Supplementary materials

Contents

Appendix A: Details of the EwE model

An EwE model for the west of Scotland was first established by Haggan & Pitcher (2005) and subsequently updated by Bailey et al. (2011), Alexander et al. (2015), and Serpetti et al. (2017)). The latter version is employed in this study. EwE is a mass-balance foodweb model that can include a large number of species or species [functional] groups modelled as biomass pools. It is useful to investigate trophic flows, quantify prey-predators interactions, and assess ecosystem health due to the large number of trophic levels modelled (i.e. from producers to top predators). EwE comprises two components: Ecopath, a mass-balance model accounting for energy transfers in the ecosystem, which depicts a 'snapshot' of the ecosystem in a given year; and Ecosim, the dynamic component that enables temporal simulations based on Ecopath (Walters et al., 1997). Ecopath is defined by two main equations: (i) the first one describes the equality of production terms for each functional group in the ecosystem between the biological production, and the sum of: predation mortality, fisheries catches, biomass accumulation, net migration and other (i.e. unexplained) sources of mortality; (ii) the second equation describes, for each functional group, the energy balance between consumption and the sum of production, respiration and unassimilated food (Christensen and Pauly, 1992; Polovina, 1984). Ecosim uses a time-dependent differential equation based on Ecopath. Ecosim enables temporal dynamic simulations of fisheries by varying the exploitation rates applied to each group (and subsequently biomasses and catches) whilst the Ecopath parameters (e.g. diet composition) remain constant and equal to the start year (i.e. 'snapshot' year modelled in Ecopath).

The specific area that the EwE model corresponds to ~110,000 km2 of the continental shelf of VIa depth delineated by the 200 m depth contour (see Fig. 1 in the main text). The model comprises 41 functional groups which span ~5 trophic levels and include all the major commercial fish and shellfish species, their main prey (i.e. small fish and plankton groups) and predators (large fish, seabirds and mammals), as well as five fishing fleets. The cod, haddock and whiting groups are split between immature (age 0 and 1) and mature (age 2 and above) components (termed stanzas in EwE). The start year of the model on which Ecopath is based was 1985 while the dynamic component Ecosim was calibrated from 1985 to 2013 (see Serpetti et al. (2017) for details).

References

Alexander, K.A., Heymans, J.J., Magill, S., Tomczak, M.T., Holmes, S.J., Wilding, T.A., 2015. of Scotland shelf ecosystem using a foodweb model 72, 436–449.

Bailey, N., Bailey, D., Bellini, L., Fernandes, P., Fox, C., Heymans, S., Holmes, S., Howe, J., Hughes, S., Magill, S., McIntyre, F., McKee, D., Ryan, M., Smith, I., Tyldsley, G., Watret, R., Turrell, W., 2011. The West of Scotland Marine Ecosystem : A Review of Scientific Knowledge. Mar. Scotl. Sci. Rep. 292.

Christensen, V., Pauly, D., 1992. ECOPATH II—a software for balancing steady-state ecosystem models and calculating network characteristics. Ecol. Modell. 61, 169–185.

Haggan, N., Pitcher, T.J., 2005. Fisheries Centre Research Reports Ecosystem Simulation Models of Scotland ' s West Coast and Sea Lochs. Fish. Cent. Res. Reports 13.

Polovina, J.J., 1984. Model of a coral reef ecosystem. The ECOPATH model and its application to French Frigate Shoals. Coral Reefs 3, 1–11.

Serpetti, N., Baudron, A.R., Burrows, M.T., Payne, B.L., Helaouët, P., Fernandes, P.G., Heymans, J.J., 2017. Impact of ocean warming on sustainable fisheries management informs the Ecosystem Approach to Fisheries. Sci. Rep. 7, 1–15. https://doi.org/10.1038/s41598-017-13220-7

Walters, C., Christensen, V., Pauly, D., 1997. Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. Rev. Fish Biol. Fish. 7, 139–172.

