The following supplements accompany the article

Spatial analysis of North Sea cod recruitment: concurrent effects of changes in spawning stock biomass, temperature and herring abundance

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Supplement 1. Additional information regarding the adjustment of gear types

The trawl gear denotes the combination of the trawl type, the rigging (such as the length of the sweeps and the distance between trawl doors) and the type of trawl gear (which could be only a wire, or supplied with so-called bobbins for use on rocky grounds). The International Bottom Trawl Survey (IBTS) originated in the 1960s as a collection of national surveys, focusing on young herring *Clupea harengus* (at that time, it was called the International Young Herring Survey). Although the survey has always used small-meshed bottom trawls, the exact type of trawl varied in the beginning: the Netherlands, England and Scotland used Dutch Herring trawls, while Germany used a Herring Trawl (ICES 2010). It gradually became clear that the survey also yielded valuable information on other fish species, such as cod and haddock; thus, the objectives were broadened and herring trawls were slowly replaced by multipurpose gear (ICES 2012). In 1976, 6 different types of survey were being used by 8 different nations (Table S1). In 1977, ICES recommended that all ships should use the GOV (chalut à Grande Ouverture Verticale) trawl. This trawl was gradually phased in, and by 1983 all 8 nations were using the GOV trawl (although there still may be variations in rigging among countries, such as the length of the sweeps used at different depths and the types of ground gear). Fishing speed was standardised to 4 knots (measured as trawl speed). The duration of a tow was 1 h until 1977; all nations eventually changed to 30 min (but the fish catch is always given as catch per hour).

The IBTS database has slots that could be used to provide details on rigging, etc., but they have rarely been used, so the only information given is on 'gear type', which is one out of 12 values (for this particular survey). In addition to the GOV hauls, we used data from the 4 most common gears in use (see Table S1, Fig. S1): DHT (Dutch Herring Trawl), H18 (Herring Bottom Trawl 180 feet), HT (Herring Bottom Trawl) and SOV (SOV-NET). We have been able to find 2 studies comparing GOV gear with other types of gear, one comparing

H18 and GOV and one comparing DHT and GOV. The first, Ehrich (1991), was based on an experimental study using both kinds of gear in the same area; the authors found that larger cod were caught in significantly larger amounts by the GOV than by the DHT, while the capture rate of smaller (<32 cm) cod depended on what type of ground gear was attached to the trawl, rather than the type of trawl (most small cod escaped between the bobbins when bobbin ground gear was used). It is questionable whether the gear conversion factors found in their study can be directly used in our study, as their study was conducted in June. Also, they did not include herring (which is not found near the bottom in summer). The second study (ICES 2004, Chapter 6.2.2) compared (among other things) the DHT with the GOV trawl ('in various riggings'), within the same 10 × 10 nautical miles in Quarter 1, 1977 to 2003, using data that have not been collected specifically for this comparison. They found that, for most species, the DHT was more efficient than the GOV. However, for cod and herring, the 2 gear types had almost exactly the same capture rate. For the HT and SOV trawls, we found no published comparisons with the GOV.

We define the catch efficiency ratio (CAR) as the expected catch of a given fish group (e.g. mature cod) by a non-GOV trawl divided by the expected catch of the same fish group by a GOV trawl towed at the same place at the same time. Thus, for each fish group F there are 4 catch efficiency ratios: $\mathrm{CAR}_{\mathrm{DHT/GOV},\,F}$, $\mathrm{CAR}_{\mathrm{H18/GOV},\,F}$, $\mathrm{CAR}_{\mathrm{HT/GOV},\,F}$ and $\mathrm{CAR}_{\mathrm{SOV/GOV},\,F}$. Estimating GOV is hampered by (1) the patchiness of fish, leading to high variability in catch even within short distances (Ehrich 1991), and the fact that different gears are not perfectly interspersed spatially; some are used more often in the north and some are used more often in the south, etc. (Fig. S1). We started with the basic idea that we expect the difference between hauls to increase with increasing distance between hauls, and with increasing time between the hauls (but we remind the reader that we only used surveys from 1 January to 31 March). So, for each haul of gear X in a given year, we found the spatial and temporal distance to all GOV hauls within 200 km, and then calculated the catch ratio between the X haul and the GOV haul for each pair (excluding all pairs where either X or GOV caught no fish; see Table S2). We then applied linear regression to log(catch ratio) as a function of distance (in km) and the number of days between hauls. Following the basic idea, the intercept of the model (i.e. the expected ratio when the hauls are taken on the same day and are zero kilometres apart) should be an estimator of the 'true' log(CAR) between X and GOV hauls. The estimated log(CAR) (i.e. the intercept), calculated for each fish type, each non-GOV trawl type and each year, is shown in Fig. S2. By visual examination of these graphs (paying special attention to years with high sample size), we identified 5 cases where the log(CAR) tends to be either higher or lower than zero, indicating that CAR ≠ 1 (in 4 of these cases, CAR was <1, i.e. catch was higher in the GOV trawl; Table S3). In these cases, we adjusted the haul numbers using exp(weighted mean of intercept), excluding years with few samples (<150 pairwise comparisons). As weights, we used 1/SE of the intercept, estimated using bootstraps of the hauls. In the other cases, we chose to keep the original numbers (i.e. CAR = 1; Table S1).

