The following supplement accompanies the article

Phenological trends and trophic mismatch across multiple levels of a North Sea pelagic food web

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Supplement

Phenology trends

Table S1. Phenology trends (estimate) and standard errors (SE) for each species/group over the study period (1983 to 2006)

Trophic level	Species/group	n	Estimate	SE	*t*-value	p-value	R^2
Primary producer	*Paralia sulcata*	23	2.277	1.019	2.235	0.036	19.216
Primary producer	*Skeleton costatum*	21	–0.709	0.373	–1.902	0.072	16.000
Primary producer	*Thalassiosira* spp.	23	–0.387	0.381	–1.016	0.321	4.685
Primary producer	*Rhizosol stylifera*	19	1.090	1.073	1.015	0.324	5.714
Primary producer	*Rhizosol semispina*	20	–0.205	0.610	–0.336	0.741	0.623
Primary producer	*Hyalochaete* spp.	23	0.059	0.366	0.161	0.874	0.123
Primary producer	*Phaeoceros* spp.	23	0.940	0.461	2.039	0.054	16.528
Primary producer	*Asterionella* spp.	21	–0.895	0.501	–1.786	0.090	14.380
Primary producer	*Thalassionema nitzschoides*	22	–0.051	0.490	–0.105	0.918	0.055
Primary producer	*Nitzsch delicatissima*	22	–0.800	0.564	–1.418	0.172	9.137
Primary producer	Phytoplankton colour index	23	–0.019	0.009	–1.989	0.060	15.848
Primary producer	Summed phytoplankton	23	–0.006	0.011	–0.585	0.565	1.605
Primary consumer	Calanus spp. Stages I–IV	23	–0.637	0.454	–1.403	0.175	8.569
Primary consumer	*Temora longicornis*	23	–1.125	0.406	–2.772	0.011	26.788
Primary consumer	*Calanus finmarchicus*	23	–0.096	0.442	–0.217	0.831	0.223
Primary consumer	*Calanus helgolandicus*	23	1.228	0.764	–1.607	0.123	10.945
Primary consumer	Copepod nauplii	23	–0.020	0.012	–1.692	0.105	11.997
Primary/Secondary consumer	Sandeel hatch date (1983–1995)	13	2.162	0.535	4.044	0.002	59.790
Primary/Secondary consumer	Sandeel hatch date (1995–2006)	12	–1.888	0.604	–3.125	0.011	49.400
Top predator	Guillemot median egg	24	0.302	0.094	3.200	0.004	31.760
Top predator	Razorbill median egg	24	0.149	0.107	1.394	0.177	8.115
Top predator	Shag median ringing	24	–0.510	0.526	–0.970	0.343	4.098
Top predator	Kittiwake first egg	24	0.707	0.206	3.436	0.002	34.918
Top predator	Puffin first egg	24	0.247	0.144	1.712	0.101	11.757

Correlations between phenology trends and climate

The lack of relationships between phenology and SST appear genuine. We detrended the analyses by including year, but this did not alter our conclusions. The timing of seabird breeding for the different species was more strongly correlated with 'year' than with any of the explanatory variables considered, and the explanatory variable is often more strongly correlated with year than with the response variable. Therefore the explanatory and response variables are only weakly correlated with each other.

Relationships between predator and prey phenologies

Table S2. Linear regression of phenology of upper trophic level species/group against the phytoplankton phenology measured as the month of central tendency for the summed top 10 most abundant phytoplankton (the alternative measure of phytoplankton colour index is reported in Table 2). *T* is the central tendency for monthly plankton data

Response	Explanatory	Slope estimate	SE	*t*	p-value
Calanus finmarchicus T	Summed total phytoplankton abundance *T*	–0.302	0.277	–1.091	0.288
C. helgolandicus T	Summed total phytoplankton abundance *T*	–0.400	0.513	–0.780	0.444
Calanus spp. stages *T*	Summed total phytoplankton abundance *T*	0.070	0.305	0.230	0.820
Temora longicornis T	Summed total phytoplankton abundance *T*	0.159	0.303	0.525	0.605
Copepod spp. nauplii *T*	Summed total phytoplankton abundance *T*	0.156	0.250	0.621	0.541
Sandeel hatch	Summed total phytoplankton abundance *T*	0.165	0.140	1.180	0.251