Appendix B: Market price for commercial fish and shellfish species

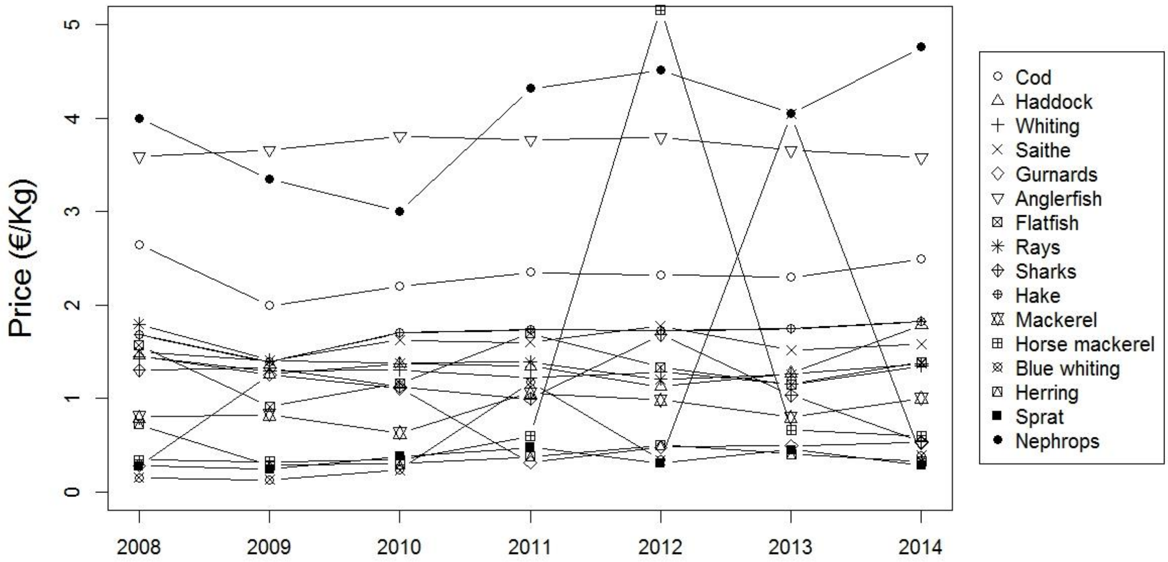

Figure B.1. Market price (€ per kilogram) for commercially caught fish and shellfish species obtained from the STECF database (https://stecf.jrc.ec.europa.eu/).

