Time-dynamic food web modelling to explore environmental drivers of ecosystem change on the Kerguelen Plateau

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Frontiers in Marine Science, doi 10.3389/fmars.2020.00641

Appendix

Ecopath model

The section presents the balanced parameters of the Ecopath model (from Subramaniam et al. 2020) used to initialise the Ecosim model presented in this study (Table A1 and Table A2).

Table A1: Balanced model parameters. B = Biomass in t km^{-2}, P/B = production/biomass in y^{-1}, Q/B = consumption/biomass in y^{-1}, EE = ecotrophic efficiency, BA = biomass accumulation.

Group name	Trophic level	B	P/B	Q/B	P/Q	EE	BA (t km^{-2})	BA rate (y^{-1})
Baleen whales	3.8	0.027	0.02	6.53	0.0037	0	0	0
Killer whales	5.3	9.3E-06	0.047	10.73	0.0044	0	0	0
Toothed whales and dolphins	5.3	0.0011	0.074	12.79	0.0058	0	0	0
Sperm whale	5.7	0.0017	0.038	5.12	0.0074	0	0	0
Antarctic fur seal	4.8	0.00034	0.26	55.9	0.0047	0.02	0	0
Southern elephant seal	5.4	0.011	0.22	34.02	0.0065	0.00	0	0
Penguins	4.5	0.017	0.159	43.80	0.0036	0.01	0	0
Albatrosses	5.1	3.4E-05	0.07	56.79	0.0012	0.42	0	0
Other seabirds	4.2	0.00085	0.138	314.36	0.0004	0.01	0	0
Cephalopods	4.8	0.28	6.7	17.18	0.39	0.95	0	0
Juvenile Patagonian toothfish	5.0	0.61	0.2	2	0.1	0.79	0.21	0.34
Adult Patagonian toothfish	5.1	0.195	0.105	1.02	0.1	0.45	0.066	0.34
Mackerel icefish	4.1	1.15	0.42	2	0.21	0.93	0	0
Myctophids	3.8	4.4	1	8	0.125	0.95	0	0
Small mesopelagic fish	3.9	2.9	0.5	6.1	0.11	0.94	0	0
Large mesopelagic fish	4.1	1.5	0.22	2.39	0.15	0.91	0	0
Other demersal fish	3.6	1.298	0.502	7.33	0.08	0.93	0	0
Large deep-sea demersal fish	4.3	0.29	0.22	1.5	0.16	0.91	0	0
Krill	3.1	14	1.8	12.86	0.14	0.90	0	0
Other macrozooplankton	2.4	11	4.87	34.79	0.14	0.93	0	0
Mesozooplankton	2.9	22	10.13	33.77	0.3	0.83	0	0
Microzooplankton	2.8	26	52	148.57	0.35	0.86	0	0
Zoobenthos	3.1	32	1	2.85	0.35	0.70	0	0
Bacteria	2.0	19	87	290	0.3	0.95	0	0
Phytoplankton	1.0	33	140	0		0.48	0	0
Macroalgae	1.0	0.7	5.22	0		0.56	0	0
Carcass	1.0					0.82	0	0
Detritus	1.0	197.61				0.89	0	0

Data sources

This section details the trends used to calibrate the model (Table A3) and climate data used to perform correlations (Table A4).

Model fits

This section presents all model version and scenarios fitted during the calibration of the model (Table A5), fits from the best-fit model with original vulnerabilities (Fig A1) and original vulnerabilities used to fit model 3 (Fig A6).

Table A2: Diet from the balanced Ecopath model.

	Functional group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	Baleen whales	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Killer whales	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Toothed whales and dolphins	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Sperm whale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Antarctic fur seal	0	0.015	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	Southern elephant seal	0	0.015	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Penguins	0	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	Albatrosses	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	Other seabirds	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	Cephalopods	0	0.1	0.55	0.75	0.025	0.547	0.08	0.48	0.13	0.130	0.3	0.3	0	0	0	0.1	0	0.19	0	0	0	0	0	0
11	Juvenile patagonian toothfish	0	0.01	0.01	0.05	0.001	0.02	0	0.09	0	0.018	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	Adult patagonian toothfish	0	0.01	0.01	0.05	0.001	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	Mackerel icefish	0	0.02	0.02	0.02	0.001	0.005	0.08	0.02	0	0.068	0.04	0.04	0	0	0	0	0	0	0	0	0	0	0	0
14	Myctophids	0	0.03	0.05	0.01	0.92	0.179	0.24	0.04	0.01	0.379	0.06	0.1	0	0	0.05	0.27	0	0.22	0	0	0	0	0	0
15	Small mesopelagic fish	0	0.07	0.05	0.01	0.02	0.04	0.03	0.06	0.04	0.047	0.37	0.09	0.12	0	0	0.09	0	0.04	0	0	0	0	0	0
16	Large mesopelagic fish	0	0.16	0.1	0.01	0.007	0.02	0.042	0.11	0.02	0.042	0	0.02	0.02	0	0	0	0	0	0	0	0	0	0	0
17	Other demersal fish	0	0.07	0.1	0.05	0.02	0.09	0.01	0.02	0.06	0.095	0.03	0.23	0	0	0	0	0	0	0	0	0	0	0	0
18	Large deep-sea demersal fish	0	0.23	0.01	0.05	0.005	0.09	0	0.04	0	0	0	0.12	0	0	0	0	0	0	0	0	0	0	0	0
19	Krill	0.3	0	0.05	0	0	0	0.47	0.02	0.4	0.150	0.08	0	0.7	0.35	0.24	0.1	0.1	0.15	0	0	0	0	0.02	0
20	Other macrozooplankton	0.2	0	0.05	0	0	0	0.06	0.0018	0.33	0.031	0.02	0	0.1	0.3	0.07	0.1	0.25	0.04	0	0.072	0	0	0.08	0
21	Mesozooplankton	0.5	0	0	0	0	0	0	0.00022	0	0.042	0	0	0.06	0.35	0.54	0.05	0.3	0.07	0.45	0.144	0.02	0	0.1	0
22	Microzooplankton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15	0	0.48	0.2	0.1	0
23	Zoobenthos	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0	0	0.07	0.14	0.24	0.15	0	0	0	0	0.2	0
24	Bacteria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0.2	0
25	Phytoplankton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0.592	0.5	0.4	0.25	0
26	Macroalgae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0.15	0.1	0.13	0	0	0	0	0	0
27	Carcass	0	0	0	0	0	0	0	0.12	0.01	0	0	0	0	0	0	0	0.01	0.01	0	0	0	0	0.01	0
28	Detritus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.192	0	0	0.04	1

Table A3: Sources of time-series data used to calibrate Ecosim. MNHN = Muséum national d'Histoire naturelle, AFMA = Australian Fisheries Management Authority.

Species	**Years**	**Biomass (source)**	**Catch**
Southern right whale	1993–2015	Counts during aerial survey (Bannister et al., 2015)	
Southern elephant seal	1956–2009	Number of breeding females on Kerguelen Island (Authier et al., 2011)	
Black-browed albatross	1978–2017	Population of one colony on Kerguelen Island (Weimerskirch et al., 2018)	
Patagonian toothfish:			
French EEZ Longline	2005–2018	CPUE provided by MNHN	MNHN
Australian EEZ Longline	2003–2018	CPUE provided by AFMA	AFMA
Australian EEZ Trawl	1997–2018	CPUE provided by AFMA	AFMA
Mackerel icefish	1997–2018	Estimated biomass (CCAMLR, 2018)	CCAMLR (2018)
French EEZ model estimated biomass	1979–2019	MNHN	
Australian EEZ model estimated biomass	1982–2016	AFMA	

Table A4: Climate data sources

Variable	**Years**	**Description**	**Units**
SST[1]	1986-2018	NCEP Reanalysis (Kalnay et al., 1996)	°C
SAM[2]	1986-2012	Difference of zonal mean sea level pressure between 40°S and 65°S	NA
Chl a[3]	2002-2018	MODIS-Aqua	mg m^{-3}
Zonal wind[4]	1986-2018	NCEP Reanalysis (Kalnay et al., 1996)	Surface μ wind ms^{-1}

[1]`https://www.esrl.noaa.gov/psd/data/20thCean/timeseries/monthly/SAM/`
[2]`https://www.esrl.noaa.gov/psd/data/20thC_ean/timeseries/monthly/SAM/`
[3]`https://giovanni.gsfc.nasa.gov/`
[4]`https://www.esrl.noaa.gov/psd/data/timeseries/`

Table A5: All model configurations and scenario fits used to find the best-fitting model. V refers to vulnerabilities, pp refers to anomaly spline points. K = total number of parameters estimated in the scenario, NV = number of vulnerabilities estimated, NSpline = number of spline points estimated. Best-fitting scenario is highlighted in bold.