LITERATURE CITED

Ehrich S (1991) Comparative fishing experiments by research trawlers for cod and haddock in the North Sea. J Cons Int Explor Mer 47:275–283

ICES (International Council of the Exploration of the Sea) (2004) Report of the Working Group on Fish Ecology. ICES Living Resources Committee. ICES CM 2004/G:09

ICES (International Council of the Exploration of the Sea) (2010) Manual for the International Bottom Trawl Surveys, Revision VIII. Series of ICES survey protocols: SISP 1–IBTS VIII. ICES, Copenhagen

ICES (International Council of the Exploration of the Sea) (2012b) Trawl survey details. Available at: http://datras.ices.dk/Home/Descriptions.aspx (accessed 7 December 2012)

Table S1. Number of hauls using different gear types. In standardisation towards the GOV (Grande Ouverture Verticale) trawl (marked in grey). Other gear types defined in Supplement 1 text

Gear	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
BOT	0	30	11	0	23	0	0	0	0	0	0	0	0	0	0
DHT	43	55	55	105	88	79	80	68	36	0	0	0	0	0	0
FOT	0	0	0	16	0	23	18	22	2	0	0	0	0	0	0
GOV	49	46	39	2	34	37	31	188	185	328	222	281	323	395	434
H12	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0
H18	18	25	27	42	59	37	58	27	53	7	34	18	48	4	0
HOB	0	0	0	0	0	15	61	0	0	0	0	0	0	0	7
HT	20	14	20	28	37	30	36	21	31	0	0	0	0	0	0
KAB	0	0	0	0	0	0	0	48	45	0	0	0	0	0	0
SOV	0	0	0	31	41	49	34	0	40	0	19	27	0	0	0
VIN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. S1. Distributions of the 5 gear types used in this study by year). Gear types defined in Supplement 1 text. *Y*-axis is °N; *x*-axis is °E

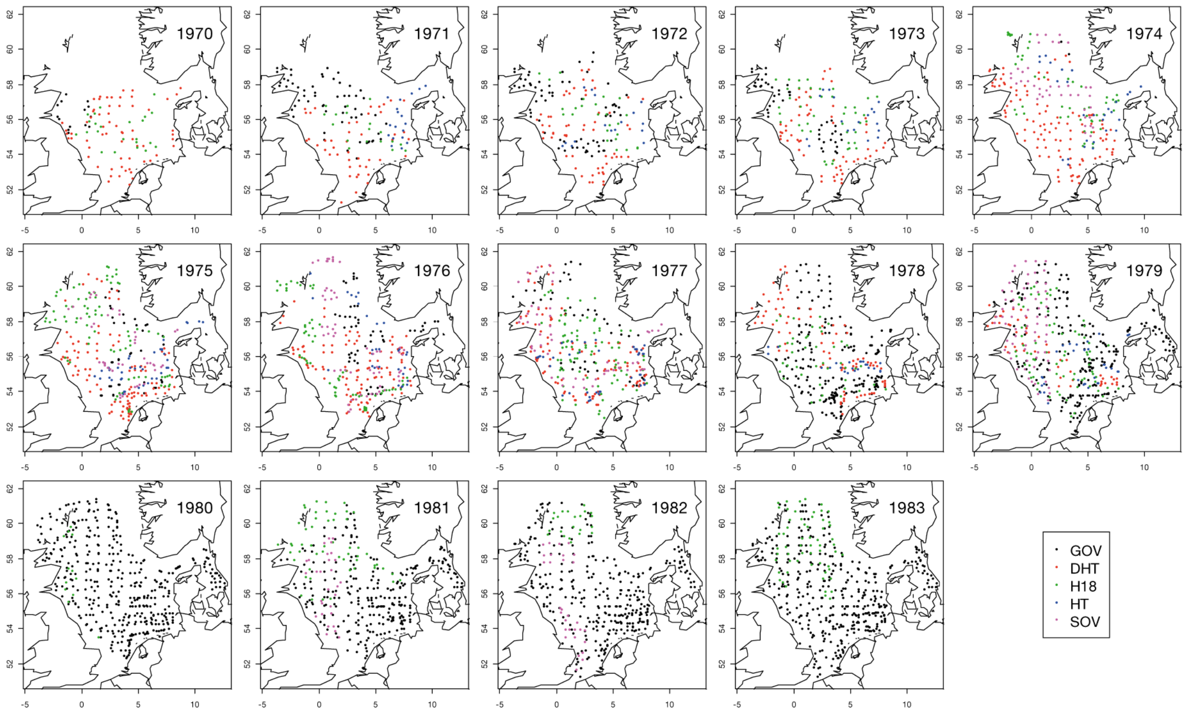

Table S2. *Gadus morhua*. Number of haul pairs categorised by the abundance count for each variable. Grande Ouverture Verticale (GOV) represents the abundance in the GOV haul of the pair, while X represents the abundance in the other trawl of the pair (either DHT, H18, HT, or SOV). For instance, for the DHT–GOV haul pairs, 114 haul pairs had no Age 1 cod in either of the hauls, while 132 of the pairs had Age 1 cod in both hauls, but more Age 1 cod in the GOV haul than in the DHT haul). Gear types defined in Supplement 1 text

	GOV = 0 X = 0	GOV > 0 X = 0	GOV = 0 X > 0	GOV > 0 X > 0		
				GOV > X	GOV < X	GOV = X
Age 1 cod						
X = DHT	114	75	195	132	189	9
X = H18	203	152	73	76	74	6
X = HT	15	32	62	37	104	2
X = SOV	142	97	31	29	22	4
Mature cod						
X = DHT	63	92	148	217	192	2
X = H18	33	109	91	182	167	2
X = HT	30	45	64	60	53	0
X = SOV	28	112	54	62	69	0
Age 1 herring						
X = DHT	63	115	99	360	219	2
X = H18	104	121	75	217	148	2
X = HT	19	25	15	89	89	0
X = SOV	54	68	17	76	25	1
Mature herring						
X = DHT	249	196	197	135	80	1
X = H18	187	184	143	99	54	0
X = HT	96	58	49	22	12	0
X = SOV	69	100	22	43	7	0