Appendix C: Cost coefficients

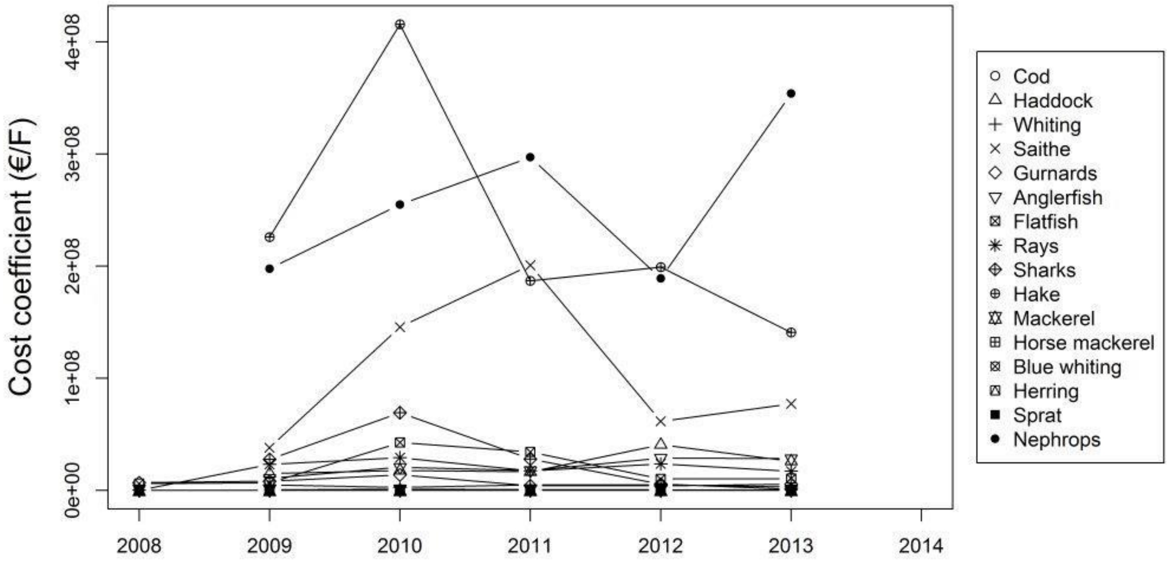

Fig. C.1. Historical time series of cost coefficients (€ as a function of fishing mortality) for commercially caught fish and shellfish species, calculated following the methods from Quaas et al. (2012).

Appendix D: Details of MCA indicators

Table D.1. Table presenting details of MCA indicators.

MCA indicator	Abbreviation in MCA	Definition	Unit
Cod SSB	Cod20; Cod25	SSB of cod in VIa in 2020 and 2025	1000t
Whiting SSB	Whi20; Whi25	SSB of whiting in VIa in 2020 and 2025	1000t
Haddock SSB	Had20; Had25	SSB of haddock in VIa in 2020 and 2025	1000t
Saithe TSB	Sai20; Sai25	TSB of saithe in VIa in 2020 and 2025	1000t
Hake TSB	Hake20; Hake25	TSB of hake in VIa in 2020 and 2025	1000t
Nephrops TSB	Nep20; Nep25	TSB of Nephrops in VIa in 2020 and 2025	1000t
Balanced evenness	BE_20; BE_25	Index described in Annex D.	Number
Prey fish species	Prey20;Prey25	Sum of TSB of the following species/functional groups: Blue whiting (*Micromesistius poutassou*), Norway pout (*Trisopterus esmarkii*), sprat (*Sprattus sprattus*), sandeel (various species), herring (*Clupea harengus*).	1000t 1000t
Seabird biomass	Bird20; Bird25	TSB of seabird species included in the model	1000t
Seal biomass	Seal20; Seal25	TSB of seal species (Grey seal *Halichoerus grypus* and Harbor seal (*Phoca vitulina*).	
Catch value (by fleet)	VPel20, VPel25 VDem20,VDem25 VNep20;VNep25	Catch value for by fleet (pelagic, demersal and nephrops)	Euro
Profit (by fleet)	PPel20,PPel25; PDem20;PDem25 PNep20;PNep25	Profit proxy (by fleet)	Euro

Appendix E: The Balanced Evenness index (Food Web Evenness index)

Calculation of the balanced evenness index (henceforth referred to as the Food Web Evenness index, FEW) is a two-step process. First the expected biomass (B_{ie}) of each species (or functional group, trophospecies, depending on the aggregation level of the model) i is calculated, then an inverted dissimilarity index (Bray-Curtis, *BC*, or Canberra metric, *C*) is used to measure how close the observed biomasses of species are to their expected biomasses.

To calculate expected biomasses, we define a state of 'food web evenness' as decreasing biomasses with increasing trophic levels and equal biomasses within trophic levels. For example, if we assume that biomasses at consecutive integer trophic levels differ by a factor of 10, and total biomass at the second trophic level is $B*$, then expected biomass on the third trophic level is $0.1B*$, and on the fourth trophic level $0.01B*$. If there are no further trophic levels, then total biomass in the community equals $(1 + 0.1 + 0.01) \cdot B^*$. Biomasses within a trophic level are expected to be equal, thus, if there are four species at trophic level 2, they are all expected to have biomasses equal to $B^*/4$.