Name	K	NVs	NSpline	SS	AIC	AICc
			Model 3			
Baseline and 5v + 7pp	**12**	**5**	**7**	**23.31684**	**-317.749**	**-316.088**
Baseline and 5v + 2pp	7	5	2	25.30	−315.02	−314.51
Baseline and 10v + 2pp	12	10	2	23.63	−315.48	−313.82
Baseline and 2pp	2	0	2	27.19	−313.21	−313.18
Baseline and 5v + 12pp	17	5	12	21.95	−316.15	−312.62
Baseline and 17pp	17	0	17	21.96	−316.06	−312.53
Baseline and 5v + 17pp	22	5	17	20.41	−315.78	−309.58
Baseline and 7pp	7	0	7	26.33	−308.13	−307.61
Baseline and 12pp	12	0	12	24.76	−307.44	−305.78
Baseline	0	0	0	29.09	−305.63	−305.63
Baseline and 15v + 2pp	17	15	2	22.90	−308.85	−305.31
Baseline and 10v + 7pp	17	10	7	23.47	−304.60	−301.07
Baseline and 5v	5	5	0	28.15	−300.97	−300.73
Baseline and 10v + 12pp	22	10	12	21.94	−303.36	−297.16
Baseline and 22pp	22	0	22	22.00	−302.90	−296.69
Baseline and 5v + 22pp	27	5	22	20.37	−302.42	−292.67
Baseline and 10v + 17pp	27	10	17	20.40	−302.19	−292.44
Baseline and 10v	10	10	0	28.19	−289.72	−288.61
Baseline and 15v + 12pp	27	15	12	21.54	−292.86	−283.11
Baseline and 15v + 7pp	22	15	7	23.84	−289.07	−282.87
Baseline and 20v + 12pp	32	20	12	19.74	−293.17	−278.90
Baseline and 5v + 27pp	32	5	27	19.80	−292.64	−278.37
Baseline and 10v + 22pp	32	10	22	19.94	−291.39	−277.11
Baseline and 15v + 17pp	32	15	17	20.30	−288.33	−274.05
Baseline and 15v	15	15	0	28.56	−275.73	−273.04
Baseline and 25v + 2pp	27	25	2	23.46	−278.18	−268.43
Baseline and 30v	30	30	0	22.89	−273.70	−261.36
Baseline and 5v + 32pp	37	5	32	19.37	−280.61	−260.73
Baseline and 20v	20	20	0	28.22	−265.34	−260.31
Baseline and 15v + 22pp	37	15	22	19.49	−279.60	−259.72
Baseline and 32pp	32	0	32	22.10	−273.75	−259.48
Baseline and 30v + 2pp	32	30	2	22.65	−269.49	−255.22
Baseline and 20v + 17pp	37	20	17	20.02	−274.94	−255.06
Baseline and 25v	25	25	0	26.64	−261.91	−253.69
Baseline and 10v + 27pp	37	10	27	20.21	−273.35	−253.47
Baseline and 30v + 7pp	37	30	7	21.34	−264.00	−244.12
Baseline and 25v + 7pp	32	25	7	24.31	−257.32	−243.04
Baseline and 25v + 12pp	37	25	12	22.16	−257.49	−237.61
Baseline and 10v + 32pp	42	10	32	19.43	−263.07	−236.37
Baseline and 15v + 27pp	42	15	27	19.71	−260.60	−233.90
Baseline and 30v + 12pp	42	30	12	19.74	−260.35	−233.65
Baseline and 25v + 17pp	42	25	17	19.93	−258.67	−231.97
Baseline and 20v + 22pp	42	20	22	20.04	−257.79	−231.10
Baseline and 25v + 22pp	47	25	22	19.12	−247.48	−212.61
Baseline and 30v + 17pp	47	30	17	19.37	−245.22	−210.35
Baseline and 15v + 32pp	47	15	32	19.73	−242.07	−207.20
Baseline and 27pp	27	0	27	34.03	−214.19	−204.44
Baseline and 20v + 27pp	47	20	27	20.13	−238.64	−203.77
Baseline and 30v + 22pp	52	30	22	18.69	−231.43	−186.86
Baseline and 20v + 32pp	52	20	32	19.32	−225.73	−181.16

Baseline and 25v + 27pp	52	25	27	19.56	−223.65	−179.08
Baseline and 30v + 27pp	57	30	27	19.23	−204.85	−148.85
Baseline and 25v + 32pp	57	25	32	20.09	−197.32	−141.32
Baseline and 30v + 32pp	62	30	32	17.94	−193.09	−123.70
			Model 4			
Baseline and 2pp	2	0	2	25.75	−206.40	−206.37
Baseline and 10v + 2pp	12	10	2	21.52	−207.14	−204.89
Baseline and 17pp	17	0	17	19.48	−207.27	−202.42
Baseline	0	0	0	27.57	−201.59	−201.59
Baseline and 5v + 7pp	12	5	7	22.16	−203.34	−201.08
Baseline and 5v + 2pp	7	5	2	24.77	−200.59	−199.91
Baseline and 7pp	7	0	7	25.28	−197.98	−197.30
Baseline and 12pp	12	0	12	22.82	−199.54	−197.28
Baseline and 5v	5	5	0	26.37	−196.93	−196.61
Baseline and 5v + 17pp	22	5	17	18.12	−202.74	−194.11
Baseline and 5v + 12pp	17	5	12	20.88	−198.27	−193.41
Baseline and 10v + 7pp	17	10	7	21.25	−196.02	−191.16
Baseline and 10v	10	10	0	26.11	−186.85	−185.33
Baseline and 10v + 12pp	22	10	12	19.48	−193.27	−184.64
Baseline and 5v + 22pp	27	5	22	16.85	−196.77	−183.00
Baseline and 22pp	22	0	22	20.34	−187.70	−179.07
Baseline and 15v + 7pp	22	15	7	21.01	−183.46	−174.82
Baseline and 15v + 2pp	17	15	2	24.55	−177.21	−172.35
Baseline and 15v	15	15	0	25.89	−175.55	−171.87
Baseline and 10v + 17pp	27	10	17	18.66	−183.54	−169.77
Baseline and 27pp	27	0	27	19.69	−176.53	−162.76
Baseline and 20v + 2pp	22	20	2	23.37	−169.63	−161.00
Baseline and 15v + 12pp	27	15	12	20.02	−174.36	−160.59
Baseline and 20v + 7pp	27	20	7	20.73	−169.84	−156.07
Baseline and 20v	20	20	0	26.03	−161.39	−154.42
Baseline and 10v + 22pp	32	10	22	17.69	−173.51	−153.06
Baseline and 15v + 17pp	32	15	17	18.20	−169.85	−149.40
Baseline and 25v + 2pp	27	25	2	22.08	−161.65	−147.88
Baseline and 25v + 7pp	32	25	7	18.73	−166.10	−145.64
Baseline and 32pp	32	0	32	19.72	−159.40	−138.94
Baseline and 25v	25	25	0	25.28	−150.37	−138.84
Baseline and 30v	30	30	0	21.62	−154.43	−136.86
Baseline and 20v + 12pp	32	20	12	20.66	−153.33	−132.87
Baseline and 5v + 32pp	37	5	32	17.13	−158.87	−129.91
Baseline and 10v + 27pp	37	10	27	17.82	−153.75	−124.79
Baseline and 30v + 2pp	32	30	2	22.03	−145.00	−124.55
Baseline and 15v + 22pp	37	15	22	18.21	−150.99	−122.03
Baseline and 25v + 12pp	37	25	12	19.07	−144.95	−115.99
Baseline and 20v + 22pp	42	20	22	16.48	−142.99	−103.40
Baseline and 30v + 7pp	37	30	7	21.26	−130.81	−101.85
Baseline and 25v + 17pp	42	25	17	16.76	−140.82	−101.24
Baseline and 15v + 27pp	42	15	27	17.86	−132.54	−92.96
Baseline and 10v + 32pp	42	10	32	18.10	−130.81	−91.23
Baseline and 30v + 12pp	42	30	12	19.07	−124.00	−84.41
Baseline and 25v + 22pp	47	25	22	15.63	−126.39	−73.66
Baseline and 20v + 27pp	47	20	27	16.42	−119.94	−67.20
Baseline and 30v + 17pp	47	30	17	16.85	−116.60	−63.87
Baseline and 5v + 27pp	32	5	27	36.45	−79.54	−59.08
Baseline and 15v + 32pp	47	15	32	17.95	−108.38	−55.65
Baseline and 20v + 17pp	37	20	17	37.02	−58.74	−29.78
Baseline and 30v + 22pp	52	30	22	16.41	−93.44	−24.56
Baseline and 20v + 32pp	52	20	32	16.44	−93.26	−24.38
Baseline and 25v + 27pp	52	25	27	17.13	−87.88	−19.00