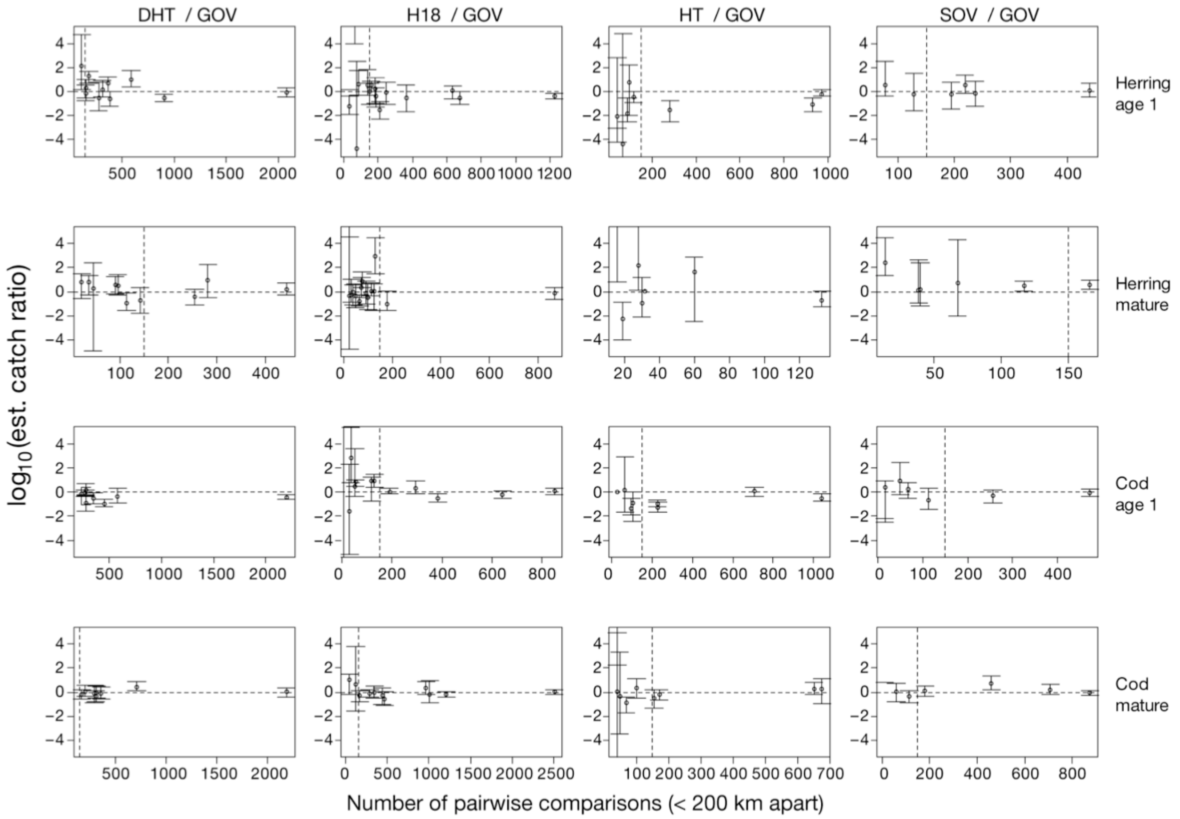

Fig. S2. *Gadus morhua* and *Clupea harengus*. Estimated catch ratio for each non-Grande Ouverture Verticale (GOV) gear relative to GOV (columns) for 4 different groups of fish (rows), plotted against sample size (*x*-axis). The estimated catch ratio equals the estimated intercept from a regression of catch ratio as a function of distance in space and time (see 'Materials and methods: Database'). The error bars show 95% confidence intervals estimated by bootstrapped samples (simultaneous bootstrap of both non-GOV hauls and GOV hauls). The dotted vertical line indicates a sample size of 150 pairwise comparisons; only the catch ratios to the right of this line were used to calculate the overall catch ratios for a given fish group). Other gear types defined in Supplement 1 text

Table S3. *Gadus morhua* and *Clupea harengus*. Catch ratios actually used for adjusting the non-GOV gears DHT, H18m HT and SOV (gear types defined in Supplement 1 text). Where catch ratios = 1, there was not enough evidence to show that the data does not indicate a stable catch ratio ≠1. For the others, we used the weighted mean of the log(ratio) for all years where there was >150 pairwise comparisons, using 1/SD(log(ratio)) as the weights. The weighted mean was then back-transformed (using exp)

	DHT/GOV	H18/GOV	HT/GOV	SOV/GOV
Herring Age 1	1.00	1.00	0.46	1.00
Herring mature	1.00	0.62	1.00	1.76
Cod Age 1	0.66	1.00	0.53	1.00
Cod mature	1.00	1.00	1.00	1.00