Phenology of sandeel size thresholds

We use a modified version of the mismatch hypothesis, and our prediction was that parent birds should time mid-chick-rearing to coincide with sandeels *Ammodytes marinus* having attained some threshold size, since individual seabirds are expected to balance increasing prey quality through the season with the fitness advantages of breeding as early as possible (Daunt et al. 2007, Harris et al. 2007). Accordingly we defined an annual 'mismatch index' for each seabird species as the difference (in days) between mid-chick rearing date and the date sandeels reached a threshold size.

We explored how well seabirds tracked different thresholds. The threshold reported in the present paper was 55 mm, because there was evidence that the correlation between the timing of seabird breeding and the timing of threshold sizes being attained by sandeels was better for higher threshold values. However, due to particularly slow growth in some years, most notably 2004, sandeels failed to reach a threshold >55 mm by 1 August in some years. Omitting years from the analysis is problematic, because these are years when growth is very slow and hence size thresholds are attained late in the season, and using lower thresholds facilitates analysis of the entire study period.

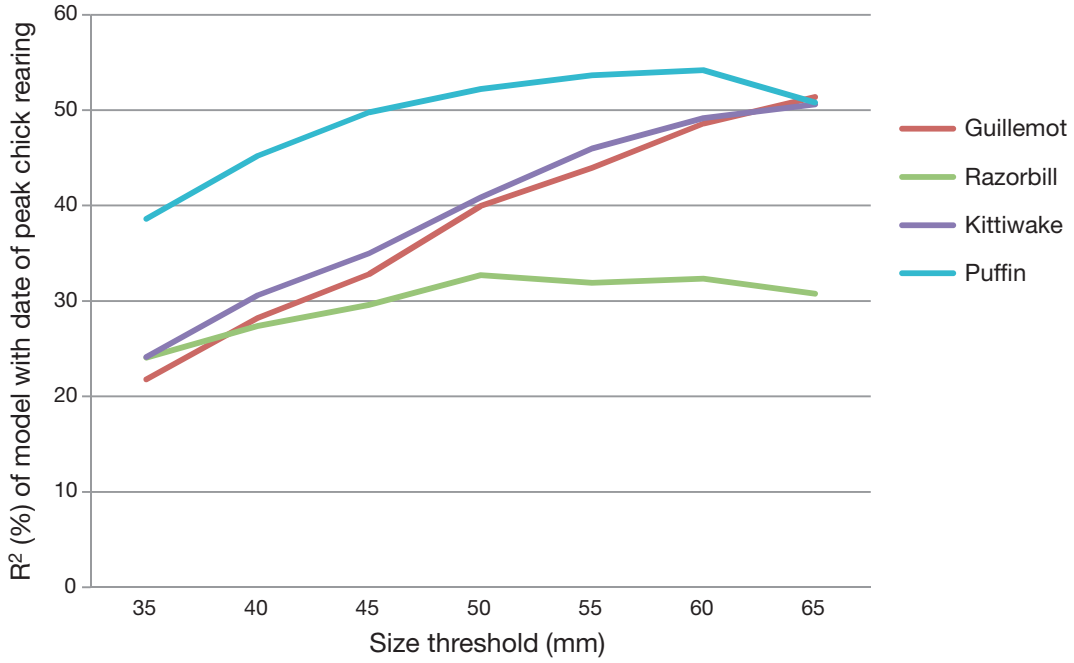

Fig. S1. *Ammodytes marinus*. Model R^2 values for regressions between the timing of peak chick rearing in seabirds and the date that sandeels attain a particular size threshold for the time series between 1983 and 2006 (with 1993 and 2004 removed from the data as sandeels failed to reach a threshold of ≤60 mm in these years)