Baseline and 25v + 32pp	57	25	32	15.54	−70.34	18.33
Baseline and 30v + 27pp	57	30	27	22.85	−20.16	68.51
Baseline and 30v + 32pp	62	30	32	24.18	21.91	134.81
			Model 1			
Baseline and 5v	5	5	0	17.26	−176.18	−175.77
Baseline	0	0	0	19.91	−171.95	−171.95
Baseline and 5v + 2pp	7	5	2	17.07	−172.76	−171.88
Baseline and 10v	10	10	0	15.96	−172.57	−170.64
Baseline and 2pp	2	0	2	19.86	−168.09	−168.05
Baseline and 5v + 6pp	11	5	6	16.26	−168.11	−165.72
Baseline and 6pp	6	0	6	18.64	−165.94	−165.32
Baseline and 10v + 2pp	12	10	2	15.94	−167.61	−164.71
Baseline and 10pp	10	0	10	18.28	−158.44	−156.50
Baseline and 5v + 10pp	15	5	10	15.73	−160.96	−156.19
Baseline and 15v	15	15	0	15.96	−159.46	−154.68
Baseline and 10v + 6pp	16	10	6	15.68	−158.55	−153.03
Baseline and 15v + 2pp	17	15	2	15.86	−154.48	−148.16
Baseline and 10v + 10pp	20	10	10	15.15	−150.20	−141.05
Baseline and 20v	20	20	0	15.40	−148.50	−139.34
Baseline and 15v + 6pp	21	15	6	15.26	−146.34	−136.10
Baseline and 20v + 2pp	22	20	2	15.40	−142.13	−130.72
Baseline and 15v + 10pp	25	15	10	14.86	−135.68	−120.29
Baseline and 25v	25	25	0	15.27	−132.88	−117.49
Baseline and 20v + 6pp	26	20	6	14.55	−134.33	−117.45
Baseline and 25v + 2pp	27	25	2	15.72	−122.61	−104.14
Baseline and 20v + 10pp	30	20	10	13.63	−125.88	−102.04
Baseline and 30v	30	30	0	15.11	−115.16	−91.33
Baseline and 25v + 6pp	31	25	6	14.44	−115.79	−89.96
Baseline and 30v + 2pp	32	30	2	15.21	−106.22	−78.28
Baseline and 25v + 10pp	35	25	10	13.73	−103.56	−68.56
Baseline and 30v + 6pp	36	30	6	14.45	−93.52	−55.91
Baseline and 30v + 10pp	40	30	10	13.67	−78.95	−29.43
			Model 2			
Baseline	0	0	0	18.12	−96.96	−96.96
Baseline and 5v	5	5	0	16.33	−93.42	−92.81
Baseline and 2pp	2	0	2	18.12	−92.78	−92.72
Baseline and 5v + 2pp	7	5	2	16.26	−88.86	−87.53
Baseline and 7pp	7	0	7	16.67	−87.12	−85.78
Baseline and 10v	10	10	0	15.17	−85.93	−82.93
Baseline and 5v + 7pp	12	5	7	14.47	−83.55	−79.00
Baseline and 10v + 2pp	12	10	2	15.16	−80.23	−75.68
Baseline and 12pp	12	0	12	16.57	−73.92	−69.37
Baseline and 15v	15	15	0	14.76	−72.81	−65.17
Baseline and 10v + 7pp	17	10	7	13.88	−70.36	−60.10
Baseline and 15v + 2pp	17	15	2	14.67	−66.39	−56.12
Baseline and 5v + 12pp	17	5	12	14.69	−66.30	−56.04
Baseline and 20v	20	20	0	12.73	−65.23	−50.03
Baseline and 20v + 2pp	22	20	2	12.71	−57.08	−37.83
Baseline and 15v + 7pp	22	15	7	12.92	−55.90	−36.65
Baseline and 10v + 12pp	22	10	12	13.99	−50.23	−30.98
Baseline and 25v	25	25	0	12.57	−44.05	−17.38
Baseline and 20v + 7pp	27	20	7	11.21	−41.88	−9.23
Baseline and 25v + 2pp	27	25	2	12.34	−35.09	−2.44
Baseline and 15v + 12pp	27	15	12	12.65	−33.29	−0.64
Baseline and 30v	30	30	0	12.33	−17.79	25.71
Baseline and 20v + 12pp	32	20	12	10.80	−14.10	38.11
Baseline and 25v + 7pp	32	25	7	11.19	−11.60	40.61
Baseline and 30v + 2pp	32	30	2	12.55	−3.48	48.73

Baseline and 25v + 12pp	37	25	12	10.64	24.45	105.18
Baseline and 30v + 7pp	37	30	7	11.13	27.63	108.36
Baseline and 30v + 12pp	42	30	12	10.67	78.43	201.43
Model 3 with fishing (mortality and catch)						
Fishing and 15v + 7pp	22	15	7	309.39	83.10	86.81
Fishing and 10v + 12pp	22	10	12	318.81	91.25	94.97
Fishing and 15v + 12pp	27	15	12	323.25	107.15	112.90
Fishing and 10v + 17pp	27	10	17	323.53	107.38	113.14
Fishing and 30v + 7pp	37	30	7	292.34	105.63	117.02
Fishing and 5v + 17pp	22	5	17	347.13	114.40	118.12
Fishing and 5v + 12pp	17	5	12	366.91	117.82	119.96
Fishing and 7pp	7	0	7	413.47	128.33	128.65
Fishing and 25v + 7pp	32	25	7	341.46	134.70	143.00
Fishing and 5v + 22pp	27	5	22	369.98	143.88	149.63
Fishing and 20v + 17pp	37	20	17	330.56	139.06	150.44
Fishing and 15v + 17pp	32	15	17	351.73	142.76	151.06
Fishing and 20v + 7pp	27	20	7	379.97	151.12	156.88
Fishing and 20v + 12pp	32	20	12	359.45	148.67	156.97
Fishing and 5v + 7pp	12	5	7	441.95	157.23	158.25
Fishing and 25v + 12pp	37	25	12	344.41	150.22	161.60
Fishing and 25v + 17pp	42	25	17	324.29	147.60	162.64
Fishing and 15v + 22pp	37	15	22	361.27	163.22	174.60
Fishing and 20v + 22pp	42	20	22	345.83	165.09	180.13
Fishing and 10v + 22pp	32	10	22	397.04	175.72	184.02
Fishing and 10v + 27pp	37	10	27	382.66	178.86	190.25
Fishing and 10v + 7pp	17	10	7	484.80	193.61	195.75
Fishing and 25v + 22pp	47	25	22	342.27	176.65	195.95
Fishing and 30v + 22pp	52	30	22	320.25	173.59	197.81
Fishing and 20v + 27pp	47	20	27	355.28	186.79	206.10
Fishing and 17pp	17	0	17	512.35	208.64	210.78
Fishing and 15v + 27pp	42	15	27	388.80	196.95	211.99
Fishing and 30v + 17pp	47	30	17	364.06	193.44	212.74
Fishing and 25v + 27pp	52	25	27	338.82	188.92	213.14
Fishing and 15v + 2pp	17	15	2	516.90	211.05	213.19
Fishing and 30v + 12pp	42	30	12	400.80	205.21	220.25
Fishing and 10v + 2pp	12	10	2	571.83	227.31	228.33
Fishing and 15v	15	15	0	556.91	226.79	228.43
Fishing and 20v + 32pp	52	20	32	367.05	210.68	234.90
Fishing and 25v + 32pp	57	25	32	341.85	207.07	236.90
Fishing and 25v	25	25	0	522.67	232.94	237.82
Fishing and 10v + 32pp	42	10	32	427.88	223.00	238.04
Fishing and 15v + 32pp	47	15	32	409.90	225.69	244.99
Fishing and 30v + 27pp	57	30	27	363.43	223.72	253.55
Fishing and 25v + 2pp	27	25	2	547.61	250.53	256.29
Fishing and 32pp	32	0	32	517.95	248.03	256.33
Fishing and 20v + 2pp	22	20	2	579.58	253.83	257.54
Fishing and 30v + 32pp	62	30	32	341.95	223.63	259.82
Fishing and 10v	10	10	0	654.66	259.74	260.43
Fishing and 20v	20	20	0	617.35	266.29	269.32
Fishing and 5v + 32pp	37	5	32	516.37	260.37	271.76
Fishing and 30v + 2pp	32	30	2	556.00	267.31	275.61
Fishing and 30v	30	30	0	589.12	277.93	285.15
Fishing and 27pp	27	0	27	643.15	294.27	300.03
Fishing and 5v + 27pp	32	5	27	628.35	300.58	308.88
Fishing and 5v	5	5	0	1063.98	381.22	381.38
Fishing and 5v + 2pp	7	5	2	1064.37	385.52	385.84
Fishing	0	0	0	1267.05	418.51	418.51
Model 1 with fishing						

Fishing and 15v + 7pp	22	15	7	510.46	238.07	243.99
Fishing and 7pp	7	0	7	658.97	247.95	248.44
Fishing and 5v + 7pp	12	5	7	622.38	248.94	250.53
Fishing and 10v + 7pp	17	10	7	583.68	249.37	252.75
Fishing and 20v + 7pp	27	20	7	514.80	253.11	262.40
Fishing and 12pp	12	0	12	673.36	263.04	264.63
Fishing and 15v + 2pp	17	15	2	634.36	264.28	267.66
Fishing and 15v + 12pp	27	15	12	534.70	259.90	269.19
Fishing and 25v + 7pp	32	25	7	503.97	263.75	277.34
Fishing and 5v + 12pp	17	5	12	675.17	275.44	278.82
Fishing and 5v + 2pp	7	5	2	784.86	279.24	279.73
Fishing and 10v + 2pp	12	10	2	735.59	278.86	280.45
Fishing and 20v + 2pp	22	20	2	631.19	276.07	281.99
Fishing and 10v + 12pp	22	10	12	633.86	276.82	282.74
Fishing and 20v + 12pp	32	20	12	533.91	274.08	287.67
Fishing and 5v	5	5	0	846.04	288.37	288.60
Fishing and 10v	10	10	0	793.33	287.82	288.89
Fishing and 2pp	2	0	2	892.81	291.72	291.74
Fishing	0	0	0	931.90	295.32	295.32
Fishing and 25v + 2pp	27	25	2	619.75	286.32	295.62
Fishing and 30v + 7pp	37	30	7	503.53	279.08	297.97
Fishing and 15v	15	15	0	786.07	297.80	300.38
Fishing and 25v + 12pp	37	25	12	527.54	287.41	306.31
Fishing and 30v + 2pp	32	30	2	611.04	298.24	311.83
Fishing and 20v	20	20	0	784.77	309.88	314.69
Fishing and 30v + 12pp	42	30	12	526.12	303.55	328.87
Fishing and 25v	25	25	0	778.96	321.73	329.57
Fishing and 30v	30	30	0	764.66	332.48	344.24
			Model 4 with fishing			
Fishing and 10v + 12pp	22	10	12	170.33	31.58	37.18
Fishing and 25v + 7pp	32	25	7	149.52	34.57	47.37
Fishing and 10v + 17pp	27	10	17	173.53	48.39	57.17
Fishing and 5v + 12pp	17	5	12	206.01	54.80	58.00
Fishing and 15v + 12pp	27	15	12	177.48	52.63	61.40
Fishing and 20v + 7pp	27	20	7	181.48	56.81	65.59
Fishing and 5v + 7pp	12	5	7	232.08	65.39	66.90
Fishing and 15v + 17pp	32	15	17	166.61	54.91	67.71
Fishing and 5v + 17pp	22	5	17	205.78	67.12	72.72
Fishing and 15v + 7pp	22	15	7	207.45	68.64	74.24
Fishing and 10v + 7pp	17	10	7	227.40	73.37	76.57
Fishing and 30v + 7pp	37	30	7	157.09	58.98	76.74
Fishing and 20v + 12pp	32	20	12	177.50	66.82	79.62
Fishing and 20v + 17pp	37	20	17	160.76	63.32	81.08
Fishing and 10v + 22pp	32	10	22	182.98	72.53	85.33
Fishing and 20v + 2pp	22	20	2	223.12	82.33	87.93
Fishing and 15v + 2pp	17	15	2	245.43	87.72	90.92
Fishing and 25v + 12pp	37	25	12	170.71	74.61	92.37
Fishing and 5v + 22pp	27	5	22	209.80	84.08	92.85
Fishing and 7pp	7	0	7	284.34	92.40	92.87
Fishing and 25v + 2pp	27	25	2	218.15	91.41	100.19
Fishing and 15v + 22pp	37	15	22	178.36	82.85	100.61
Fishing and 30v + 2pp	32	30	2	200.98	90.18	102.98
Fishing and 10v + 27pp	37	10	27	181.13	85.75	103.51
Fishing and 25v + 17pp	42	25	17	162.31	81.29	105.04
Fishing and 30v + 12pp	42	30	12	162.68	81.71	105.46
Fishing and 30v	30	30	0	213.52	95.77	106.86
Fishing and 15v	15	15	0	275.26	104.47	106.91
Fishing and 20v	20	20	0	255.67	102.83	107.38