Supplement 2. Figures illustrating models of cod and herring recruitment

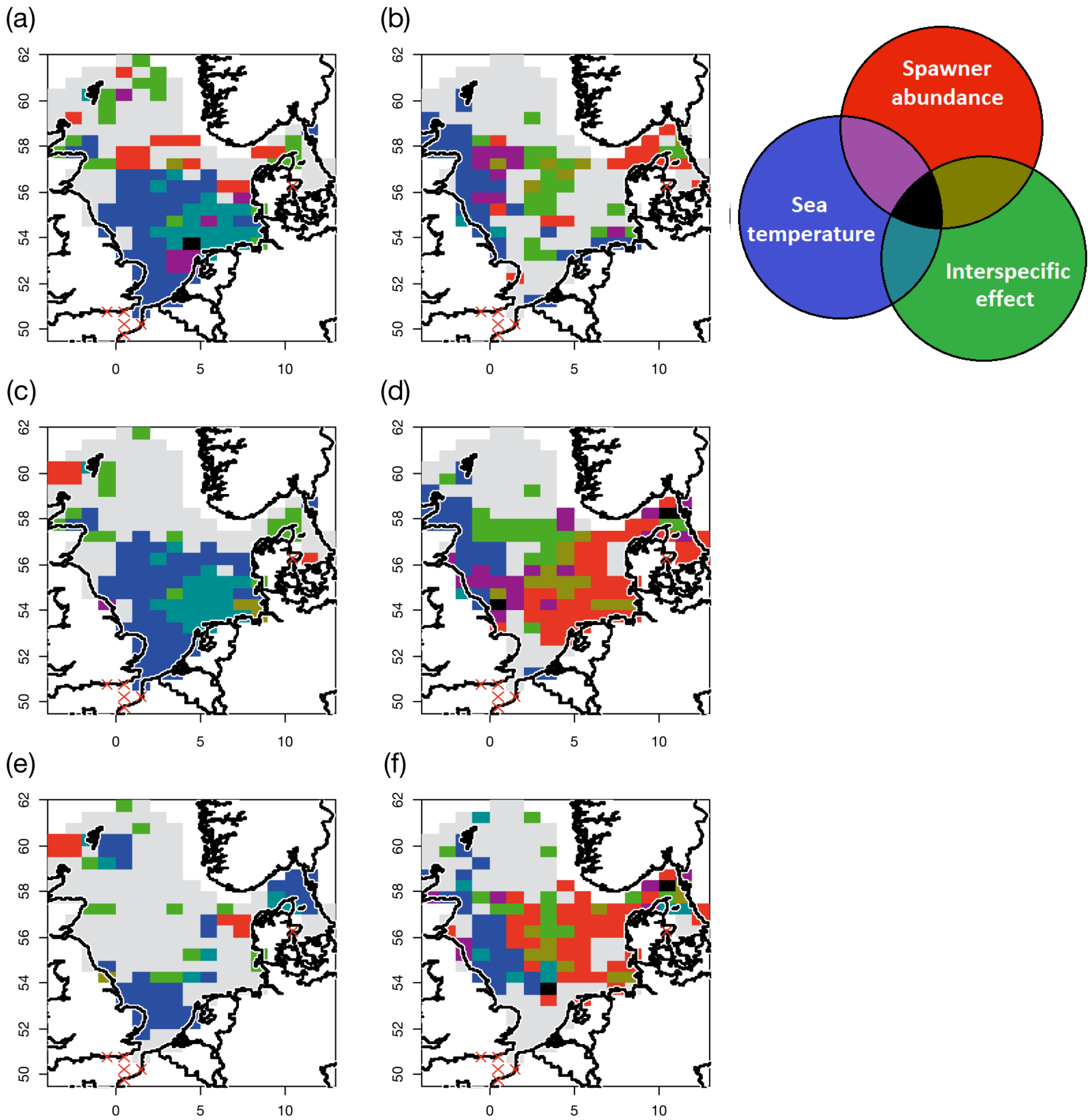

Fig. S3. *Gadus morhua* and *Clupea harengus*. The most parsimonious model for each area (the model with the lowest corrected Akaike's information criterion and with all p-values <0.05). The left column shows models for cod recruitment (a, c and e correspond to Fig. 4a, b and c in the main text, respectively), while the right column shows models for herring recruitment (b, d and f correspond to Fig. 5a,b and c in the main text, respectively). The colours indicate which model was optimal following the legend on the upper right ('inter-specific effect' is the effect of herring on cod recruitment and the effect of cod on herring recruitment), e.g., in (a), violet areas indicate where the optimal model included spawner abundance and sea temperature but not the abundance of Age 1 herring. In light grey areas, the optimal model was a model without variables (i.e. recruitment varied randomly around a constant level). Red crosses: subareas that were not analysed due to too few years of data. *Y*-axis is °N; *x*-axis is °E