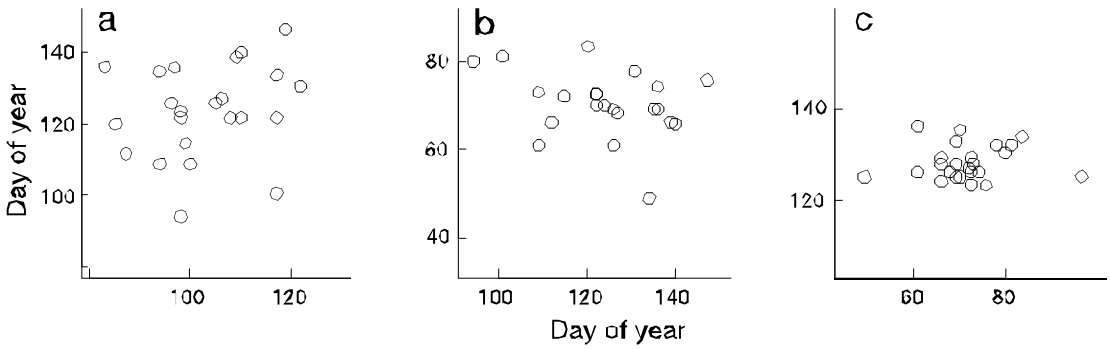

Fig. S2. Three examples of the lack of relationship between the phenology of predators and prey. In all cases the upper trophic level is shown on the *y*-axis and the lower trophic level on the *x*-axis for: (a) peak copepod nauplii abundance date regressed against peak phytoplankton colour index date; (b) sandeel mean hatch date against copepod nauplii peak abundance date; (c) guillemot median egg laying date against sandeel mean hatch date (dates as day of year)

Correlations between sandeel model parameters

Table S3. *Ammodytes marinus*. Correlations between sandeel parameters (n = 24 in all cases), with significant correlations indicated in bold

	Sandeel biomass index	Sandeel hatch date	Sandeel growth rate	Date sandeel reach 55 mm threshold
Sandeel biomass index	**1**			
Sandeel hatch date	–0.053	**1**		
Sandeel growth rate	–0.268	0.364	**1**	
Date sandeel reach 55 mm threshold	0.306	0.287	**–0.692**	**1**

Breeding success modelling

Generalised linear modelling was used to evaluate whether changes in seabird breeding success were associated with sandeel phenology and mismatch parameters. Sandeel parameters, apart from the sandeel biomass index, were obtained from the sandeel model (Frederiksen et al. 2011) and hence were not fitted together in models. We report AICc results for the full set of candidate models run for each seabird species to investigate factors correlated with breeding success.

Table S4. Modelling of breeding success for the 5 seabird species (n = 24 yr for all species except shag where n = 21 and kittiwake where n = 22). Sandeel parameters were non-independent (obtained from the modelling work of Frederiksen et al. 2011) and were not included together in the model selection. SBIlag1: sandeel biomass index in the previous year; SSTlag1: spring sea-surface temperature in the previous year; mismatch index: difference in days between the timing of mid-chick-rearing (species specific) and the predicted date that sandeels attained a size threshold of 55 mm.The best models (lowest AICc) are highlighted in bold for each species