Fishing and 10v	10	10	0	298.22	107.98	109.00
Fishing and 5v + 27pp	32	5	27	209.35	97.85	110.65
Fishing and 10v + 2pp	12	10	2	298.04	112.41	113.92
Fishing and 20v + 22pp	42	20	22	171.69	91.85	115.60
Fishing and 30v + 17pp	47	30	17	152.09	86.37	117.26
Fishing and 10v + 32pp	42	10	32	195.91	116.65	140.41
Fishing and 17pp	17	0	17	329.15	142.90	146.10
Fishing and 5v + 32pp	37	5	32	227.27	128.41	146.17
Fishing and 15v + 32pp	47	15	32	180.74	118.82	149.71
Fishing and 25v + 22pp	47	25	22	181.36	119.47	150.35
Fishing and 20v + 27pp	47	20	27	186.64	124.86	155.75
Fishing and 15v + 27pp	42	15	27	215.67	134.72	158.48
Fishing and 30v + 22pp	52	30	22	165.85	121.27	160.55
Fishing and 12pp	12	0	12	382.21	159.17	160.68
Fishing and 5v + 2pp	7	5	2	410.28	161.34	161.80
Fishing and 5v	5	5	0	420.59	161.71	161.93
Fishing and 25v + 27pp	52	25	27	178.44	135.01	174.30
Fishing and 20v + 32pp	52	20	32	178.91	135.52	174.80
Fishing and 30v + 27pp	57	30	27	163.87	139.03	188.14
Fishing and 25v + 32pp	57	25	32	186.68	163.54	212.65
Fishing and 27pp	27	0	27	423.29	216.03	224.81
Fishing and 22pp	22	0	22	534.00	246.40	252.00
Fishing and 2pp	2	0	2	739.79	261.61	261.63
Fishing and 32pp	32	0	32	469.13	249.54	262.34
Fishing	0	0	0	770.89	265.29	265.29
			Model 2 with fishing			
Fishing and 10v + 7pp	17	10	7	282.55	144.15	149.94
Fishing and 5v + 7pp	12	5	7	344.13	152.87	155.54
Fishing and 7pp	7	0	7	419.66	163.02	163.83
Fishing and 15v + 7pp	22	15	7	293.19	163.15	173.53
Fishing and 10v + 12pp	22	10	12	301.68	166.35	176.73
Fishing and 5v + 12pp	17	5	12	360.20	171.35	177.13
Fishing and 10v + 2pp	12	10	2	423.97	176.24	178.91
Fishing and 5v + 2pp	7	5	2	499.10	182.44	183.25
Fishing and 5v	5	5	0	532.83	185.25	185.63
Fishing and 15v + 2pp	17	15	2	390.39	180.36	186.15
Fishing and 12pp	12	0	12	457.76	184.83	187.50
Fishing	0	0	0	641.56	195.48	195.48
Fishing and 10v	10	10	0	524.32	195.06	196.85
Fishing and 20v + 7pp	27	20	7	297.40	181.38	198.09
Fishing and 15v + 12pp	27	15	12	303.38	183.61	200.32
Fishing and 20v + 2pp	22	20	2	388.44	194.66	205.04
Fishing and 15v	15	15	0	506.72	204.06	208.43
Fishing and 25v + 7pp	32	25	7	286.53	195.94	221.05
Fishing and 20v	20	20	0	485.35	213.46	221.82
Fishing and 25v + 2pp	27	25	2	368.62	205.42	222.14
Fishing and 20v + 12pp	32	20	12	310.49	204.93	230.05
Fishing and 25v	25	25	0	479.11	227.90	241.85
Fishing and 30v + 2pp	32	30	2	353.78	219.55	244.67
Fishing and 30v + 7pp	37	30	7	292.69	219.59	255.59
Fishing and 25v + 12pp	37	25	12	318.20	228.95	264.95
Fishing and 30v	30	30	0	477.00	245.25	266.73
Fishing and 30v + 12pp	42	30	12	312.24	251.18	301.09

Table A6: Vulnerabilities used in fitting model 3. Estimated vulnerabilities for predatory-prey interactions between juvenile Patagonian toothfish and small mesopelagic fish and small mesopelagic fish and mesozooplankton were outside the realistic range used to calibrate Ecosim models. PT = Patagonian toothfish, SMF = small mesopelagic fish

	Juvenile PT	Adult PT	SMF
Cephalopods	27.13		
Small mesopelagic fish	100		
Large bathypelagic fish		1	
Krill			1.052
Mesozooplankton			100

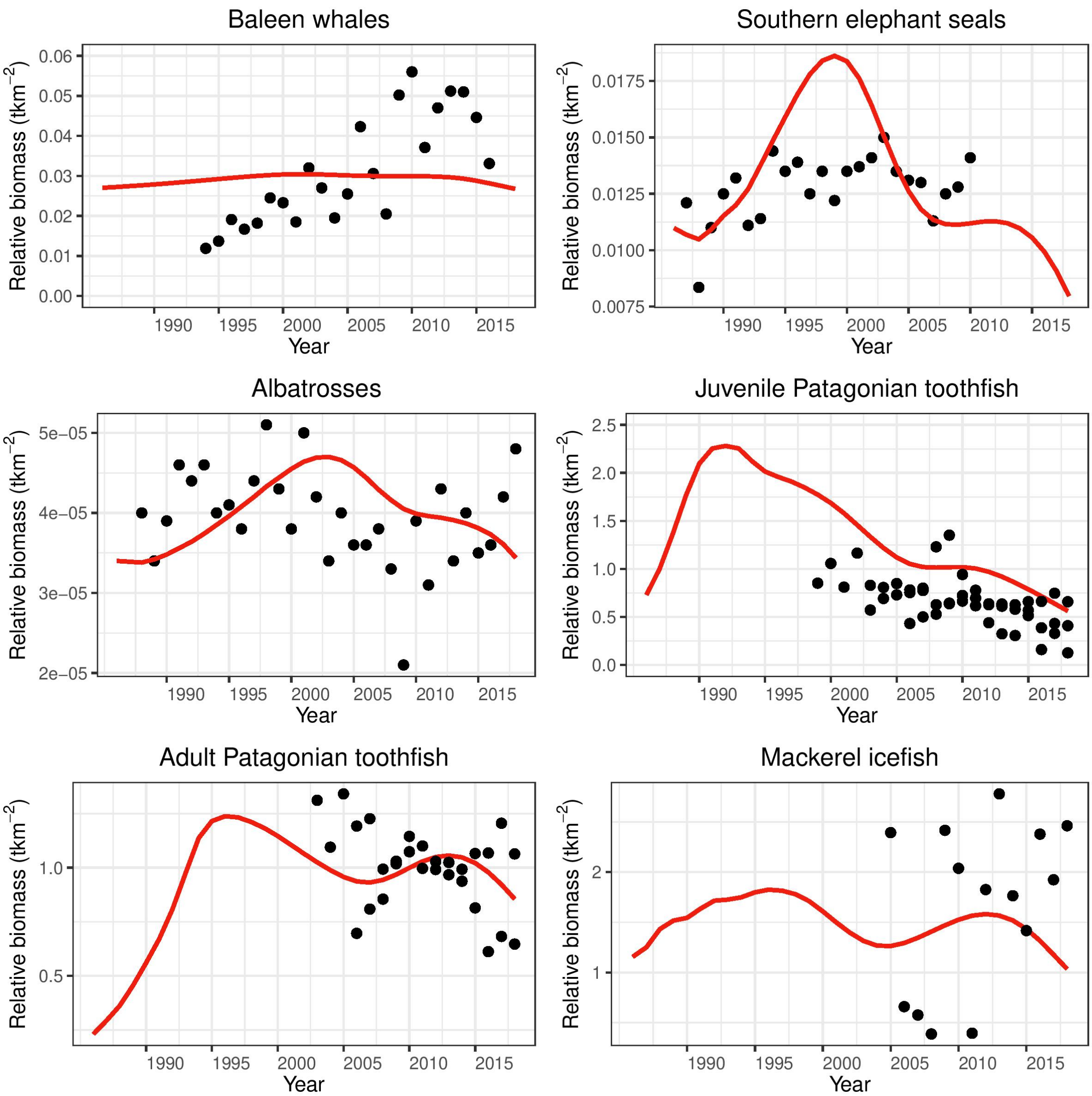

Figure A1: Fit of model to observations with original vulnerabilities (Table A6). Red line shows model fit, black points show observations.