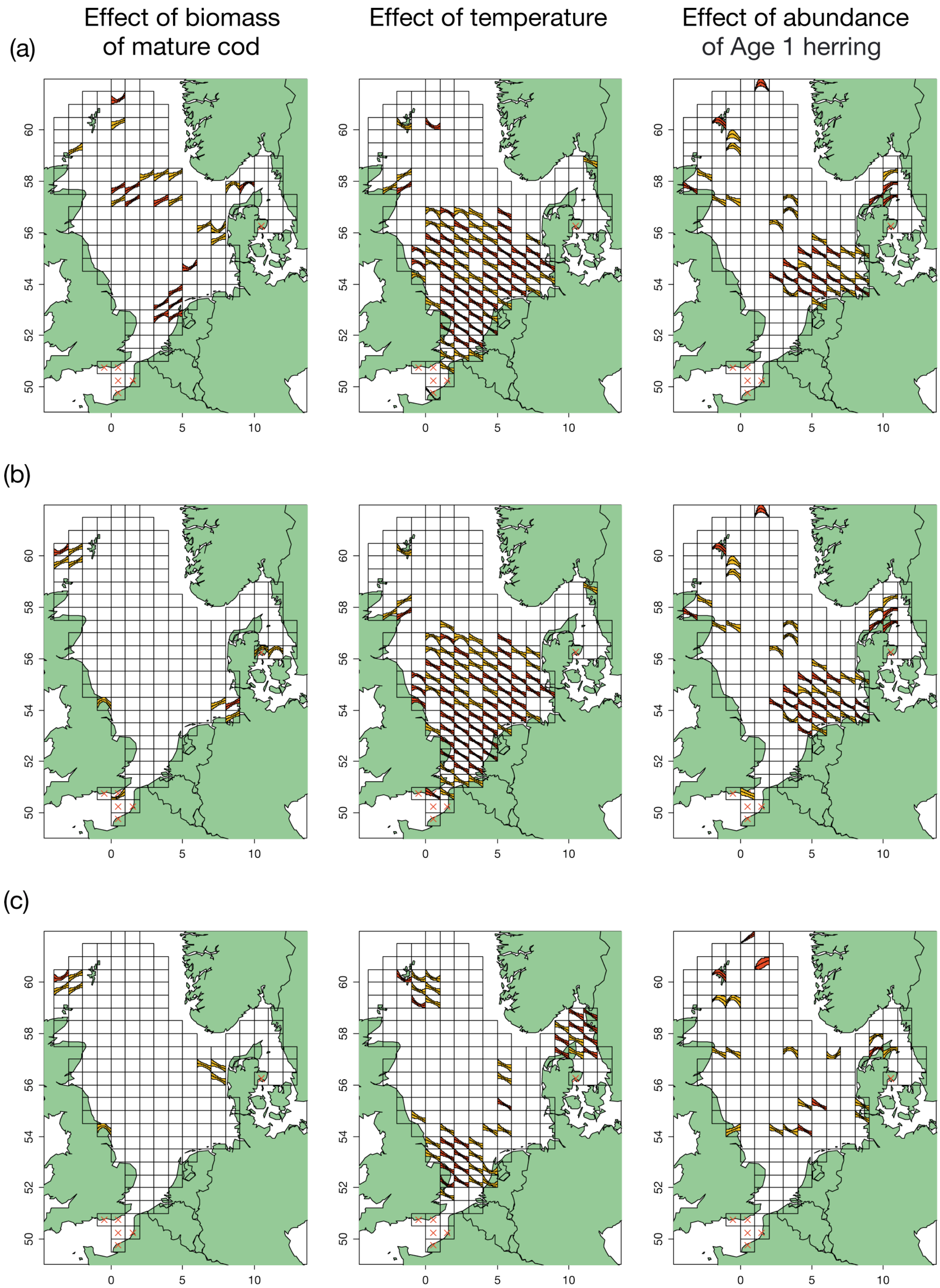

Fig. S4. *Gadus morhua* and *Clupea harengus*. The effect of each predictor variable on cod recruitment. The figure is similar to Fig. 4 in the main paper, except that for each variable, we show the actual partial effect of the variable. Each row of graphs represents one model: (a) Eq. (1), (b) Eq. (2) and (c) Eq. (3). Red curves indicate $p < 0.01$, while orange curves indicate a p-value between 0.01 and 0.05. *Y*-axis is °N; *x*-axis is °E