Species	Model	*k*	AICc	deltaAICc	Akaike weight
Guillemot	**Year+sandeel growth rate**	**4**	**–59.430**	**0.000**	**0.641**
Guillemot	Year+SSTlag1+sandeel growth rate	5	–56.250	3.180	0.131
Guillemot	Year+SBIlag1+sandeel growth rate	5	–56.240	3.190	0.13
Guillemot	Year+SSTlag1+sandeel growth rate+SBIlag1	6	–52.720	6.710	0.022
Guillemot	Year+sandeel hatch date	4	–52.350	7.080	0.019
Guillemot	SSTlag1+sandeel growth rate	4	–52.210	7.220	0.017
Guillemot	Sandeel growth rate	3	–51.670	7.760	0.013
Guillemot	SBIlag1+sandeel growth rate	4	–50.370	9.060	0.007
Guillemot	SSTlag1+sandeel growth rate+SBIlag1	5	–49.850	9.580	0.005
Guillemot	Year+SBIlag1+sandeel hatch date	5	–49.120	10.310	0.004
Guillemot	Year+mismatch index	4	–48.530	10.900	0.003
Guillemot	Year	3	–47.860	11.570	0.002
Guillemot	Year+SSTlag1+sandeel hatch date	5	–47.730	11.700	0.002
Guillemot	Year+sandeel size	4	–46.700	12.730	0.001
Guillemot	Year+SBIlag1+mismatch index	5	–45.310	14.120	0.001
Guillemot	Year+SBIlag1	4	–45.000	14.430	0
Guillemot	Year+SSTlag1+mismatch index	5	–44.370	15.060	0
Guillemot	Year+SSTlag1+sandeel hatch date+SBIlag1	6	–44.130	15.300	0
Guillemot	Year+SSTlag1	4	–44.000	15.430	0
Guillemot	Year+SBIlag1+sandeel size	5	–43.520	15.910	0
Guillemot	Year+SSTlag1+sandeel size	5	–43.150	16.280	0
Guillemot	SSTlag1+mismatch index	4	–41.890	17.540	0
Guillemot	Mismatch index	3	–41.730	17.700	0
Guillemot	SSTlag1+sandeel size	4	–41.540	17.890	0
Guillemot	Year+SSTlag1+SBIlag1	5	–40.850	18.580	0
Guillemot	Year+SSTlag1+mismatch index+SBIlag1	6	–40.770	18.660	0
Guillemot	SBIlag1+mismatch index	4	–39.890	19.540	0
Guillemot	Sandeel size	3	–39.710	19.720	0
Guillemot	Year+SSTlag1+sandeel size+SBIlag1	6	–39.610	19.820	0
Guillemot	SSTlag1+mismatch index+SBIlag1	5	–39.080	20.350	0
Guillemot	SSTlag1+sandeel size+SBIlag1	5	–38.890	20.540	0
Guillemot	SBIlag1+sandeel size	4	–38.250	21.180	0
Guillemot	SSTlag1	3	–37.430	22.000	0
Guillemot	SSTlag1+sandeel hatch date	4	–35.870	23.560	0
Guillemot	SSTlag1+SBIlag1	4	–35.630	23.800	0
Guillemot	Intercept only	2	–34.580	24.850	0
Guillemot	SBIlag1	3	–34.540	24.890	0
Guillemot	SSTlag1+sandeel hatch date+SBIlag1	5	–33.830	25.600	0
Guillemot	Sandeel hatch date	3	–33.420	26.010	0
Guillemot	SBIlag1+sandeel hatch date	4	–33.240	26.190	0
Razorbill	**Year+sandeel growth rate**	**4**	**–62.010**	**0.000**	**0.234**