Comparison of model fits to fishery-observer data

Plots of individuals counted per day per year from Gasco et al. (2019) were digitised and plotted for comparison with modelled biomass trends. Table A7 references comparisons of trends for each of the models

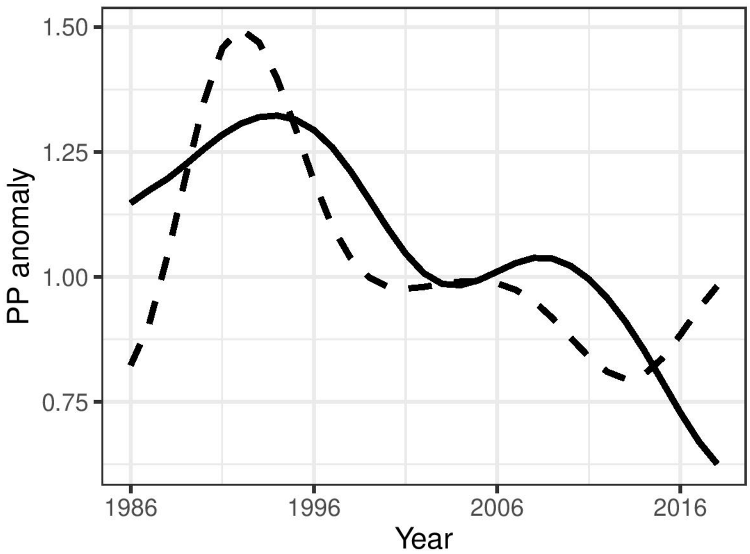

Figure A2: Estimated PP anomaly trend for best-fitting scenario with original vulnerabilities (solid line) and replaced vulnerabilities (dashed line).

described in this study. As can be seen in Table A7, the preferred model reproduced fishery-observer trends better than the model with the original vulnerabilities. Note that the observer trend for killer whales (Figs A6 and A11) is reflective of the trend presented in Gasco et al. (2019) however, the values are not. The data presented in Gasco et al. (2019) did not have clear counts that could be digitised. Therefore, the trend was reproduced by assuming that the lowest count was zero and the highest count was 1.

Table A7: Comparison of model fits to fishery-observer data

Model 3 with original vulnerabilities	Preferred model with replacement vulnerabilities
A3	A8
A4	A9
A5	A10
A6	A11
A7	A12

Correlation with anomaly data

This section presents results from correlations not discussed in the manuscript. Results from correlations with monthly anomalies for SST, zonal wind and SAM, smoothed using a running mean (see Methods) are shown in Table A8. Correlation between model output and annual and seasonal anomalies that did not have significant p-values are presented in Table A9.

Table A8: Output from Spearman rank correlations, with monthly anomaly data for environmental variables and biomass trends for selected functional groups. P values have been adjusted as described in methods. PT = Patagonian toothfish, OM = Other macrozooplankton. Significant correlations highlighted in bold (p value < 0.05).

Model trend	SST	SAM	Chl a	Zonal wind
PP anomaly	**r=-0.27, p=8.63e08**	**r=-0.14, p=0.03**	r=0.16, p=0.14	**r=0.28, p=4.51e-08**
Phytoplankton	**r=-0.27, p=8.63e-08**	**r=-0.13, p=0.03**	r=0.16, p=0.14	**r=0.28, p=4.15e-08**
Juvenile PT	r=-0.1, p=0.053	r=-0.016, p=0.78	r=-0.13, p=0.18	**r=0.26, p=1.65e-07**
Adult PT	r=0.04, p=0.44	**r=0.12, p=0.05**	r=-0.1, p=0.27	**r=0.39, p=1.04e-14**
OM	**r=-0.29, p=3.15e-08**	**r=-0.13, p=0.03**	r=0.16, p=0.14	**r=0.27, p=6.37e-08**
Krill	**r=-0.28, p=3.15e-08**	**r=-0.13, p=0.03**	r=0.18, p=0.14	**r=0.27, p=7.44e-08**

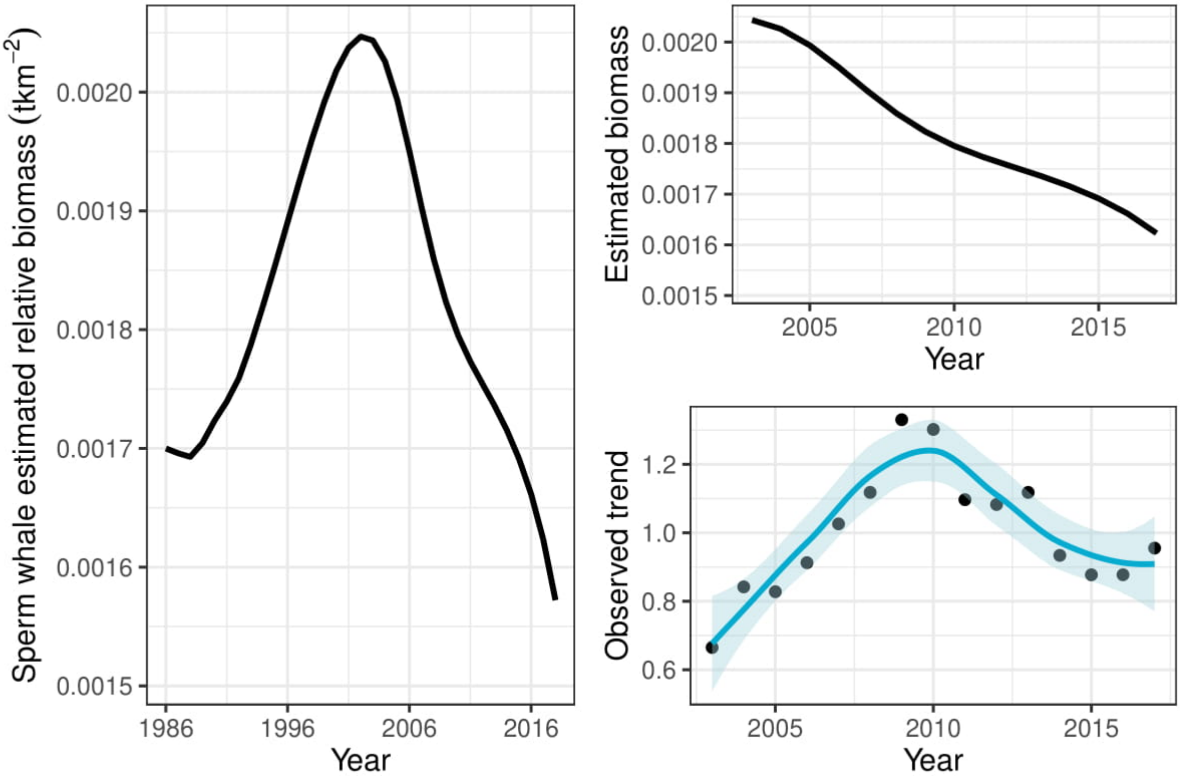

Figure A3: Comparison of modelled sperm whale biomass with fishery-observer data from Gasco et al. (2019). The estimated biomass trend for the model period (1986–2018) is shown on the left, a subsection of the trend equivalent to the fishery-observer data (2003–2017) is shown on the top right and fishery-observer data (individuals per day per year) with LOESS smoothing (blue) is presented on bottom left.

Table A9: Output from Spearman rank correlations, with annual chlorophyll (chl *a*) and winter sea surface temperature (SST). P values have been adjusted as described in methods. PT = Patagonian toothfish.

Biomass trend	**Chl *a***
PP anomaly	r=0.63, p=0.066
Phytoplankton	r=0.57 p=0.066
Juvenile PT	r=0.02, p=0.94
Adult PT	r=0.33, p=0.27
Macrozooplankton	r=0.63, p=0.066
Krill	r=0.57 p=0.066
Lagged time	**Juvenile PT with winter SST**
2 season lag	r=-0.32, p=0.09
3 season lag	r=-0.39, p=0.09
4 season lag	r=-0.32, p=0.1