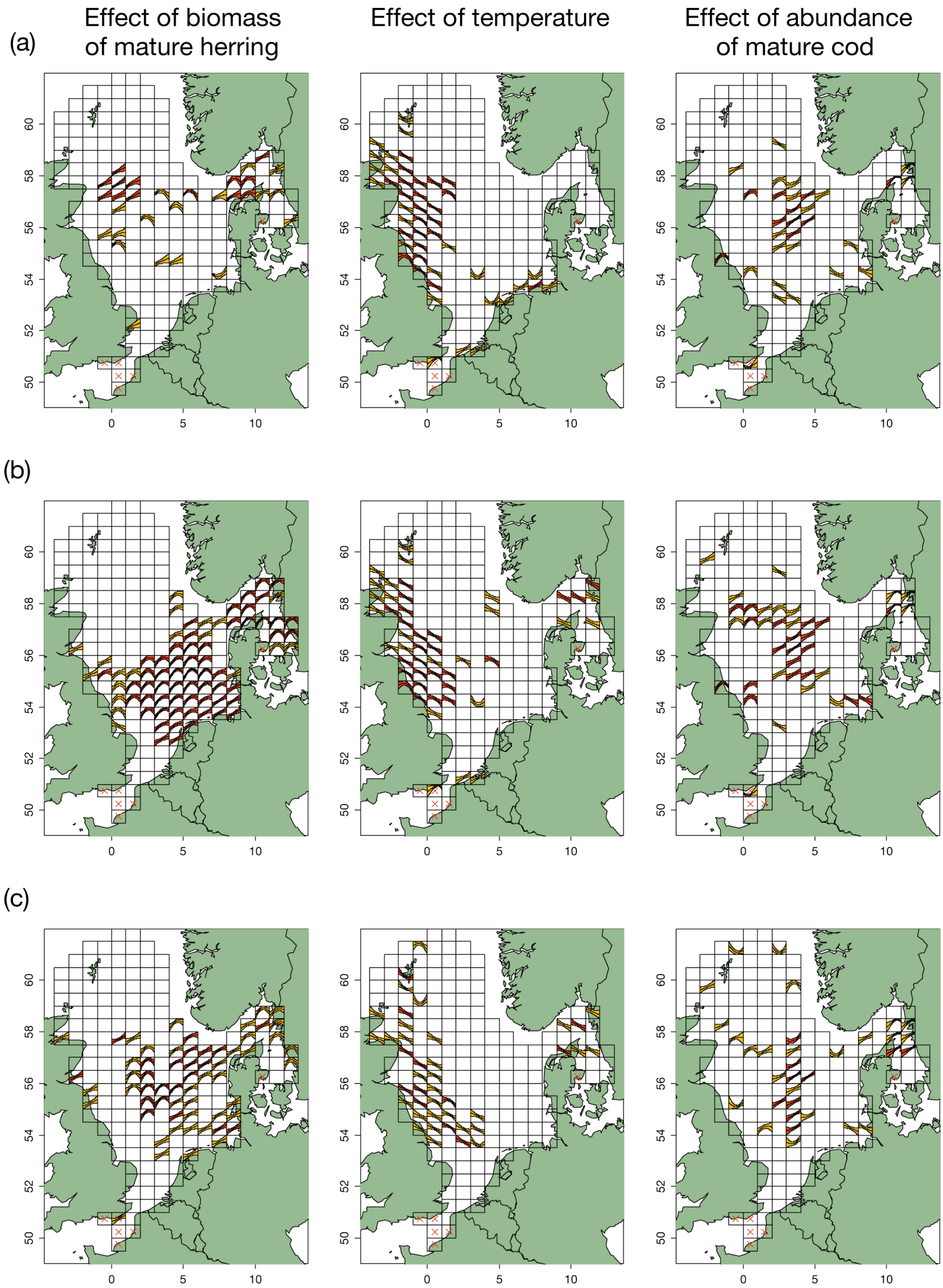

Fig. S5. *Gadus morhua* and *Clupea harengus*. The effect of each predictor variable on cod recruitment. The figure is similar to Fig. S4, except that no model selection has been performed; all 3 variables are included. Each row of graphs represents one model: (a) Eq. (1), (b) Eq. (2) and (c) Eq. (3). Colour codes: red: $p < 0.01$; orange: $0.01 < p < 0.05$; yellow: $0.05 < p < 0.10$; grey: $p > 0.10$. *Y*-axis is °N; *x*-axis is °E