Razorbill	Year	3	–61.590	0.420	0.189
Razorbill	Year+mismatch index	4	–59.920	2.090	0.082
Razorbill	Year+SBIlag1+sandeel growth rate	5	–59.740	2.270	0.075
Razorbill	Year+sandeel size	4	–59.620	2.390	0.071
Razorbill	Year+SBIlag1	4	–59.460	2.550	0.065
Razorbill	Year+sandeel hatch date	4	–59.400	2.610	0.063
Razorbill	Year+SBIlag1+mismatch index	5	–57.710	4.300	0.027
Razorbill	Year+SBIlag1+sandeel size	5	–57.210	4.800	0.021
Razorbill	Year+SSTlag1+sandeel growth rate	5	–57.140	4.870	0.02
Razorbill	Year+SBIlag1+sandeel hatch date	5	–57.130	4.880	0.02
Razorbill	Year+SSTlag1	4	–57.020	4.990	0.019
Razorbill	Sandeel growth rate	3	–56.240	5.770	0.013
Razorbill	SSTlag1+sandeel growth rate	4	–56.000	6.010	0.012
Razorbill	SSTlag1+sandeel size	4	–55.970	6.040	0.011
Razorbill	Year+SSTlag1+sandeel size	5	–55.480	6.530	0.009
Razorbill	Year+SSTlag1+mismatch index	5	–55.140	6.870	0.008
Razorbill	Sandeel size	3	–55.080	6.930	0.007
Razorbill	Mismatch index	3	–55.000	7.010	0.007
Razorbill	SSTlag1+mismatch index	4	–54.610	7.400	0.006
Razorbill	Year+SSTlag1+SBIlag1	5	–54.570	7.440	0.006
Razorbill	Year+SSTlag1+sandeel growth rate+SBIlag1	6	–54.500	7.510	0.005
Razorbill	Year+SSTlag1+sandeel hatch date	5	–54.140	7.870	0.005
Razorbill	SBIlag1+sandeel growth rate	4	–53.400	8.610	0.003
Razorbill	SSTlag1	3	–53.190	8.820	0.003
Razorbill	SSTlag1+sandeel size+SBIlag1	5	–52.930	9.080	0.002
Razorbill	SSTlag1+sandeel growth rate+SBIlag1	5	–52.860	9.150	0.002
Razorbill	Year+SSTlag1+sandeel size+SBIlag1	6	–52.730	9.280	0.002
Razorbill	Year+SSTlag1+mismatch index+SBIlag1	6	–52.570	9.440	0.002
Razorbill	SBIlag1+sandeel size	4	–52.190	9.820	0.002
Razorbill	SBIlag1+mismatch index	4	–52.100	9.910	0.002
Razorbill	SSTlag1+mismatch index+SBIlag1	5	–51.600	10.410	0.001
Razorbill	Year+SSTlag1+sandeel hatch date+SBIlag1	6	–51.430	10.580	0.001
Razorbill	Intercept only	2	–50.500	11.510	0.001
Razorbill	SSTlag1+sandeel hatch date	4	–50.310	11.700	0.001
Razorbill	SSTlag1+SBIlag1	4	–50.280	11.730	0.001
Razorbill	SBIlag1	3	–48.440	13.570	0
Razorbill	Sandeel hatch date	3	–47.870	14.140	0
Razorbill	SSTlag1+sandeel hatch date+SBIlag1	5	–47.090	14.920	0
Razorbill	SBIlag1+sandeel hatch date	4	–45.540	16.470	0
Shag	**Year+SSTlag1+sandeel growth rate+SBIlag1**	**6**	**–27.280**	**0.000**	**0.120**
Shag	SBIlag1	3	–26.810	0.470	0.095
Shag	Intercept only	2	–26.120	1.160	0.067
Shag	Year+SSTlag1+SBIlag1	5	–25.790	1.490	0.057
Shag	Year+SSTlag1	4	–25.460	1.820	0.048
Shag	Year+SSTlag1+sandeel growth rate	5	–25.430	1.850	0.048
Shag	SBIlag1+sandeel growth rate	4	–25.400	1.880	0.047
Shag	SSTlag1+SBIlag1	4	–25.190	2.090	0.042
Shag	Year+SBIlag1+sandeel growth rate	5	–24.860	2.420	0.036