We can generalize these relationships as follows: B_{ie} values are calculated based on the total expected biomass at the lowest ('reference') trophic level, $B*$, which is estimated as a certain fraction of the observed total biomass in the community Tot_B:

$$B_{ie} = \frac{B^* \cdot \varepsilon^{-(TL_i - TL^*)}}{n_i}, \qquad (1)$$

$$B^* = \frac{Tot_B}{\sum_k \varepsilon^{-(TL_k - TL^*)}} \qquad (2)$$

where $\varepsilon > 1$ is the biomass ratio of consecutive integer trophic levels (10 in the above example). It is the multiplicative inverse of transfer efficiency defined as the ratio of production at consecutive trophic levels. TL_i is the trophic level of i, TL^* is the reference trophic level, n_i is the number of species at the same trophic level as i, Tot_B is total biomass in the community and k is the total number of all (not only integer) trophic levels.

The vector of B_{ie} values can then be compared against observed biomasses (B_{io}) in a community using Bray-Curtis dissimilarity:

$$BC = (\sum_i |B_{ie} - B_{io}|) / \sum_i (B_{ie} + B_{io}) \ . \qquad (3)$$

The Bray-Curtis dissimilarity index is more suitable to track changes in more abundant species (Krebs, 1999), as it calculates the change in biomass in each group divided by the sum of biomass in the two compared communities. However, for many applications it is more relevant to give equal weight to less abundant higher trophic level species. In these cases the Canberra Metric (Lance and Williams, 1967) measure could be used. This one calculates change in biomass relative to the sum of observed and expected biomass, i.e. relative change compared to group biomass:

$$C = \frac{1}{s} \cdot \sum_i \frac{|B_{ie} - B_{io}|}{B_{ie} + B_{io}}, \qquad (4)$$

where s is the number of species in the community.

Finally, to calculate *FWE* we invert *BC* (FWE_{BC}=1-*BC*) or *C* (FWE_C=1-*C*), so higher index values express higher evenness.

An advantage of the *FWE* index is that it is independent of the total biomass in the system, in the sense that if community A has two times the total biomass of community B, but the biomass fraction of each species in the two communities are the same, *FWE* index values for communities A and B are going to be the same. Thus, *FWE* only tracks relative changes in species biomasses, i.e., in the compositional diversity of the community (it's scale invariant *sensu* Tuomisto, 2012).

It has to be noted that the 'biomass pyramid' concept does not hold for the biomass relationships at the very bottom of aquatic foodwebs due to high productivity of phytoplankton and microzooplankton. Thus, for aquatic systems it is sensible to only include multicellular organisms such as macrozooplankton or higher trophic level species when calculating this index.

References

Krebs, C.J., 1999. Estimating community parameters, in: Ecological Methodology. Addison-Welsey Education Publishers, Inc., pp. 373–409.

Lance G.N., Williams W.T. (1967): Mixed-data classificatory programs, I.) Agglomerative Systems. Australian Computer Journal 1:15-20.

Tuomisto, H., 2012. An updated consumer's guide to evenness and related indices. Oikos 121, 1203–1218. doi:10.1111/j.1600-0706.2011.19897.x

Appendix F: F_{MSY} values and F_{MSY} ranges

Table F.1. Table presenting the single point F_{MSY} values and the F_{MSY} ranges used in the modelling of the scenarios.

Fishery	Species	$F_{status\ quo}$	F_{MSY}	Reference	$F_{MSY\ lower}$	$F_{MSY\ upper}$	Reference
Demersal	Cod	0.60	0.17	ICES, 2016b	0.11	0.25	ICES, 2016a
	Whiting	0.06	0.18	ICES, 2016b	0.15	0.18	ICES, 2016a
	Haddock	0.17	0.19	ICES, 2016c	0.18	0.19	ICES, 2016c
	Saithe	0.07	0.36	ICES, 2016c	0.20	0.42	ICES, 2015
	Hake	0.04	0.28	ICES, 2016d	0.18	0.45	ICES, 2016a
	Anglerfish	0.14	0.31	ICES, 2016d	0.18*	0.41*	ICES, 2016a
Pelagic	Herring	0.21	0.16	ICES, 2016e			
	Mackerel	0.13	0.22	ICES, 2016f			
	Horse mackerel	0.30	0.09	ICES, 2016f			
	Blue whiting	0.11	0.30	ICES, 2016f			
Crustaceans	Nephrops	0.08	0.109	ICES, 2016b			

*Since no F_{MSY} range values are defined for Anglersfish in ICES area VIa the F_{MSY} range values for ICES areas IIXc and IXa were used instead as the best available proxy.