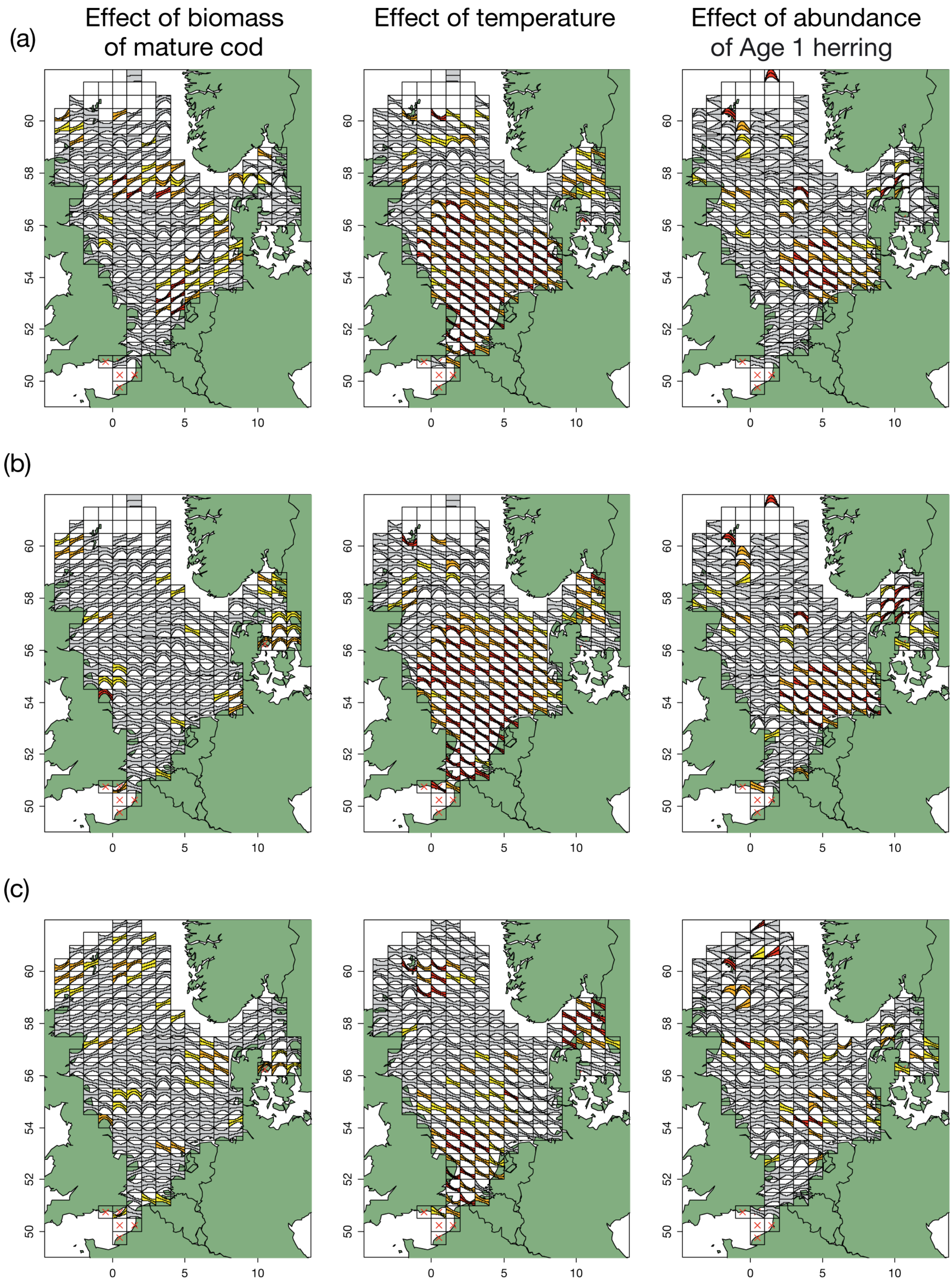

Fig. S6. *Clupea harengus* and *Gadus morhua*. The effect of each predictor variable on herring recruitment. The figure is similar to Fig. 5 in the main paper, except that for each variable, we show the actual partial effect of the variable. Each row of graphs represents one model: (a) Eq. (1), (b) Eq. (2) and (c) Eq. (3). Red curves indicate $p < 0.01$, while orange curves indicate a p-value between 0.01 and 0.05. *Y*-axis is °N; *x*-axis is °E

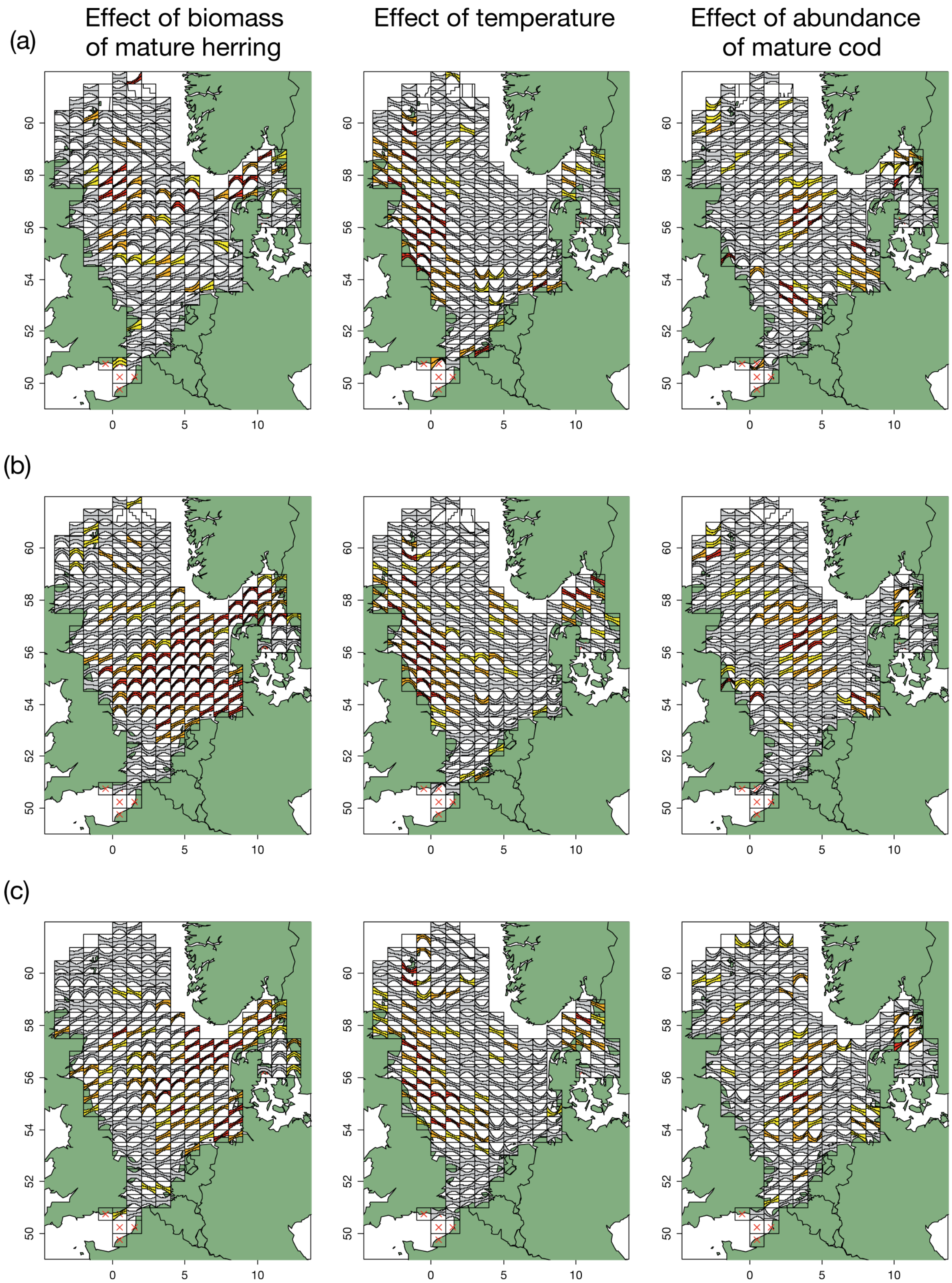

Fig. S7. *Clupea harengus* and *Gadus morhua*. The effect of each predictor variable on herring recruitment. The figure is similar to Fig. S6, except that no model selection has been performed; all 3 variables are included. Each row of graphs represents one model: (a) Eq. (1), (b) Eq. (2) and (c) Eq. (3). Colour codes: red: $p < 0.01$; orange: $0.01 < p < 0.05$; yellow: $0.05 < p < 0.10$; grey: $p > 0.10$. *Y*-axis is °N; *x*-axis is °E

