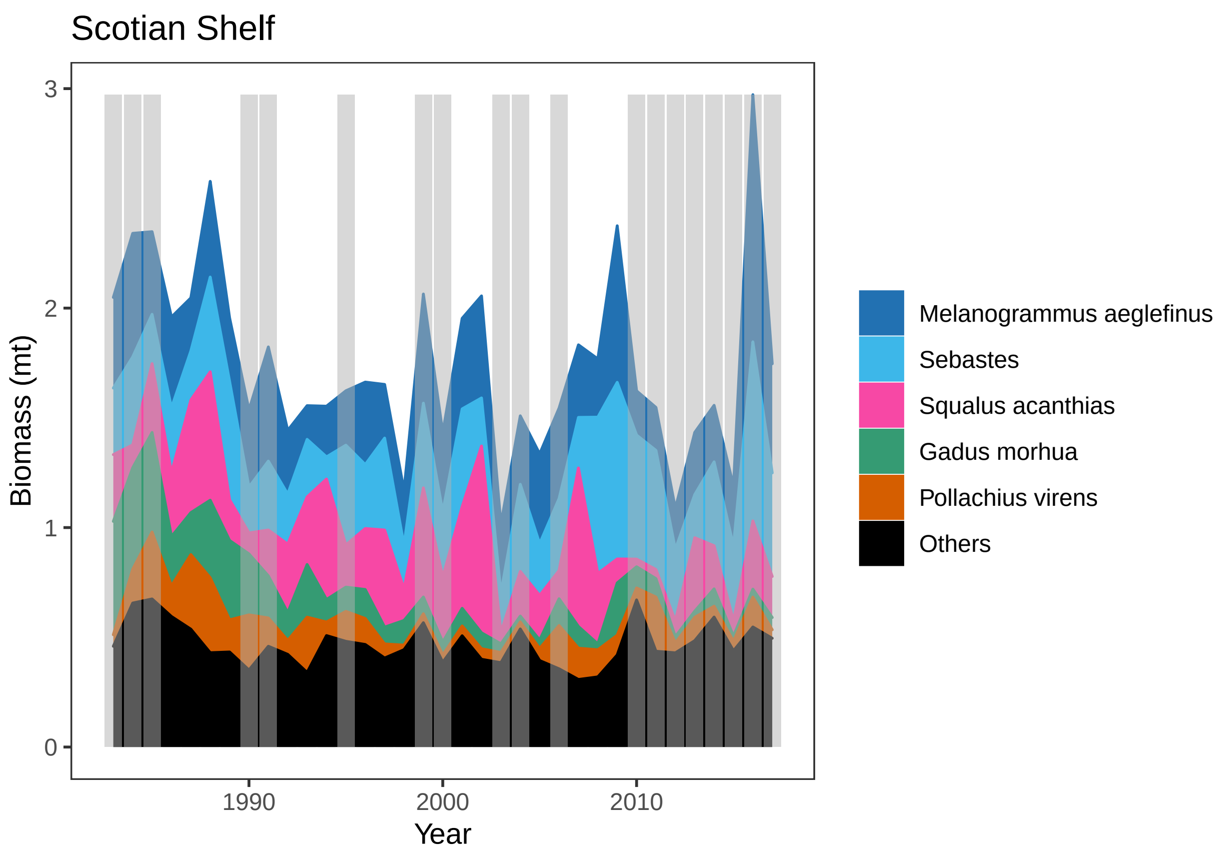

Figure 28: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

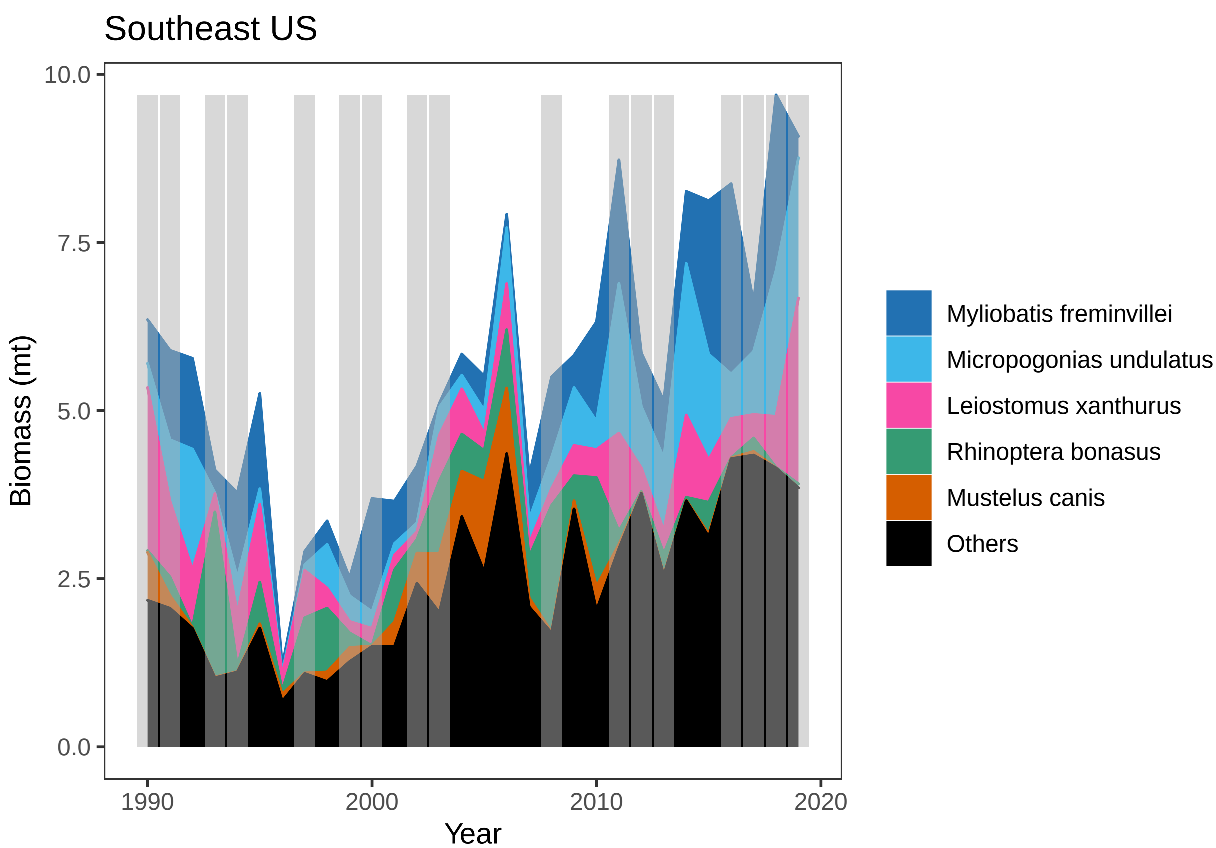

Figure 29: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

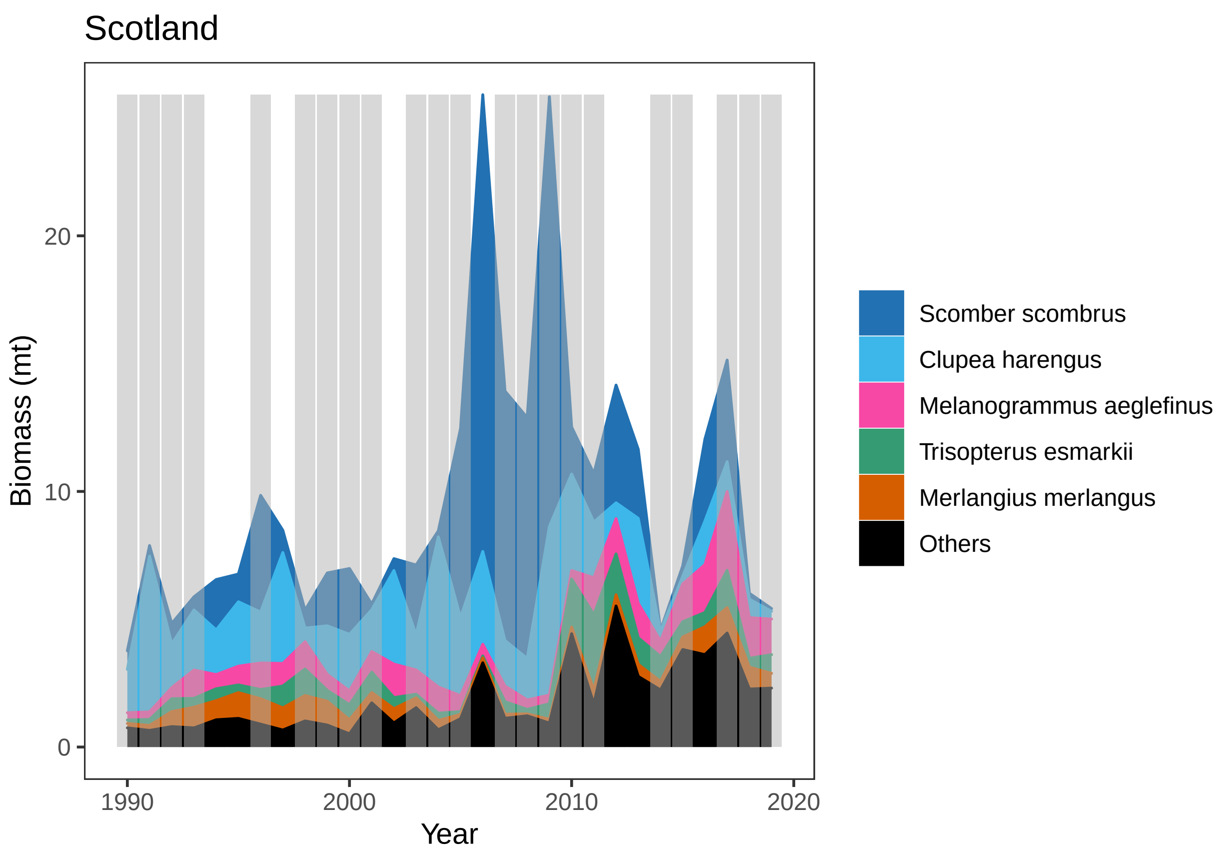