References

ICES 2016a. EU request to ICES to provide FMSY ranges for selected stocks in ICES subareas 5 to 10. Version 4, 11 July 2016. ICES Advice 2016, Book 5

ICES 2016b. Report of the Working Group for the Celtic Seas Ecoregion (WGCSE). ICES CM 2016/ACOM:13

ICES 2016c. Report of the Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (WGNSSK). ICES CM 2016/ ACOM:14

ICES 2016d. Report of the Working Group for the Bay of Biscay and the Iberian waters Ecoregion (WGBIE). ICES CM/ACOM:12

ICES 2016e. Report of the Herring Assessment Working Group for the Area South of 62˚N (HAWG). ICES CM 2016/ACOM:07

ICES 2016f. Report of the Working Group on Widely Distributed Stocks (WGWIDE). ICES CM 2016/ACOM:16

ICES 2015. EU request to ICES to provide FMSY ranges for selected North Sea and Baltic Sea stocks. ICES Advice 2015, Book 6. Version 6, 30-6-2016.

Appendix G: Spatial distribution of key demersal species

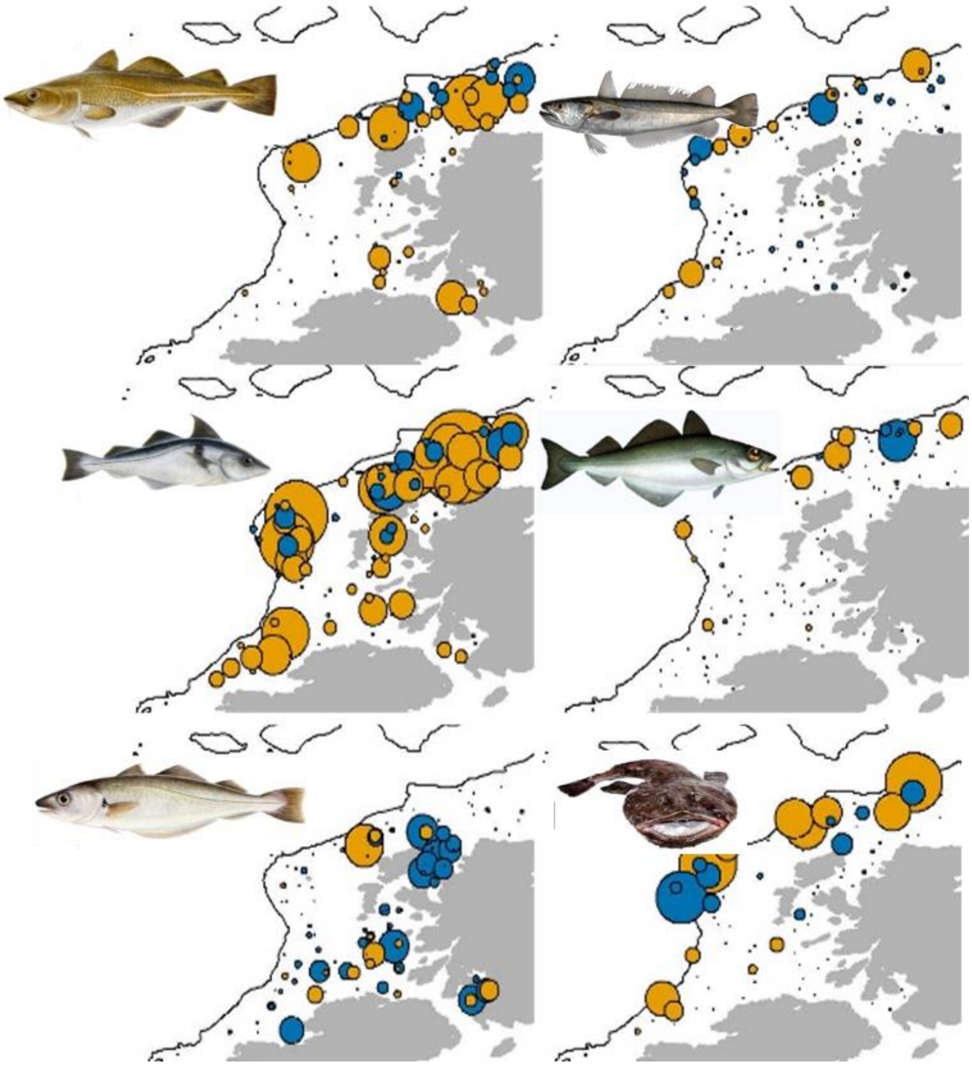

Fig. G.1. Spatial distribution of bottom-trawl survey swept-area density observations from Quarter 1 (yellow) and Quarter 3 (blue) International Bottom-Trawl Surveys for cod (*top left*), hake (*top right*), haddock (*middle left*), saithe (*middle right*), whiting (*bottom left*), and anglerfish (*bottom right*).

Appendix H: MCA scenario data

Table H.1. The table shows the forecasted estimates for indicators for each scenario in the years 2020 and 2025. The abbreviations of indicator names used in the MCA are shown in parentheses. Column headings refer to a) Scenarios names as used in the MCA: MixMEY (Mixed MEY), Gadiod Recovery (GRec), Status Quo (SQ), Maximum Sustainable