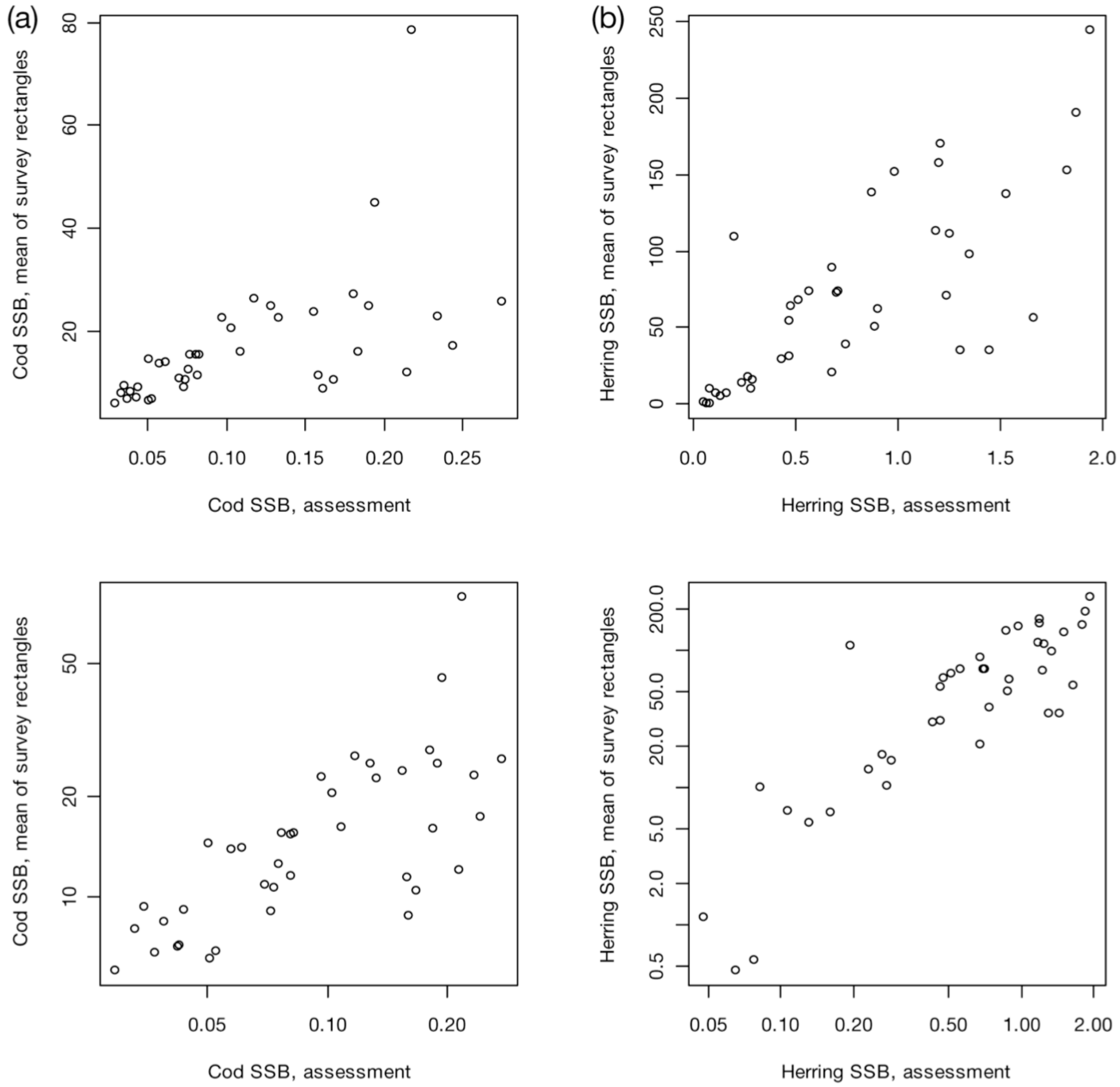

Fig. S8. *Gadus morhua* and *Clupea harengus*. Comparison of estimates of spawning stock biomass (SSB) of (a,c) cod and (b,d) herring shown on the (a,b) natural and (c,d) log-log scales. The estimates shown are the International Council on the Exploration of the Sea assessment (horizontal axis; million tonnes) and the survey data used in this paper (International Bottom Trawl Survey [IBTS] data, Quarter 1; kg h^{-1} trawl), averaged over subareas for each year (vertical axis). Note: log scales on both axes. The IBTS survey is used as part of the input (as a so-called tuning fleet) during the estimation of SSB of both cod and herring; thus, the time series are not completely independent

Supplement 3. Requirements for classification of generalised additive model effects as 'predominantly negative', 'predominantly positive', or 'non-monotonic' effects

Define $E^{xy}(x)$ as the point estimate of the effect of x on the response variable y, and $\mathrm{CI}_{\mathrm{upper}}^{xy}(x)$and $\mathrm{CI}_{\mathrm{lower}}^{xy}(x)$ as the upper and lower limits, respectively, of the 95% confidence interval (CI) of the effect of x on y.

Then, we used the following definitions to classify non-linear effects:

'Predominantly negative': $E^{xy}(\mathrm{min}(x)) > \mathrm{CI}_{\mathrm{upper}}^{xy}(\mathrm{max.}(x))$

'Predominantly positive': $E^{xy}(\mathrm{max.}(x)) > \mathrm{CI}_{\mathrm{upper}}^{xy}(\mathrm{min.}(x))$

'Non-monotonic': neither of the above (following the model selection procedure, the effect is necessarily significant at $p < 0.05$).