Shag	Year	3	–24.630	2.650	0.032
Shag	Sandeel size	3	–24.410	2.870	0.029
Shag	Mismatch index	3	–24.370	2.910	0.028
Shag	Year+SBIlag1	4	–24.330	2.950	0.027
Shag	Year+sandeel growth rate	4	–24.300	2.980	0.027
Shag	Sandeel hatch date	3	–24.010	3.270	0.023
Shag	Sandeel growth rate	3	–23.970	3.310	0.023
Shag	SBIlag1+mismatch index	4	–23.970	3.310	0.023
Shag	SSTlag1	3	–23.950	3.330	0.023
Shag	SBIlag1+sandeel hatch date	4	–23.760	3.520	0.021
Shag	Year+SSTlag1+mismatch index+SBIlag1	6	–23.690	3.590	0.02
Shag	Year+SSTlag1+sandeel hatch date	5	–23.240	4.040	0.016
Shag	Year+SSTlag1+sandeel size	5	–23.030	4.250	0.014
Shag	SSTlag1+sandeel growth rate+SBIlag1	5	–22.730	4.550	0.012
Shag	SBIlag1+sandeel size	4	–22.610	4.670	0.012
Shag	Year+SSTlag1+mismatch index	5	–22.360	4.920	0.01
Shag	Year+SSTlag1+sandeel hatch date+SBIlag1	6	–22.160	5.120	0.009
Shag	SSTlag1+sandeel hatch date	4	–22.010	5.270	0.009
Shag	SSTlag1+sandeel hatch date+SBIlag1	5	–21.940	5.340	0.008
Shag	Year+sandeel hatch date	4	–21.930	5.350	0.008
Shag	SSTlag1+mismatch index	4	–21.870	5.410	0.008
Shag	SSTlag1+mismatch index+SBIlag1	5	–21.870	5.410	0.008
Shag	Year+SSTlag1+sandeel size+SBIlag1	6	–21.860	5.420	0.008
Shag	Year+mismatch index	4	–21.770	5.510	0.008
Shag	SSTlag1+sandeel size	4	–21.760	5.520	0.008
Shag	Year+sandeel size	4	–21.690	5.590	0.007
Shag	SSTlag1+sandeel growth rate	4	–21.190	6.090	0.006
Shag	Year+SBIlag1+sandeel hatch date	5	–20.840	6.440	0.005
Shag	Year+SBIlag1+mismatch index	5	–20.840	6.440	0.005
Shag	SSTlag1+sandeel size+SBIlag1	5	–20.120	7.160	0.003
Shag	Year+SBIlag1+sandeel size	5	–19.300	7.980	0.002
Kittiwake	**SBIlag1+fishery+SSTlag1**	**5**	**–39.250**	**0.000**	**0.446**
Kittiwake	SSTlag1+SBIlag1	4	–36.970	2.280	0.143
Kittiwake	Fishery+sandeel growth rate+SBIlag1+SSTlag1	6	–36.810	2.440	0.132
Kittiwake	Fishery+sandeel size+SBIlag1+SSTlag1	6	–36.010	3.240	0.088
Kittiwake	Fishery+sandeel size+SSTlag1	5	–34.570	4.680	0.043
Kittiwake	Fishery+sandeel growth rate+SSTlag1	5	–34.550	4.700	0.043
Kittiwake	Fishery+sandeel hatch date+SBIlag1+SSTlag1	6	–34.150	5.100	0.035
Kittiwake	Fishery+sandeel hatch date+SSTlag1	5	–33.610	5.640	0.027
Kittiwake	Fishery+mismatch index +SBIlag1+SSTlag1	6	–31.370	7.880	0.009
Kittiwake	Fishery+mismatch index +SSTlag1	5	–31.330	7.920	0.009
Kittiwake	SBIlag1+fishery	4	–31.310	7.940	0.008
Kittiwake	SSTlag1+SBIlag1+sandeel hatch date	5	–31.310	7.940	0.008
Kittiwake	Fishery	3	–28.010	11.240	0.002
Kittiwake	Fishery+sandeel size	4	–27.870	11.380	0.002
Kittiwake	SSTlag1+SBIlag1+sandeel size	5	–27.320	11.930	0.001
Kittiwake	SSTlag1+SBIlag1+mismatch index	5	–26.950	12.300	0.001
Kittiwake	Fishery+sandeel size+SBIlag1	5	–26.450	12.800	0.001
Kittiwake	Fishery+sandeel growth rate	4	–26.320	12.930	0.001