Yield (MSY), Gadiod recovery and seal cull (GRecSC), Spatial F (SpatialF); b) The minimum and maximum limits for each indicator in the MCA is respectively set to the lowest and highest value across the scenarios. These limits are needs to be defined in the MCA and represent the window of opportunity for each indicator, across the modelled scenarios.

2020	**MixMEY**	**GRec**	**SQ**	**MSY**	**GRecSC**	**SpatialF**	**Min**	**Max**	**Units**
Catch value									
Demersal (VDem20)	198	220	93,1	220	224	206	93,1	224	MEUR
Pelagic (VPel20)	356	355	278	361	355	367	278	367	MEUR
Nephrops (VNep20)	50,8	49,8	57	50,6	49,6	49,2	49,2	57	MEUR
Profitability									
Demersal (PDem20)	108	95,3	68	101	99,4	45,1	45,1	108	MEUR
Pelagic (PPel20)	248	247	196	251	247	256	196	256	MEUR
Nephrops (PNep20)	30,5	29,5	36,7	30,2	29,3	28,9	28,9	36,7	MEUR
Stocks									
Haddock (Had20)	64,5	57,9	48,4	52,5	57,7	86,9	48,4	86,9	1000t
Saithe (Sai20)	150	118	351	145	122	117	117	351	1000t
Hake (Hake20)	214	168	344	168	171	116	116	344	1000t
Nephrops (Nep20)	136	133	152	135	133	131	131	152	1000t
Cod (Cod20)	3,88	5,59	0,182	5,37	5,8	9,26	0,182	9,26	1000t
Whi (Whi20)	5,88	15,5	4,07	6,06	15,5	10,1	4,07	15,5	1000t
Foodweb									
Prey fish (Prey20)	1096	1146	832	1116	1145	1101	832	1146	Mt
Balenced Evenness (BE_20)	0,5063	0,5217	0,4923	0,5154	0,5234	0,5289	0,4923	0,5289	#
Seabirds Bird20	2,81	2,09	1,83	2,08	2,1	2,04	1,83	2,81	1000t
Seals (Seal20)	7,59	7,19	8,92	7,28	6,13	6,84	6,13	8,92	1000t
2025									
Catch value									
VDem25	204	228	97,2	226	235	202	97,2	235	MEUR
VPel25	328	316	286	334	316	342	286	342	MEUR
VNep25	46,2	44,3	58,2	45,5	44	43,1	43,1	58,2	MEUR