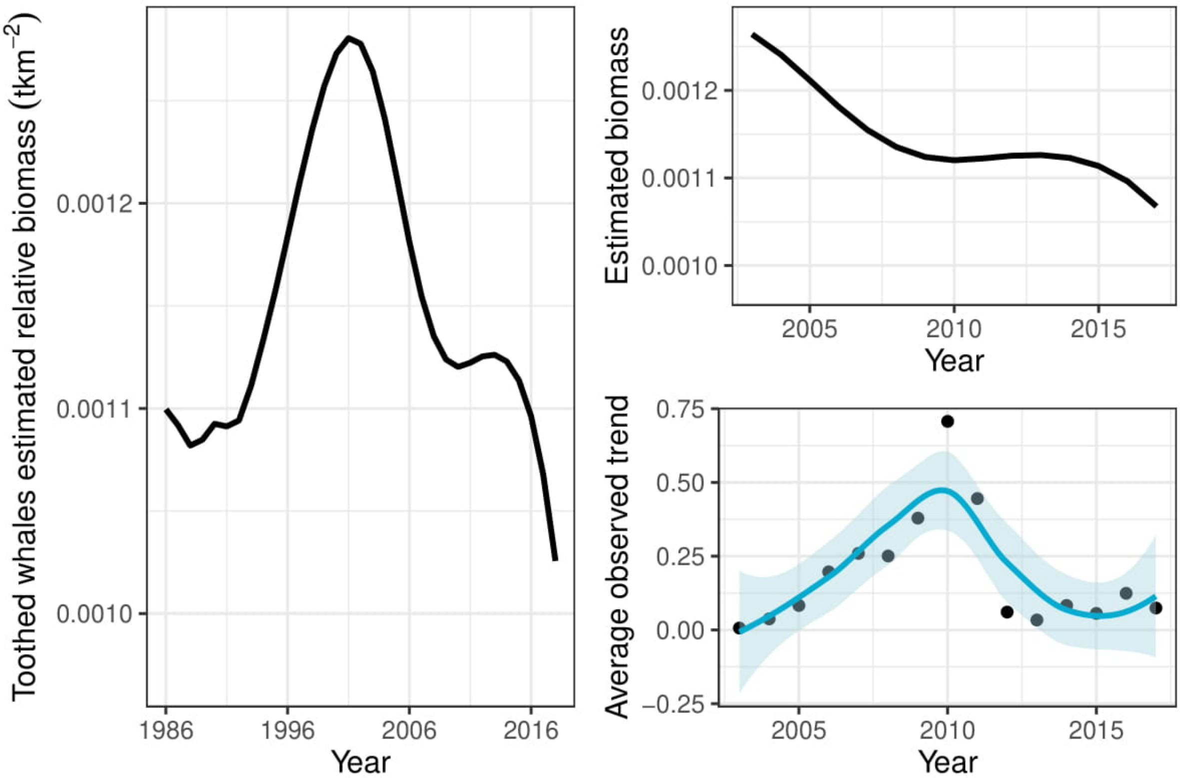

Figure A4: Comparison of modelled toothed whale biomass with fishery-observer data from Gasco et al. (2019). The estimated biomass trend for the model period (1986–2018) is shown on the left, a subsection of the trend equivalent to the fishery-observer data (2003–2017) is shown on the top right and fishery-observer data (individuals per day per year) with LOESS smoothing (blue) is presented on bottom left.

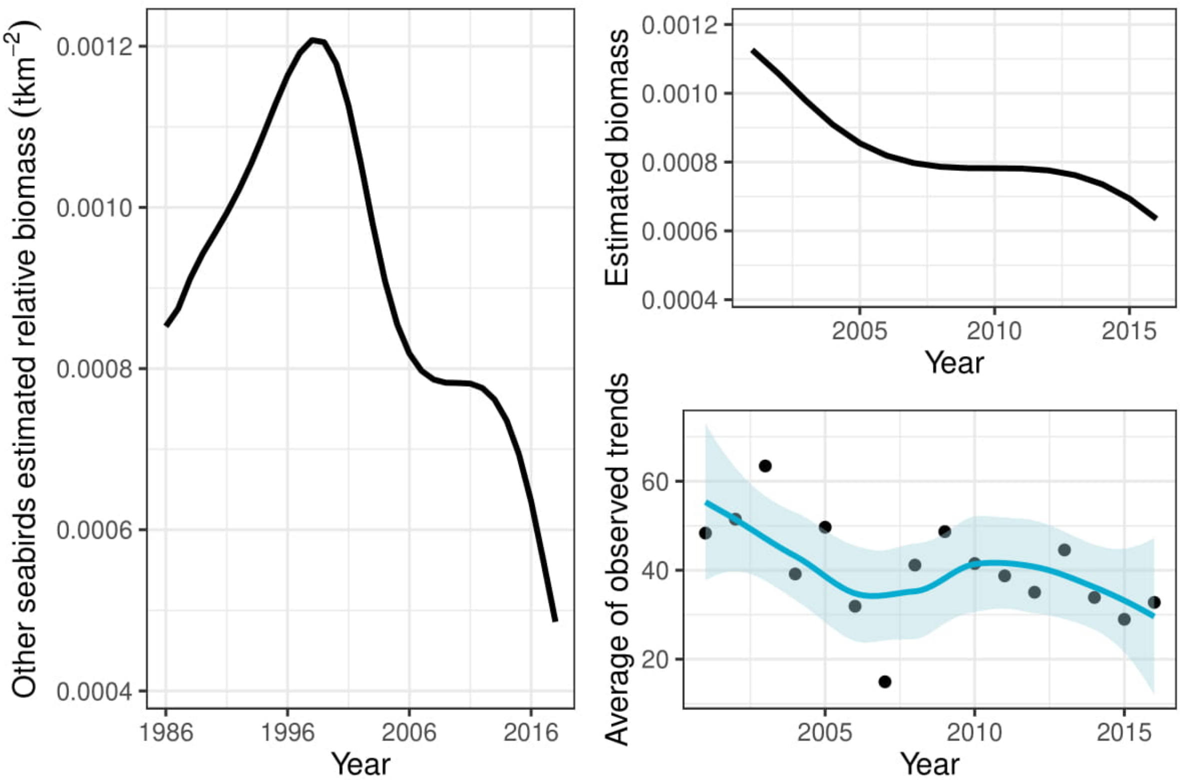

Figure A5: Comparison of modelled other seabird biomass with fishery-observer data from Gasco et al. (2019). The estimated biomass trend for the model period (1986–2018) is shown on the left, a subsection of the trend equivalent to the fishery-observer data (2001–2016) is shown on the top right and fishery-observer data (individuals per day per year) with LOESS smoothing (blue) is presented on bottom left.

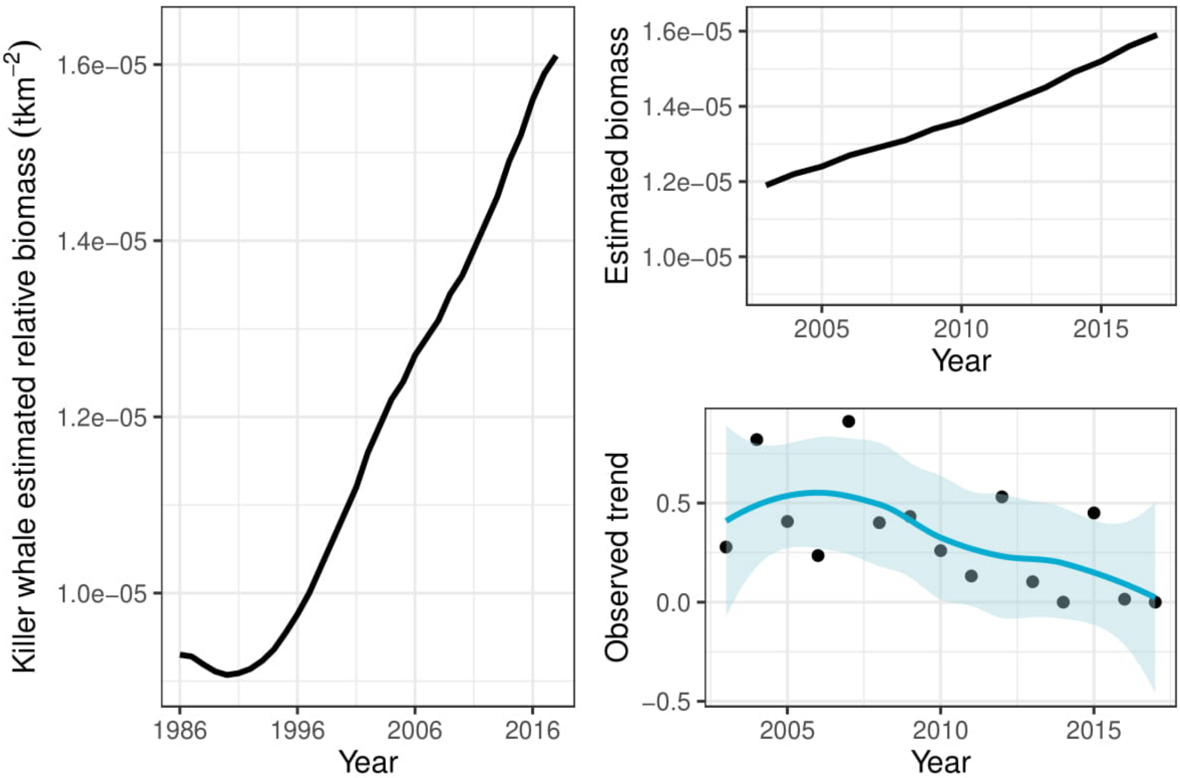

Figure A6: Comparison of modelled killer whale biomass with fishery-observer data from Gasco et al. (2019). The estimated biomass trend for the model period (1986–2018) is shown on the left, a subsection of the trend equivalent to the fishery-observer data (2003–2017) is shown on the top right and fishery-observer data (individuals per day per year) with LOESS smoothing (blue) is presented on bottom left.