Kittiwake	Fishery+sandeel hatch date	4	–25.870	13.380	0.001
Kittiwake	SSTlag1+SBIlag1+sandeel growth rate	5	–25.490	13.760	0
Kittiwake	SSTlag1	3	–25.030	14.220	0
Kittiwake	SSTlag1+mismatch index	4	–24.940	14.310	0
Kittiwake	Fishery+sandeel growth rate+SBIlag1	5	–24.820	14.430	0
Kittiwake	Sandeel hatch date	3	–24.080	15.170	0
Kittiwake	SBIlag1	3	–23.990	15.260	0
Kittiwake	Fishery+sandeel hatch date+SBIlag1	5	–23.760	15.490	0
Kittiwake	Intercept only	2	–23.640	15.610	0
Kittiwake	SBIlag1+sandeel size	4	–23.420	15.830	0
Kittiwake	SSTlag1+fishery	4	–23.370	15.880	0
Kittiwake	Fishery+mismatch index	4	–23.180	16.070	0
Kittiwake	SBIlag1+sandeel growth rate	4	–22.890	16.360	0
Kittiwake	SSTlag1+sandeel hatch date	4	–22.340	16.910	0
Kittiwake	SSTlag1+sandeel growth rate	4	–22.340	16.910	0
Kittiwake	SSTlag1+sandeel size	4	–22.230	17.020	0
Kittiwake	Mismatch index	3	–21.610	17.640	0
Kittiwake	Sandeel size	3	–21.580	17.670	0
Kittiwake	SBIlag1+sandeel hatch date	4	–21.190	18.060	0
Kittiwake	Sandeel growth rate	3	–20.950	18.300	0
Kittiwake	SBIlag1+mismatch index	4	–20.780	18.470	0
Kittiwake	Fishery+mismatch index +SBIlag1	5	–20.210	19.040	0
Puffin	**Year+SSTlag1+SBIlag1**	**5**	**–52.400**	**0.000**	**0.252**
Puffin	SSTlag1+SBIlag1	4	–50.180	2.220	0.083
Puffin	SSTlag1	3	–50.120	2.280	0.08
Puffin	Year+SSTlag1+sandeel hatch date+SBIlag1	6	–49.560	2.840	0.061
Puffin	Year+SSTlag1	4	–49.490	2.910	0.059
Puffin	Year+SSTlag1+mismatch index+SBIlag1	6	–49.020	3.380	0.046
Puffin	SSTlag1+sandeel hatch date	4	–48.950	3.450	0.045
Puffin	Year+SSTlag1+sandeel size+SBIlag1	6	–48.950	3.450	0.045
Puffin	Year+SSTlag1+sandeel growth rate+SBIlag1	6	–48.940	3.460	0.045
Puffin	SSTlag1+sandeel hatch date+SBIlag1	5	–48.930	3.470	0.044
Puffin	SSTlag1+sandeel size+SBIlag1	5	–48.610	3.790	0.038
Puffin	SSTlag1+mismatch index+SBIlag1	5	–48.460	3.940	0.035
Puffin	SSTlag1+sandeel size	4	–48.000	4.400	0.028
Puffin	SSTlag1+mismatch index	4	–47.780	4.620	0.025
Puffin	SSTlag1+sandeel growth rate	4	–47.240	5.160	0.019
Puffin	Year+SSTlag1+sandeel hatch date	5	–47.220	5.180	0.019
Puffin	SSTlag1+sandeel growth rate+SBIlag1	5	–47.090	5.310	0.018
Puffin	Year+SSTlag1+sandeel growth rate	5	–46.410	5.990	0.013
Puffin	Year+SSTlag1+sandeel size	5	–46.320	6.080	0.012
Puffin	Year+SSTlag1+mismatch index	5	–46.290	6.110	0.012
Puffin	Year+SBIlag1	4	–45.240	7.160	0.007
Puffin	Year	3	–44.460	7.940	0.005
Puffin	Year+SBIlag1+mismatch index	5	–42.170	10.230	0.002
Puffin	Year+SBIlag1+sandeel hatch date	5	–42.040	10.360	0.001
Puffin	Year+SBIlag1+sandeel growth rate	5	–42.040	10.360	0.001
Puffin	Year+SBIlag1+sandeel size	5	–42.010	10.390	0.001
Puffin	Year+sandeel growth rate	4	–41.600	10.800	0.001

Puffin	Year+mismatch index	4	–41.590	10.810	0.001
Puffin	Year+sandeel size	4	–41.570	10.830	0.001
Puffin	Year+sandeel hatch date	4	–41.560	10.840	0.001
Puffin	Mismatch index	3	–35.220	17.180	0
Puffin	Intercept only	2	–34.780	17.620	0
Puffin	Sandeel size	3	–34.520	17.880	0
Puffin	Sandeel growth rate	3	–33.840	18.560	0
Puffin	SBIlag1+mismatch index	4	–32.630	19.770	0
Puffin	Sandeel hatch date	3	–32.440	19.960	0
Puffin	SBIlag1	3	–32.150	20.250	0
Puffin	SBIlag1+sandeel size	4	–31.780	20.620	0
Puffin	SBIlag1+sandeel growth rate	4	–31.020	21.380	0
Puffin	SBIlag1+sandeel hatch date	4	–29.540	22.860	0

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