Profitability									
PDem25	114	104	72,1	107	110	41,3	41,3	114	MEUR
PPel25	229	221	202	233	221	239	202	239	MEUR
PNep25	25,9	24	37,9	25,2	23,7	22,8	22,8	37,9	MEUR
Stocks									
Had25	79,2	70,1	57,1	63	69,2	98,3	57,1	98,3	1000t
Sai25	145	111	350	143	117	108	108	350	1000t
Hake25	202	157	358	157	161	108	108	358	1000t
Nep25	123	118	156	122	118	115	115	156	1000t
Cod25	11,9	19,7	0,0394	16,9	20,5	31,3	0,0394	31,3	1000t
Whi25	10,1	38,5	4,43	10,1	37,7	18,8	4,43	38,5	1000t
Foodweb									
Prey25	1199	1233	803	1233	1228	1174	803	1233	Mt
BE_25	0,5204	0,5262	0,4767	0,5317	0,526	0,529	0,4767	0,5317	#
Bird25	2,85	2,43	1,76	2,44	2,43	2,31	1,76	2,85	1000t
Seal25	7,09	6,65	9,24	6,75	5,32	6,36	5,32	9,24	1000t

Appendix I: Detailed MCA evaluation results

Table I.1. Table presenting contributions by each indicator to the overall scenario evaluation score in the MCA.

Year	Indicator	MixMEY	Grec	SQ	MSY	GRecSC	SpatialF
2020	Demersal catch value	0,072	0,087	0,000	0,087	0,090	0,078
2020	Pelagic catch value	0,039	0,039	0,000	0,042	0,039	0,045
2020	Nephrops catch value	0,009	0,004	0,045	0,008	0,002	0,000
2020	Demersal profitability	0,090	0,072	0,033	0,080	0,078	0,000
2020	Pelagic profitability	0,039	0,038	0,000	0,041	0,038	0,045
2020	Nephrops profitability	0,009	0,004	0,045	0,008	0,002	0,000
2020	Cod SSB	0,005	0,007	0,000	0,007	0,008	0,012
2020	Whiting SSB	0,003	0,009	0,002	0,003	0,009	0,006
2020	Haddock SSB	0,018	0,018	0,018	0,018	0,018	0,018
2020	Hake TSB	0,018	0,018	0,018	0,018	0,018	0,014
2020	Saithe TSB	0,008	0,007	0,018	0,008	0,007	0,007
2020	Neprops TSB	0,018	0,018	0,018	0,018	0,018	0,018
2020	Balanced Evenness	0,009	0,019	0,000	0,015	0,020	0,024
2020	Prey fish biomass	0,020	0,024	0,000	0,022	0,024	0,021
2020	Seabird biomass	0,024	0,006	0,000	0,006	0,007	0,005
2020	Seal biomass	0,023	0,021	0,022	0,022	0,000	0,016
2025	Demersal catch value	0,039	0,048	0,000	0,047	0,050	0,038
2025	Pelagic catch value	0,019	0,013	0,000	0,021	0,013	0,025
2025	Nephrops catch value	0,005	0,002	0,025	0,004	0,002	0,000
2025	Demersal profitability	0,050	0,043	0,021	0,045	0,047	0,000
2025	Pelagic profitability	0,018	0,013	0,000	0,021	0,013	0,025
2025	Nephrops profitability	0,005	0,002	0,025	0,004	0,002	0,000
2025	Cod SSB	0,013	0,026	0,000	0,020	0,027	0,030
2025	Whiting SSB	0,005	0,023	0,002	0,005	0,022	0,009
2025	Haddock SSB	0,015	0,015	0,015	0,015	0,015	0,015
2025	Hake TSB	0,015	0,015	0,015	0,015	0,015	0,010
2025	Saithe TSB	0,007	0,005	0,015	0,007	0,005	0,005
2025	Neprops TSB	0,015	0,015	0,015	0,015	0,015	0,015
2025	Balanced Evenness	0,016	0,018	0,000	0,020	0,018	0,019
2025	Prey fish biomass	0,018	0,020	0,000	0,020	0,020	0,017
2025	Seabird biomass	0,020	0,012	0,000	0,013	0,012	0,010
2025	Seal biomass	0,019	0,016	0,019	0,017	0,000	0,014
	Total score	0,684	0,677	0,372	0,692	0,653	0,541