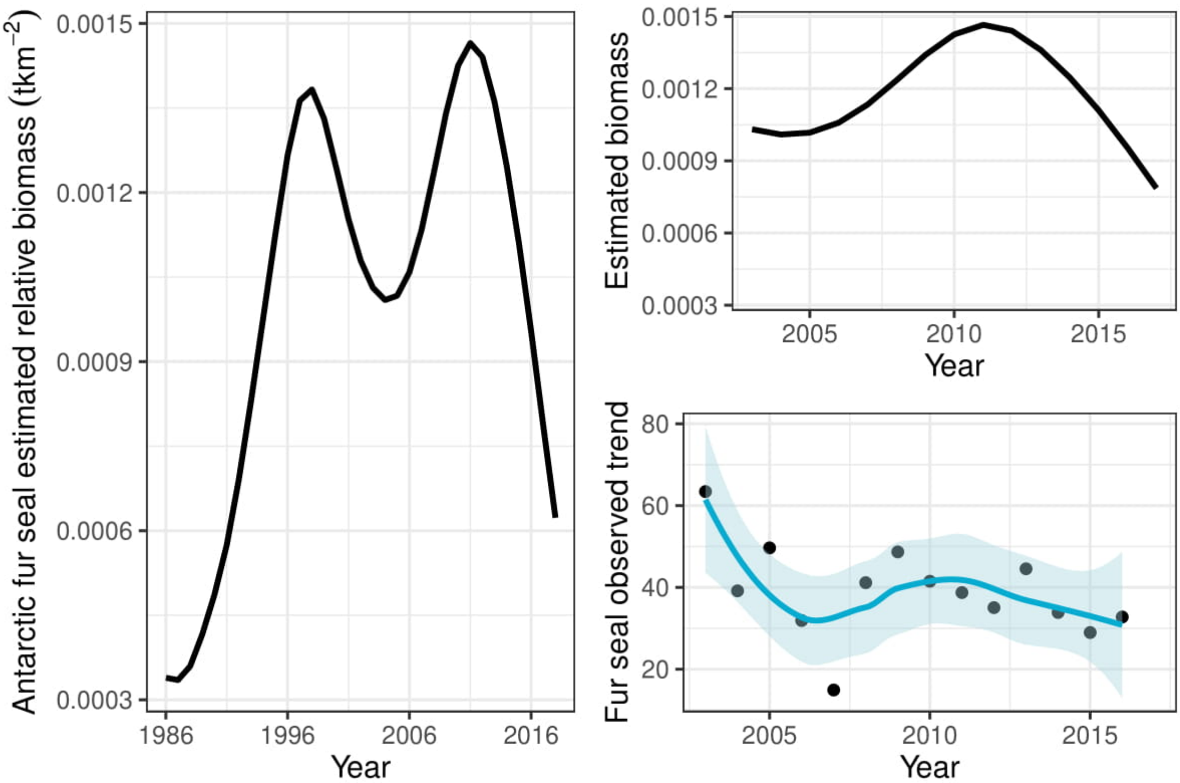

Figure A7: Comparison of modelled fur seal biomass with fishery-observer data from Gasco et al. (2019). The estimated biomass trend for the model period (1986–2018) is shown on the left, a subsection of the trend equivalent to the fishery-observer data (2003–2017) is shown on the top right and fishery-observer data (individuals per day per year) with LOESS smoothing (blue) is presented on bottom left.

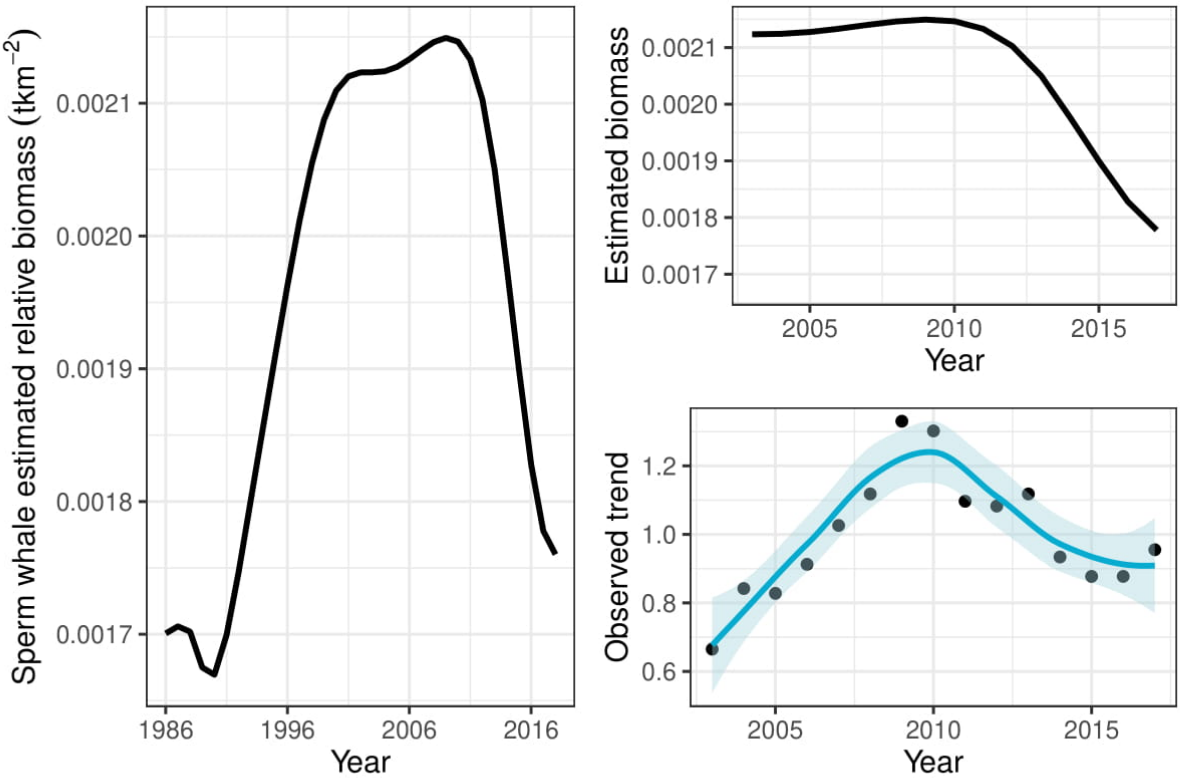

Figure A8: Comparison of modelled sperm whale biomass with fishery-observer data from Gasco et al. (2019). The estimated biomass trend for the model period (1986–2018) is shown on the left, a subsection of the trend equivalent to the fishery-observer data (2003–2017) is shown on the top right and fishery-observer data (individuals per day per year) with LOESS smoothing (blue) is presented on bottom left.

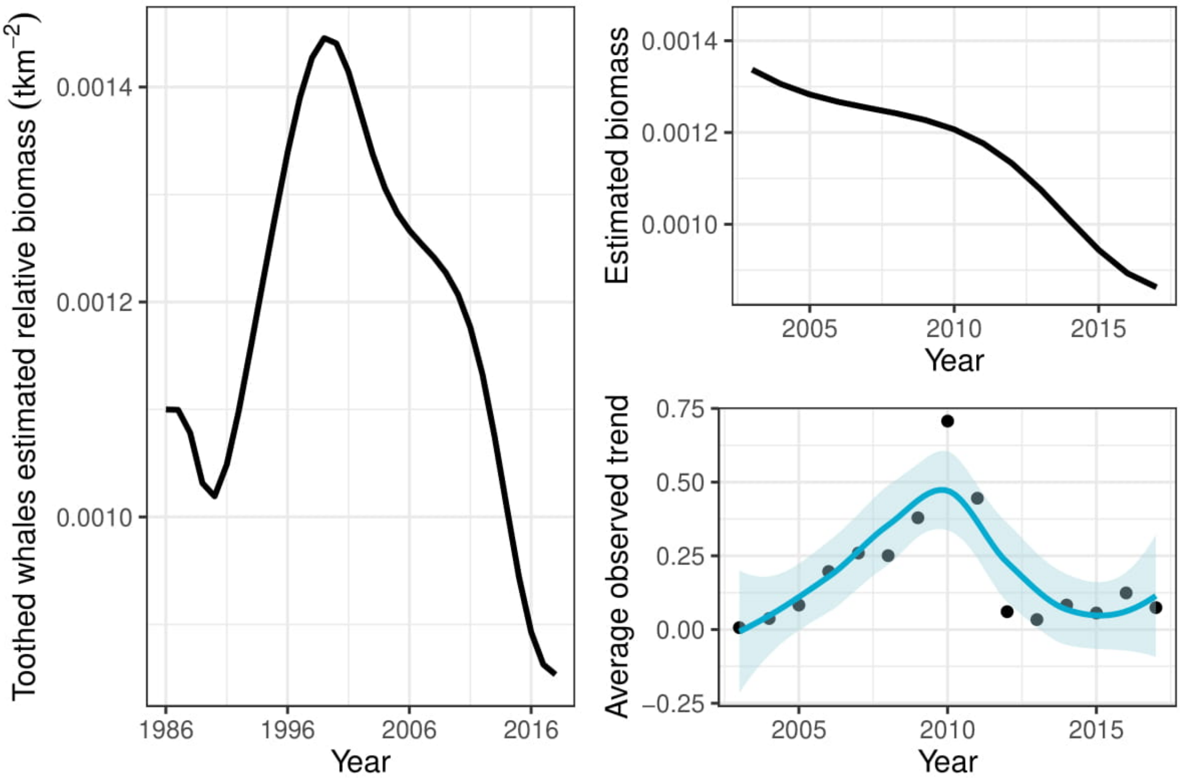

Figure A9: Comparison of modelled toothed whale biomass with fishery-observer data from Gasco et al. (2019). The estimated biomass trend for the model period (1986–2018) is shown on the left, a subsection of the trend equivalent to the fishery-observer data (2003–2017) is shown on the top right and fishery-observer data (individuals per day per year) with LOESS smoothing (blue) is presented on bottom left.