Figure 30: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

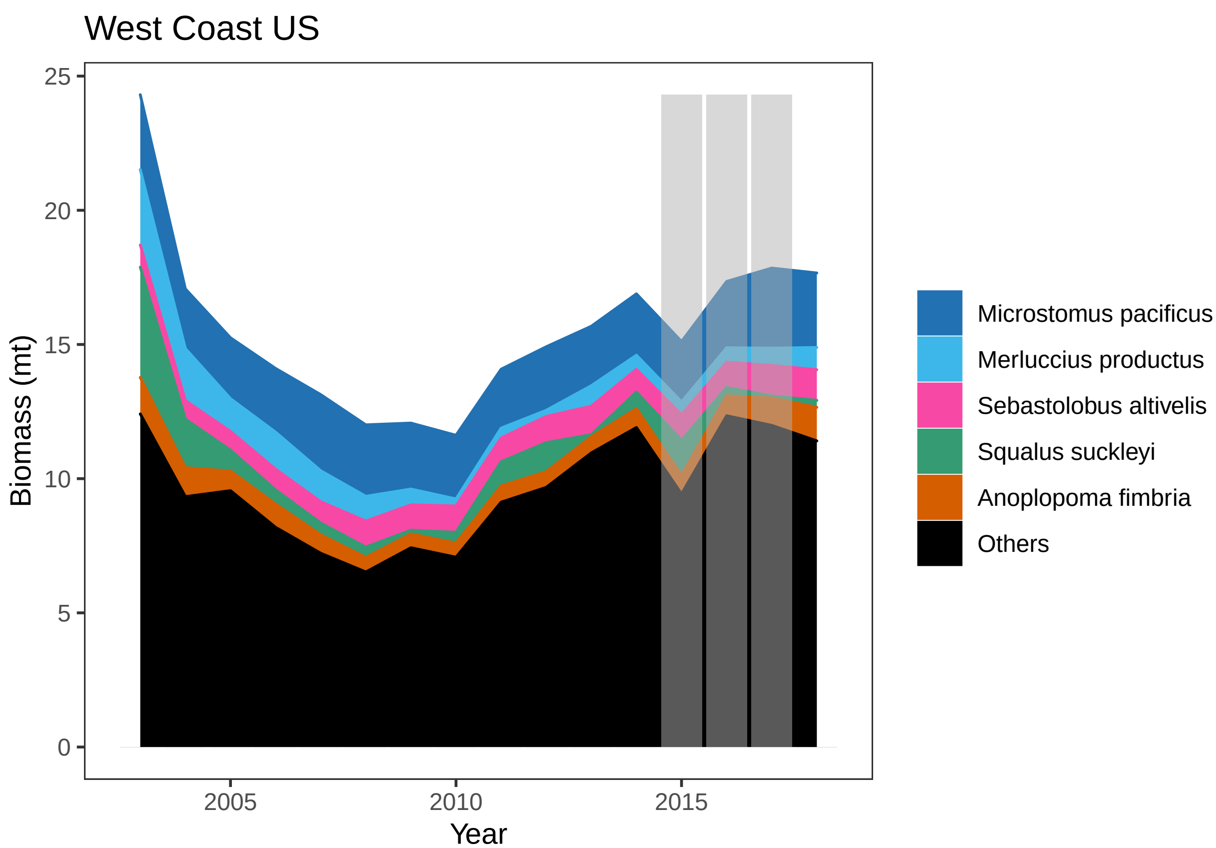

Figure 31: Biomass trends and historical MHWs by region. The top five taxa by biomass are highlighted. Shaded grey rectangles denote when any MHWs occurred in the preceding survey-year (e.g., 2015 in the Eastern Bering Sea time-series corresponds to the survey that began in June 2015, and MHW data from June 2014 - May 2015). British Columbia and the Gulf of Alaska are biennial surveys; all others are annual.

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