Appendix J. Variability of economic indicators

Table J.1. Table presenting the variability of economic indicators across the scenarios for the fleets expressed as coefficient of variation.

	2020		2025	
Fleet	Catch value	Profitability	Catch value	Profitability
Demersal	0,259	0,283	0,259	0,315
Pelagic	0,096	0,092	0,061	0,058
Nephrops	0,057	0,095	0,121	0,213

Appendix K: Selected plots from the sensitivity analysis

The sensitivity analysis can be conducted graphically in the interactive MCA program at the web-location: https://mareframe.github.io/dsf/dev/MCA2/DST.html?model=scotland_weighted

To get the same visual outputs as those described below, the user should exclude the MSY alternative from the analysis in accordance with the reasoning provided in the main text (double click on" MSY" and click "exclude alternative").

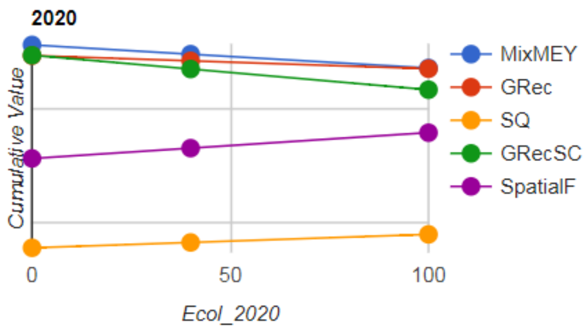

Fig. K.1. Sensitivity of the decision rank for changes in the weight for ecology in 2020. The initial weight is 40. The gadoid recovery strategy will outperform the mixed MEY strategy only if the decision weight assigned to the ecological objectives approaches 100.

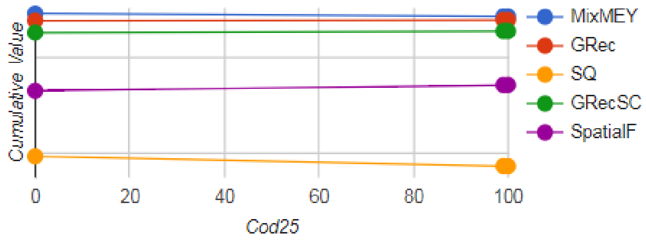

Figure K.2. Sensitivity of the decision rank for changes in the weight for the cod stock in 2025. The assigned weight is 100. Even a reduction to of the cod stock estimate to zero will not alter the top ranking decision.

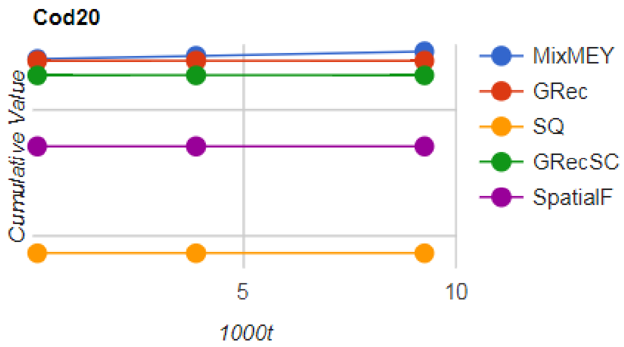

Figure K.3. Impact of uncertainty in the stock projection on the decision rank using the biomass estimate for the cod stock as an example. The prediction by the ecosystem model is 3.88 thousand tonnes in 2020. The mixed MEY strategy will perform best even if the prediction is highly biased. Note that the results are conditional for everything else being fixed in the decision model.