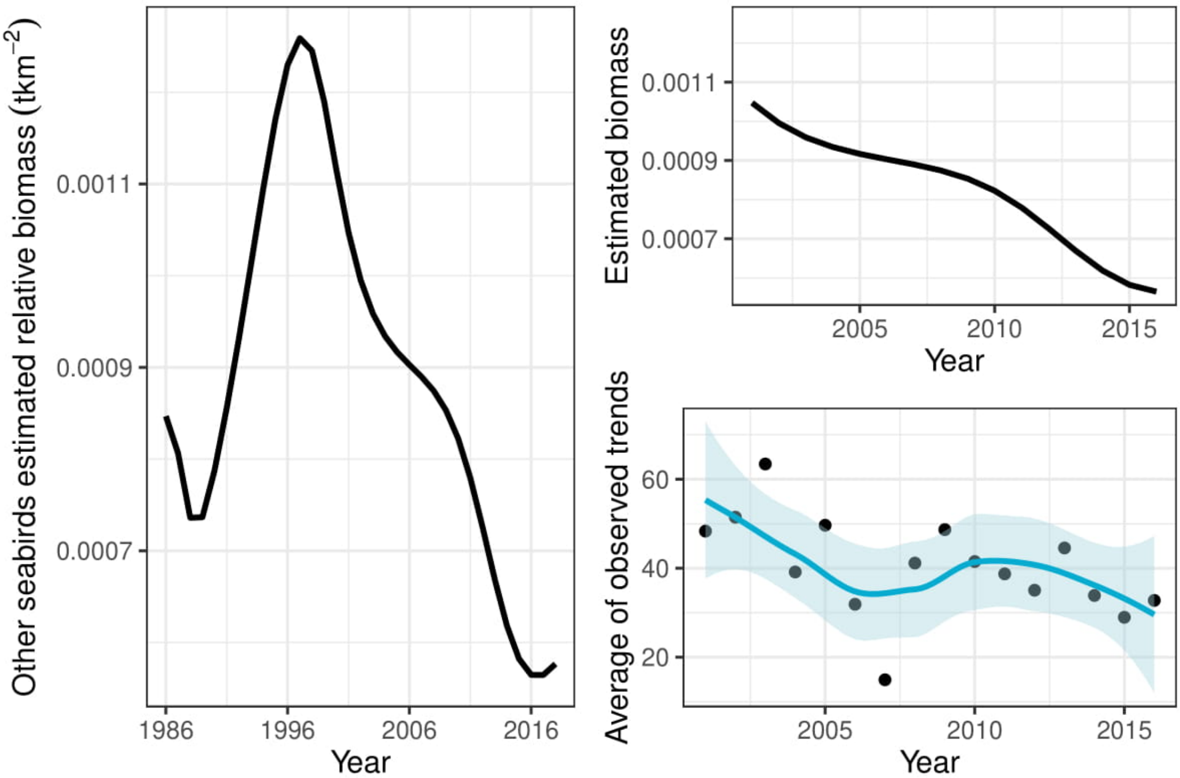

Figure A10: Comparison of modelled other seabird biomass with fishery-observer data from Gasco et al. (2019). The estimated biomass trend for the model period (1986–2018) is shown on the left, a subsection of the trend equivalent to the fishery-observer data (2001–2016) is shown on the top right and fishery-observer data (individuals per day per year) with LOESS smoothing (blue) is presented on bottom left.

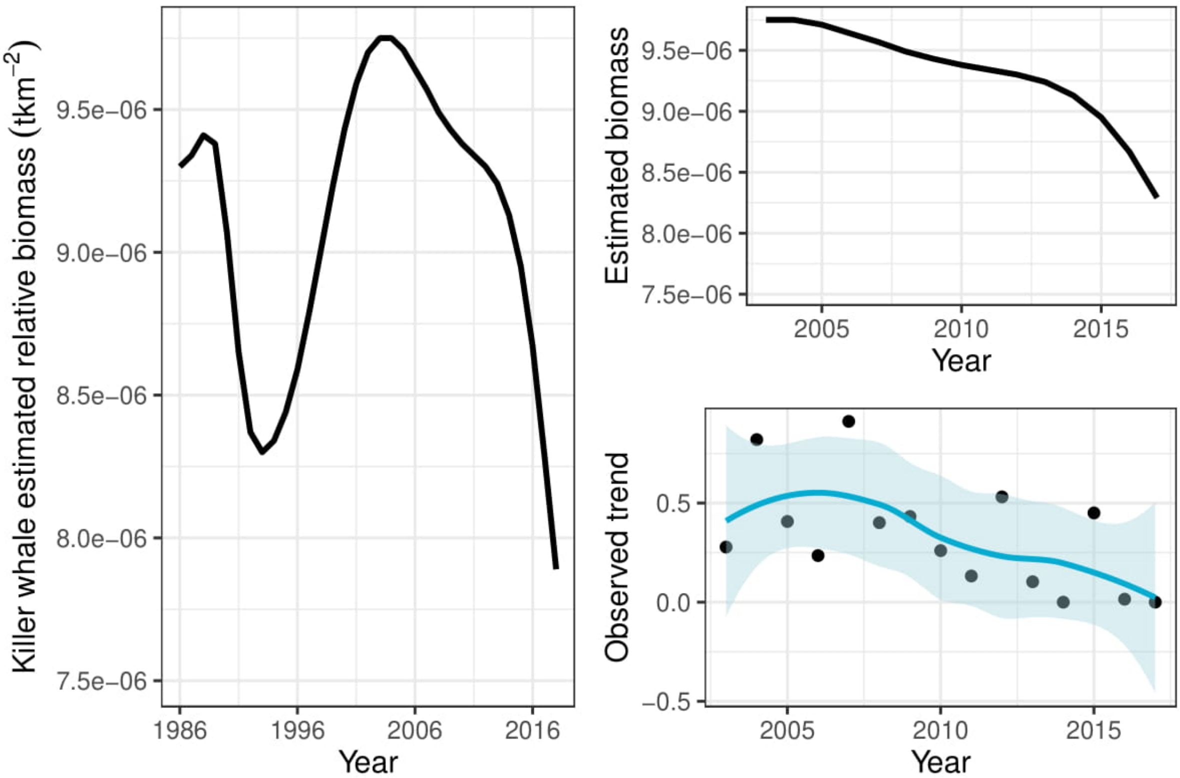

Figure A11: Comparison of modelled killer whale biomass with fishery-observer data from Gasco et al. (2019). The estimated biomass trend for the model period (1986–2018) is shown on the left, a subsection of the trend equivalent to the fishery-observer data (2003–2017) is shown on the top right and fishery-observer data (individuals per day per year) with LOESS smoothing (blue) is presented on bottom left.

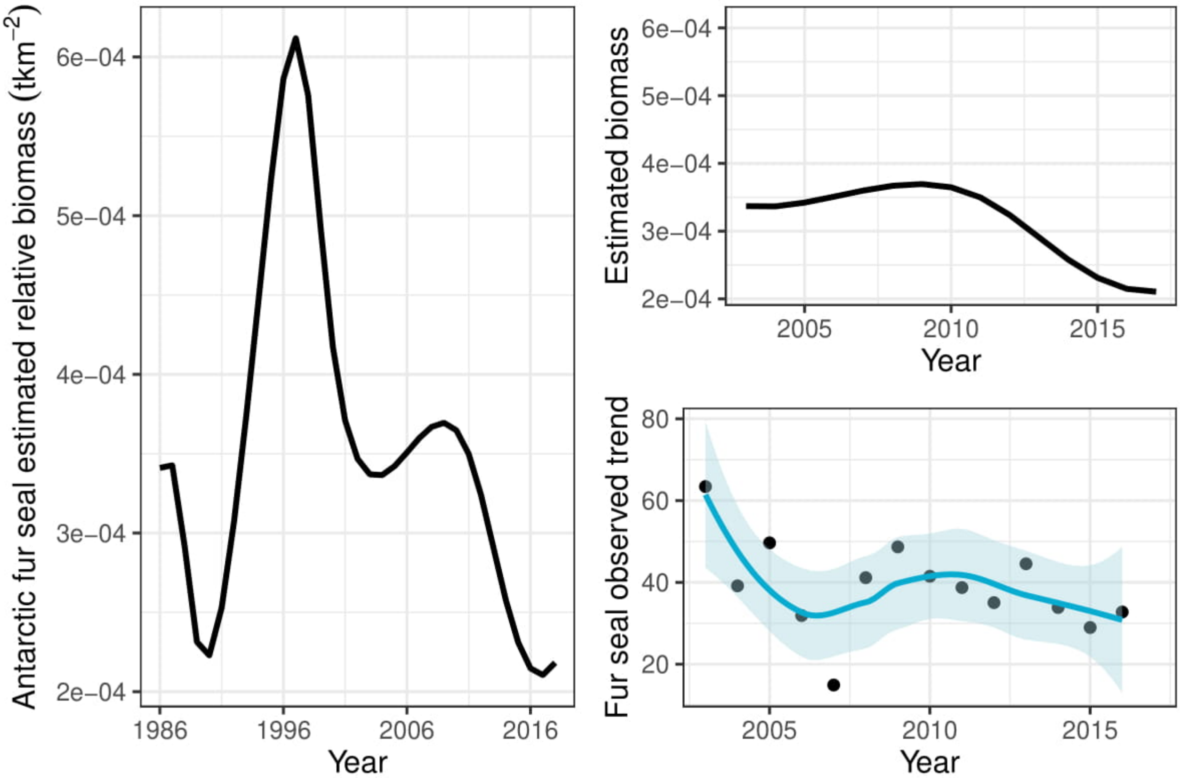

Figure A12: Comparison of modelled fur seal biomass with fishery-observer data from Gasco et al. (2019). The estimated biomass trend for the model period (1986–2018) is shown on the left, a subsection of the trend equivalent to the fishery-observer data (2003–2017) is shown on the top right and fishery-observer data (individuals per day per year) with LOESS smoothing (blue) is presented on bottom left.

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